MINERAL AND WATER RESOURCES OF COLORADO

Report compiled by

UNITED STATES GEOLOGICAL SURVEY

in collaboration with the

COLORADO MINING INDUSTRIAL DEVELOPMENT BOARD

for

UNITED STATES SENATE COMMITTEE ON INTERIOR AND INSULAR AFFAIRS

at request of

SENATOR GORDON ALLOTT

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U. S. SENATOR GORDON ALLOTT
Requested Preparation
of Report

U. S. SENATOR PETER DOMINICK
Cooperated in Securing
Approval of Senate Interior
and Insular Affairs Committee

"Colorado's mineral and water resources are highly important to the future advancement of our economy. It is most fortunate that this carefully prepared report of the United States Geological Survey in collaboration with the Mining Industrial Development Board and other agencies has been made available through the request of Senator Gordon Allott, and the cooperation of Senator Peter Dominick, both members of the Committee on Interior and Insular Affairs, United States Senate.

GOVERNOR JOHN A. LOVE

"The report will be distributed throughout Colorado and numerous other states, and made available for libraries, universities, colleges and schools. In fact, will be available as long as the supply lasts for the enlightenment and education of those seeking greater knowledge of these highly important resources. In offering this report to the citizens of Colorado, it is hoped the report will be used as a quick reference for reliable information, and encourage greater development of our mineral and water resources."

John A. Love

STATE OF COLORADO

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2d Session } { No. 115

MINERAL AND WATER RESOURCES OF COLORADO

REPORT

OF THE

UNITED STATES GEOLOGICAL SURVEY

IN COLLABORATION WITH

THE COLORADO MINING INDUSTRIAL DEVELOPMENT BOARD

PREPARED AT THE REQUEST OF

SENATOR GORDON ALLOTT
OF COLORADO

OF THE

COMMITTEE ON INTERIOR AND
INSULAR AFFAIRS
UNITED STATES SENATE

OCTOBER 11, 1968.—Ordered to be printed with illustrations

U.S. GOVERNMENT PRINTING OFFICE
21-417 O WASHINGTON : 1968

SENATE RESOLUTION 417

Submitted by Mr. Allott of Colorado

IN THE SENATE OF THE UNITED STATES,
Agreed to October 11, 1968.

Resolved, That the compilation entitled "Mineral and Water Resources of Colorado", a report by the United States Geological Survey, prepared at the request of Senator Gordon Allott of the Committee on Interior and Insular Affairs, be printed with illustrations as a Senate document; and that there be printed one thousand additional copies of such document for the use of that committee.

FRANCIS R. VALEO,
Secretary.

MEMORANDUM FROM THE CHAIRMAN

To Members of the Senate Committee on Interior and Insular Affairs:

I am transmitting for your information a report entitled "Mineral and Water Resources of Colorado," prepared by the U.S. Geological Survey at the request of our colleague, Senator Gordon Allott.

This detailed survey will be particularly helpful to government and business leaders in Colorado. It will also be valuable to the Congress and members of this committee as we consider legislation regarding mineral and water development.

HENRY M. JACKSON, *Chairman.*

FOREWORD

The U.S. Geological Survey, with the collaboration of the Colorado Mining Industrial Development Board, and the cooperation of the Colorado Water Conservation Board, has done a most creditable job in preparing this report. I requested its preparation for the purpose of making the significant data concerning Colorado's mineral and water resources widely available to all who may have need of such information in a composite form.

Colorado's development has depended almost entirely upon its mineral and water resources. While in early years, mineral resources played the key role in Colorado's development, in more recent years, Colorado's expanding agricultural community has moved water resources to the forefront. In any event, the importance of both of these vital resources to the economic well-being of Colorado cannot be overestimated.

I wish to express my thanks to all those in Colorado, Washington, D.C., and elsewhere who have contributed so effectively to the making of this report.

GORDON ALLOTT,
U.S. Senator.

MINERAL AND WATER RESOURCES OF COLORADO

REPORT

OF THE

UNITED STATES GEOLOGICAL SURVEY

IN COLLABORATION WITH

THE COLORADO MINING INDUSTRIAL DEVELOPMENT BOARD

PREPARED AT THE REQUEST OF

SENATOR GORDON ALLOTT

OF COLORADO

OF THE

COMMITTEE ON INTERIOR AND INSULAR AFFAIRS

UNITED STATES SENATE

LETTER OF TRANSMITTAL

U.S. DEPARTMENT OF THE INTERIOR,
GEOLOGICAL SURVEY,
Washington, D.C., June 4, 1964.

Hon. GORDON ALLOTT,
U.S. Senate, Washington, D.C.

DEAR SENATOR ALLOTT: I am pleased to transmit herewith a summary report on the mineral and water resources of Colorado which has been prepared by the Geological Survey in collaboration with the Colorado Mining Industrial Development Board. It has been prepared in response to your request of June 14, 1963.

The report describes the mineral commodities known to occur in Colorado, together with information on their manner of occurrence, distribution, and relative importance to the present and future mineral industry of the State. Surface and ground water supplies of the major regions of the State are described in considerable detail, with generalized information on the chemical quality of water and on waterpower. The narrative discussion on most commodities is supplemented by maps and diagrams illustrating the distribution of resources and the availability of water supplies.

It is hoped that the data in the report will be adequate to supply the information you desire.

Sincerely,

THOMAS B. NOLAN, *Director.*

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INTRODUCTION

This report describes in summary form the mineral and water resources of Colorado. Its purpose is to give factual information about the present supplies of minerals and water in the State and a realistic appraisal of the supplies available for future production and consumption. Insofar as possible, the report is presented in nontechnical language. It is intended mainly for use by Government officials at the Federal, State, and county levels; by leaders in industry and commerce; and by the schools and the lay public. Specialists in the fields of mineral commodities and water will find little that is new to them, but it is hoped that even they will find the report in general a useful compendium. References to pertinent sources of additional information are cited in the text and listed at the end of the sections on geology, mineral commodities, and water supply.

This report is divided into three main parts:

(1) The introductory part gives a brief general description of the geology of Colorado, generalized geologic and structural maps, and information on topographic and geologic mapping in the State.

(2) The part on the mineral industry is introduced with a brief historic sketch, followed by separate sections on several dozen mineral commodities. If appropriate, each commodity section lists the principal uses of that commodity, reviews its production and relative importance in the State and the Nation, briefly describes the principal kinds of occurrences and the productive and potential sources in Colorado, and concludes with an appraisal of the resources and outlook. Maps showing the distribution of deposits and occurrences in Colorado accompany the discussions.

(3) The section on water resources discusses the quantity, quality, and distribution of surface- and ground-water supplies that are being utilized and those that might be available for development, by geographic parts of the State. Additional information is presented in maps, graphs, and tables.

In this report the term "resources" applies to materials in the ground that are known to be minable now, plus materials that are likely to become minable at some time in the future. "Reserves," on the other hand, are materials that may or may not be completely explored but which may be quantitatively estimated and are considered to be economically exploitable at the time of the estimate. "Ore" is mineral material that may be mined at a profit, and the term "ore reserves" is applied to mineral deposits currently being mined, or to deposits known to be of such size and grade that they may be profitably mined.

Each section of this report was written by a specialist on the subject. The report was prepared in cooperation with the Colorado Mining Industrial Development Board, Colorado Water Conservation Board, Colorado State Engineer, and the Colorado Mining Association. In addition to employees of the U.S. Geological Survey, sections of the report were prepared through the State agencies by representatives of the mineral industry in Colorado, who generously contributed their time and knowledge without compensation. Those sections of the report for which authorship is not specifically credited have been prepared by R. P. Fischer assisted by the staff of the Geological Survey. Special acknowledgment is made to the Colorado Bureau of Mines and the U.S. Bureau of Mines for cooperation and the compilation of certain statistical data.

Much of the experience and background knowledge that permitted the contributions to this report by staff members of the Geological Survey were supported directly or indirectly by the long-established programs of financial cooperation between the State of Colorado and the U.S. Geological Survey. Among past and present agencies maintaining such cooperative programs are the Colorado State Geological Survey Board, Colorado Metal Mining Fund, Colorado Mineral Resources Board, Colorado Division of Natural Resources, Colorado Mining Industrial Development Board, Colorado Water Conservation Board, Office of the State Engineer, and other State and local agencies.

GEOLOGY

(By Ogden Tweto, U.S. Geological Survey, Denver, Colo.)

Colorado is divided by the Rocky Mountains into three parts that differ in topography, geology, natural resources, climate, and human activities. The eastern part, in the Great Plains province, is characterized geologically by relatively undisturbed, flat-lying sedimentary rocks. Its economic life, controlled principally by geology and a rigorous semiarid climate, depends in part on the production of mineral fuels, but to a greater degree on agriculture, the character of which is largely determined by the availability of water. The middle part of the State, the mountain province, has rocks of many kinds and ages divided into many different structural units. In this province are the rich ore deposits and mining districts that have brought Colorado wealth and fame, and, thanks to the availability of water, irrigated valleys that support a great livestock industry as well as farming of many kinds. The western part of the State, in the Plateau province, in some ways resembles the plains and in some ways the mountains. Like the plains, it is characterized by relatively undisturbed sedimentary rocks, but as in the mountains, the upland areas are at high altitudes and are separated by deep valleys and canyons. The province yields both mineral fuels and metallic and nonmetallic minerals; agriculturally, because of its altitude and semiarid climate, it is principally an area of stock raising except in irrigated valleys where rich and varied crops are grown.

TOPOGRAPHY

The Great Plains part of Colorado is an almost flat surface into which countless shallow valleys have been incised. The plains surface slopes gently eastward, from an altitude of 6,000–7,000 feet near the mountains to 3,500–4,000 feet near the Kansas border. The main valleys, as those of the Arkansas and South Platte Rivers, are as much as 1,000 feet below this level, but most other valleys are shallower, and many of the small ones are less than 100 feet below the plains surface.

The mountainous part of Colorado has a sharp eastern border, where the mountains rise abruptly above the plains along a slightly sinuous line, but the western border is irregular and not sharply separable from the plateau lands to the west. Within the mountainous tract are long subparallel ranges and subcircular mountain groups separated by valleys or broad basins. Two main ranges, the Front Range on the east and the Park Range to the west, extend from south-central Colorado northward into Wyoming. Between them is a line of basins known as South, Middle, and North Parks. A high, structurally domed area known as the White River Plateau lies west of the Park Range in northwestern Colorado, and in central Colorado the generally elliptical Sawatch Range lies west of the Park Range. West of the Sawatch Range are the Elk and West Elk mountain groups. In

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southern Colorado, a short range known as the Wet Mountains lies at the edge of the plains. West of it is the long and narrow Sangre de Cristo Range, which extends from the Arkansas River southward into New Mexico. Near the New Mexico border, this range fronts on the plains. West of the Sangre de Cristo is a broad basin, the San Luis Valley, and west of that, the San Juan Mountains, almost a hundred miles in diameter.

The broad mesas of the plateau lands in the western part of the State range from 6,000 to 11,000 feet in altitude, and the valleys between them are 2,000–5,000 feet lower. On the east the plateaus grade irregularly into the mountains, and on the north they end against the Uinta Mountains, a transverse range that extends from the northwestern corner of Colorado westward into Utah. To the west and south the plateau surface, dotted by small mountain groups and long low ridges, extends far into Utah and New Mexico.

In average altitude, Colorado is the highest State in the Union, and indeed, the highest area of its size on the North American Continent. All the larger mountain ranges exceed 12,000 feet in altitude, and almost all of them contain peaks that exceed 14,000 feet. Even the Plains are a mile or more above sea level in their western part. This high land is literally the summit of the continent, and from it major rivers flow outward in all directions, as the North and the South Platte, the Arkansas, the Rio Grande, the San Juan, the Colorado, and the Yampa, a major tributary of the Green River in Utah.

STRATIGRAPHY

Rock units of many kinds, ages, and origins are exposed at the surface in Colorado, and still others are known to exist at depth. The nature and distribution of these rocks not only influence the topography of the State and the life and activity of its citizens, but in large measure control the occurrence and character of all mineral deposits. Distribution of the rocks is shown in figure 1, a much generalized geologic map of the State. Like most geologic maps, this one classifies rocks mainly as to age but partly as to character and partly as to origin. This is done because it provides the simplest classification and because it emphasizes the historical succession of events, which is the unifying theme of all of geology. In keeping with the map and this principle, the rocks of Colorado are discussed below in order of age and in the historical context of geologic events.

The principal stratigraphic units in Colorado are listed in table 1, as are their general ages and approximate correlations, and their general distribution by major geographic sections in the State. In the following sections of this report, the formations that are listed in this table will not be identified by age; the reader is referred to this table if he is interested in the age relations.

Precambrian rocks.—Very ancient rocks classed collectively as Precambrian or basement rocks made up large parts of the Front, Park, and Sawatch Ranges and are exposed also in other mountain ranges and in the bottoms of many of the deep canyons in western Colorado. In general they are a mixture of metamorphic and igneous rocks. The metamorphic rocks, which are the older, are principally gneisses and schists of various kinds but include subordinate quartzites, marbles,

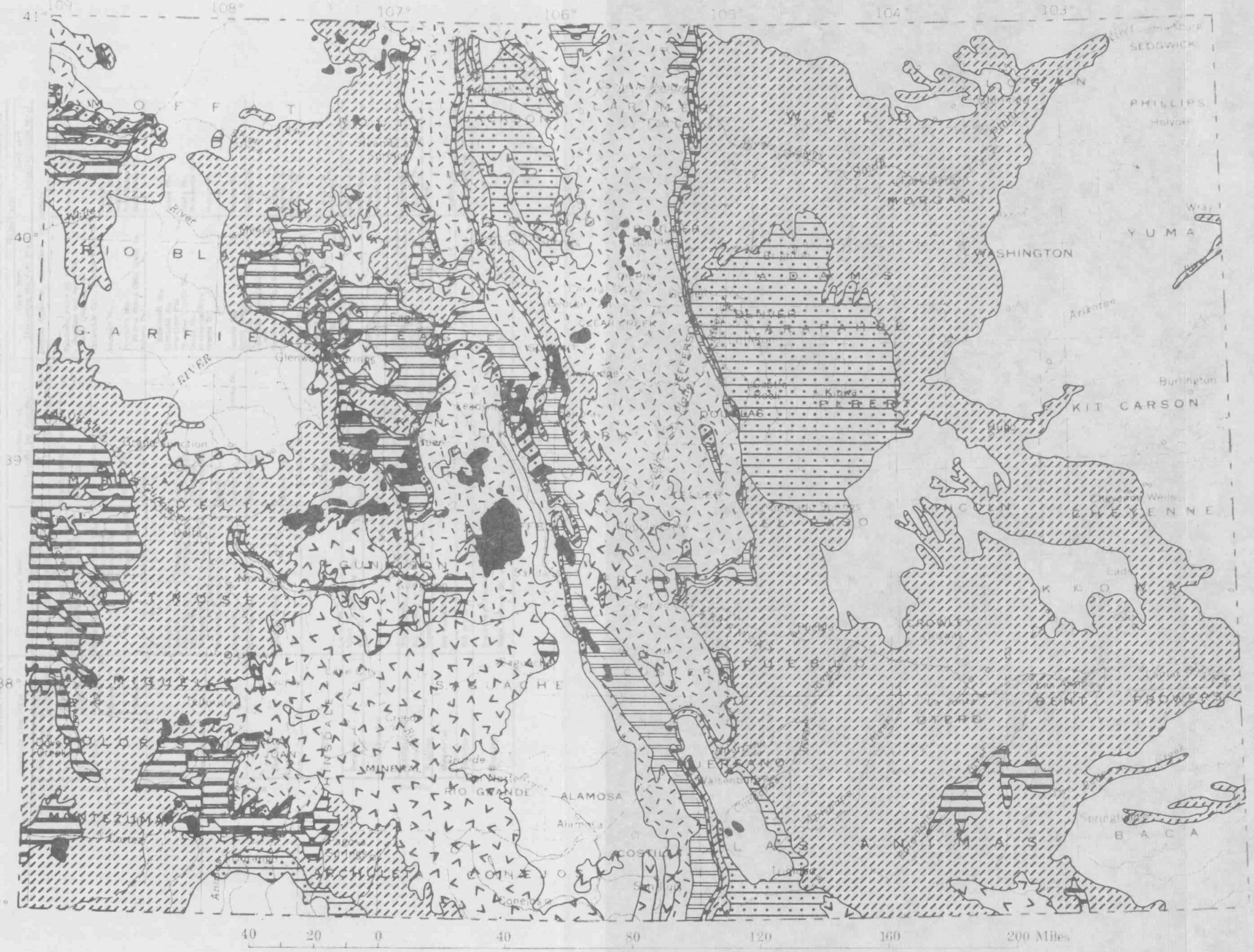

FIGURE 1.—Generalized geologic map of Colorado.

EXPLANATION

SEDIMENTARY ROCKS

Tertiary rocks, except lowest

Lowest Tertiary and uppermost Cretaceous rocks

Cretaceous rocks, except uppermost

Jurassic and Triassic rocks

Permian and Pennsylvanian rocks

Mississippian through Cambrian rocks

IGNEOUS AND METAMORPHIC ROCKS

Cenozoic volcanic rocks

Cenozoic intrusive rocks

Precambrian igneous and metamorphic rocks

Compiled by Ogden Tweto from geologic map of the United States (U. S. Geol. Survey, 1932), geologic map of Colorado (U. S. Geol. Survey, 1935), and other published and unpublished sources.

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Table 1.--Nomenclature of principal stratigraphic units in Colorado

Shows general ages and succession of formations, but correlation between columns is only approximate.
Grp., group; Fm., formation; Mb., member; Cgl., conglomerate; Dol., dolomite; Ls., limestone; Qtzt., quartzite; Ss., sandstone; Sh., shale.
Formations that are contiguous within columns but which do not occur in the same areas and hence are not found in contact are separated by asterisks (***).

Geologic time units			Plains area		Mountain area (except San Juan Mts.)	Plateau area: South part (including San Juan Mts.)	Plateau area: North part (including Uinta Mts.)
			Northern area	Southern area			
Cenozoic	Quaternary	Recent Pleistocene	Various alluviums and gravels		Various glacial deposits, alluviums, and gravels	Various glacial deposits, alluviums, and gravels	Various glacial deposits, alluviums, and gravels
	Tertiary	Pliocene	Ogalalla Fm.	Ogalalla Fm.	Alamosa Fm. Dry Union Fm., Santa Fe Fm. ***	Volcanic rocks of the San Juan and West Elk Mts. (Many names)	Browns Park Fm.
		Miocene	Arikaree Fm.	Devils Hole Fm.	North Park Fm.		
		Oligocene	White River Grp.	Farisita Cgl.	White River Fm.	Telluride Cgl., Blanco Basin Fm.	
		Eocene		Huerfano Fm. Cuchara Fm.		Wasatch Fm.	Bridger Fm. Green River Fm. Wasatch Fm.
		Paleocene		Poison Canyon Fm.	Coalmont Fm.	Torrejon and Puerco Fms.; Ohio Creek Fm.	Fort Union Fm. Ohio Creek Fm.
Mesozoic	Cretaceous		Denver and Dawson Fms. Arapahoe Fm. Laramie Fm. Fox Hills Ss. Pierre Sh. Niobrara Fm. Benton Sh. {Carlile Sh., Greenhorn Ls., Graneros Sh.} Dakota Ss.	Raton Fm. Vermejo Fm. Trinidad Ss.	Middle Park Fm. Laramie Fm. Fox Hills Ss. Pierre Sh. Niobrara Fm. Benton Sh. Dakota Ss. Lakota Fm.	Animas Fm. McDermott Mb. Kirtland Sh. Fruitland Fm. Pictured Cliffs Ss. Lewis Sh. Mesaverde Grp. Mancos Sh. Dakota Ss. Burro Canyon Fm.	Lance Fm. Lewis Sh. Mesaverde Grp. Mancos Sh. Dakota Ss.
	Jurassic		Morrison Fm. Ralston Creek Fm.		Morrison Fm. Entrada Ss.	Morrison Fm. Junction Creek Ss. *** Summerville Fm., Wanakah Fm. Entrada Ss.	Morrison Fm. Curtis Fm. Entrada Ss. Carmel Fm. Navajo Ss.
	Triassic				Chinle Fm.	Navajo Ss. Kayenta Fm. Wingate Ss. Dolores Fm., Chinle Fm. Moenkopi Fm.	Chinle Fm. Moenkopi Fm.
Paleozoic	Permian		Lykins Fm. Lyons Ss. Ingleside Fm. Fountain Fm.		Chugwater Fm. ***	Cutler Fm.	Park City Fm. Weber Ss.
	Pennsylvanian				Maroon Fm.—Sangre de Cristo Fm. *** Minturn Fm. Eagle Valley Evaporite *** Belden Fm., Kerber Fm.	Rico Fm. Hermosa Fm. Paradox Mb. Molas Fm.	Morgan Fm.
	Mississippian		Not exposed		Leadville Ls.	Leadville Ls.	Madison Ls.
	Devonian		Not exposed		Chaffee Fm. {Dyer Dol. Mb., Parting Qtzt. Mb.}	Ouray Ls. Elbert Fm.	Chaffee Fm.
	Silurian		Absent		Absent	Absent	Absent
	Ordovician		Not exposed		Fremont Ls. Harding Ss. Manitou Fm.	Absent	Manitou Fm.
	Cambrian		Not exposed		Peerless Fm. Sawatch Qtzt.	Ignacio Qtzt.	Sawatch Qtzt., Lodore Fm.
Precambrian			Granites and related rocks of at least three different ages. Idaho Springs Fm. and various other named and unnamed metamorphic rock units.				

slates, and phyllites. Intruded into these oldest rocks are granites and related rocks of at least three different ages within Precambrian time.

The metamorphic rocks are both metasedimentary and metavolcanic; that is, they formed by the recrystallization and transformation of older sedimentary and volcanic rocks. They are roughly divisible into two groups. One group, possibly the older and by far the more abundant, occurs in all areas of exposed Precambrian rocks, and deep oil wells indicate that it lies beneath the Plains also. The rocks of this group go by different names in different places, but in a large area in central Colorado, they are referred principally to the Idaho Springs Formation. The second group consists of somewhat less metamorphosed and less deformed quartzites, conglomerates, slates, phyllites, and argillites that occur principally in the southwestern and northwestern corners of the State. These rocks have been generally regarded as younger than the intensely metamorphosed rocks mentioned above, but they could be equivalent in age although differing in character because of difference in history.

Among the granitic rocks, the oldest are fairly dark, generally granodioritic and gneissic rocks that occur in small batholiths, stocks, and irregular bodies throughout most of the Precambrian terrane. The Boulder Creek Granodiorite, which forms a batholith about 20 miles long immediately west of Boulder, is typical of this oldest group of granitic rocks. Next younger is a group of light-colored, only locally foliated granites, which form several medium-sized batholiths and many smaller plutons. The Silver Plume Granite of the central Front Range is typical of this group. Still younger is a group of coarse-grained, generally dark-orange-pink, massive granites exemplified by the Pikes Peak Granite. The Pikes Peak occurs in a large batholith that makes up a large part of the southern Front Range, and generally correlative granites form smaller bodies in several other places.

As determined by the radioactive isotope technique, the age of the Pikes Peak Granite is about 1 billion years (Aldrich and others, 1958; Hutchinson, 1960). The granites of the next older group, including the Silver Plume Granite, are known from several determinations to be about 1.3 billion years old (Aldrich and others, 1958; Hutchinson, 1960; Giffin and Kulp, 1960). Age of the oldest granites, including the Boulder Creek, is uncertain because of the widespread heating effects of the second or middle group of granites, but is at least 1.5 billion years. The gneisses and schists into which these granites were intruded are, of course, older still, but at present there is no way of knowing whether they are just a little older, or vastly older.

Although the Precambrian rocks have been under study for many years, they are as yet imperfectly known; moreover, the information on them has not yet been brought together but is scattered through dozens of reports on local areas. A few brief summaries for larger areas exist however, as for the Front Range (Lovering and Goddard, 1950); Sawatch Range (Stark and Barnes, 1935); Gunison River area (Hunter, 1925); and San Juan Mountains (Larsen and Cross, 1956).

Paleozoic rocks.—The Paleozoic Era, which began about 600 million years ago and ended about 230 million years ago, is represented in Colorado entirely by sedimentary rocks, and these are divided into several formations (table 1). The lithologic character and the original distribution and thickness of these formations were controlled by the nature and position of the basins in which the sediments accumulated and the source areas from which the sediments came. After deposition, some formations were in places thinned or completely removed by erosion, so they are now more restricted in distribution than they were originally. Based on geologic characteristics and the history that they imply, the Paleozoic rocks of Colorado fall naturally into two broad divisions.

The older division, comprising rocks of Cambrian, Ordovician, Devonian, and Mississippian ages, consists principally of quartzites, dolomites, and limestones that were deposited slowly in shallow but widespread seas. The rocks of this division are relatively thin, ranging from 500 to 2,000 feet in total thickness, and they are in general only the thin edges of units that accumulated to far greater thicknesses farther west in Utah and Nevada. The general features of these rocks have been described by Johnson (1945) and by the Rocky Mountain Association of Geologists (1961).

Paleozoic rocks of the younger division, comprising those of Pennsylvanian and Permian ages, are much more varied in composition and much thicker than those of the older division, even though they represent a markedly shorter span of geologic time. They include siltstone, sandstone, conglomerate, limestone, dolomite, gypsum, and salt, some of which are marine and some continental in origin. Most of them accumulated in deep basins or troughs close to mountainous land areas from which the sediments were derived. One major land area of late Paleozoic time, known as the Front Range Highland, occupied the site of most of the present Front Range, Wet Mountains, northern half of the Park Range, and Middle and North Parks. A second major land area, the Uncompahgre-San Luis Highland, extended southeastward from eastern Utah, through the vicinity of Grand Junction, the San Juan Mountains, and San Luis Valley, into New Mexico. Clastic rocks and, more locally, carbonate rocks, gypsum, and salt accumulated to thicknesses averaging perhaps 10,000 feet in the trough between these two highlands and on the southwest side of the Uncompahgre Highland, in what is known as the Paradox basin. East of the Front Range Highland, the accumulation was not so great; coarse sediments reached a thickness of about 5,000 feet near the highland border but were thinner and finer grained eastward. The general characteristics of the late Paleozoic rocks of Colorado have been described by Brill (1944; 1952); the Rocky Mountain Association of Geologists (1958); and Mallory (1960).

Mesozoic rocks.—Mesozoic sedimentary rocks, comprising those of Triassic, Jurassic, and Cretaceous ages, are widely exposed in Colorado. Through much of the State, they total more than 10,000 feet in thickness, and of this, the great bulk is Cretaceous in age. General features of the Triassic and Jurassic rocks have been described by Oriel and Craig (1960); those of the Cretaceous rocks have been described by Haun and Weimer (1960), and, for parts of Colorado, by Dane and others (1937); Lee and Knowlton (1917); Reeside (1924); and Fisher and others (1960).

The Triassic rocks, less than 1,000 feet thick except near the western edge of the State, resemble the late Paleozoic rocks both in character and distribution. The Jurassic rocks—principally shale and sandstone—are more widespread because some of the younger ones covered the old Front Range and Uncompahgre Highlands, but except near the western border of the State, they are generally less than 1,000 feet thick. Most of the Triassic and Jurassic rocks were deposited on land, as in shallow basins, or along the courses of sluggish rivers, or as sand dunes. In contrast, most of the Cretaceous rocks were deposited in a vast inland sea or in swamps along its shores. This sea, which existed through the period roughly 135 to perhaps 65 million years ago was the last one ever to encroach on Colorado. The sediments deposited in it, mainly shale, sandstone, and shaly limestone, and related coastal swamp deposits, including much coal, once formed a blanket 5,000-12,000 feet thick over all of Colorado.

Many of the Cretaceous shales contain layers of bentonite, an alteration product of volcanic ash, and some of the youngest Cretaceous rocks contain pebbles and grains of volcanic rock. These coarser volcanic particles, along with other features of composition and texture in the youngest Cretaceous rocks, are evidence of the beginning of the Laramide orogeny, an epoch of mountain building that reached a zenith early in the succeeding Cenozoic Era. Most of the present-day mountains of Colorado came into being at this time.

Cenozoic rocks.—The rocks of the Cenozoic Era, the youngest major unit of geologic time, are partly clastic sedimentary rocks of continental origin and partly igneous. Those deposited in the early part of the Tertiary Period were influenced in character by the continuing Laramide orogeny, and they are, of course, part of the evidence for that orogeny. They include much conglomerate and feldspathic and clayey sandstone derived from the rising mountains, and they contain abundant volcanic debris that testifies to igneous activity that accompanied the mountain building. The rocks of this time accumulated principally near the mountain borders and in the intermontane basins, and it is in these areas that they are best seen today. At the same time that these sedimentary rocks were accumulating, and continuing for a time after, intrusive igneous rocks were emplaced in countless bodies in some parts of the mountain area. These intrusive rocks are of special significance because ore deposits of many kinds are related to them, as discussed in a following section.

During the latter part of the early Tertiary, when mountain-building was drawing to a close, thick deposits of fine-grained sediments accumulated in a swampy lake that occupied an extensive basin in northwestern Colorado and the adjoining parts of Utah and Wyoming. These sediments now compose the Green River Formation (Bradley, 1931; Donnell, 1961), which contains Colorado's great resources of oil shale.

In middle and late Tertiary time, beginning roughly 40 million years ago, the main mountain ranges were worn down by erosion but were periodically reelevated by crustal movements and, in places, by growth of volcanoes. Floods of debris eroded from the mountains were carried eastward and deposited as a thick blanket over the Plains. Similar debris accumulated also in many of the intermontane basins and valleys, and in northwestern Colorado. During this same time, volcanic eruptions occurred on a grand scale in southwestern Colorado, where a pile of volcanic rocks some 5,000 cubic miles in volume was built up, and related valuable ore deposits were formed. This pile, together with smaller and older uplifts protruding from beneath its western edge, constitutes the San Juan Mountains (Larsen and Cross, 1956).

During the Pleistocene, a part of the late Cenozoic that began about a million years ago and ended roughly 10,000 years ago, the mountain area was repeatedly glaciated (Richmond, 1960; Tweto, 1961). Glacial erosion created many of the striking landforms that characterize Colorado's great resource in mountain scenery; it also exposed some ore deposits, but it partly or wholly destroyed others. The glaciers deposited moraines in many of the mountain valleys, and streams flowing from the glaciers deposited sand and gravel in long ribbons down the valleys. These deposits of glacial age are the chief sources of sand and gravel in Colorado, and also the source of most of the State's placer gold.

STRUCTURE

Colorado is part of the stable interior of the North American continent, and as a consequence its structure—and its history since the Precambrian—is simpler than that of many of the other western states. Viewed broadly, the Plains and the plateau lands are areas of flat or gently dipping sedimentary rocks which are stacked on one another like layers of a cake. Many of the mountains, on the other hand, are giant upwarps of the earth's crust, from which the original cover of sedimentary rocks has been removed by erosion, exposing the underlying Precambrian rocks. Other mountains, such as the San Juans, are not so much upwarps as masses of volcanic rocks piled high above their surroundings. In the mountains particularly, but also on a smaller scale in the rest of the State, movements of the earth's crust have deformed the rocks, both bending them to create folds, domes, and basins, and fracturing them to create faults, joints, and shear zones. These structural features are economically significant in many ways. The fractures in many places guided the movements of solutions that deposited ores; folds have guided the movements of fluids such as petroleum and gas and in places control their resting place; and the great monoclinal upturns at the mountain fronts, coupled with erosion, have brought many of the deep lying sedimentary layers and their associated economic products into practical reach. The main structural features of the State are shown in figure 2.

The Precambrian rocks were extensively deformed before any of the younger rocks were deposited and hence are structurally the most complex rocks in the State. In most places they are tightly and intricately folded and also extensively faulted, but they have not yet been studied widely enough to establish their regional structural pattern, let alone its significance. One recently recognized regional feature, however, has an important bearing on mineral resources. This is a zone of Precambrian shearing that extends northeastward across the entire mountain area; this zone localized the much younger intrusive rocks and ore deposits of the Colorado mineral belt, discussed below (Tweto and Sims, 1963).

Structural features younger than Precambrian are principally products of the Laramide orogeny (Late Cretaceous and early Tertiary) or are of even younger Tertiary age. Vestiges of structures that

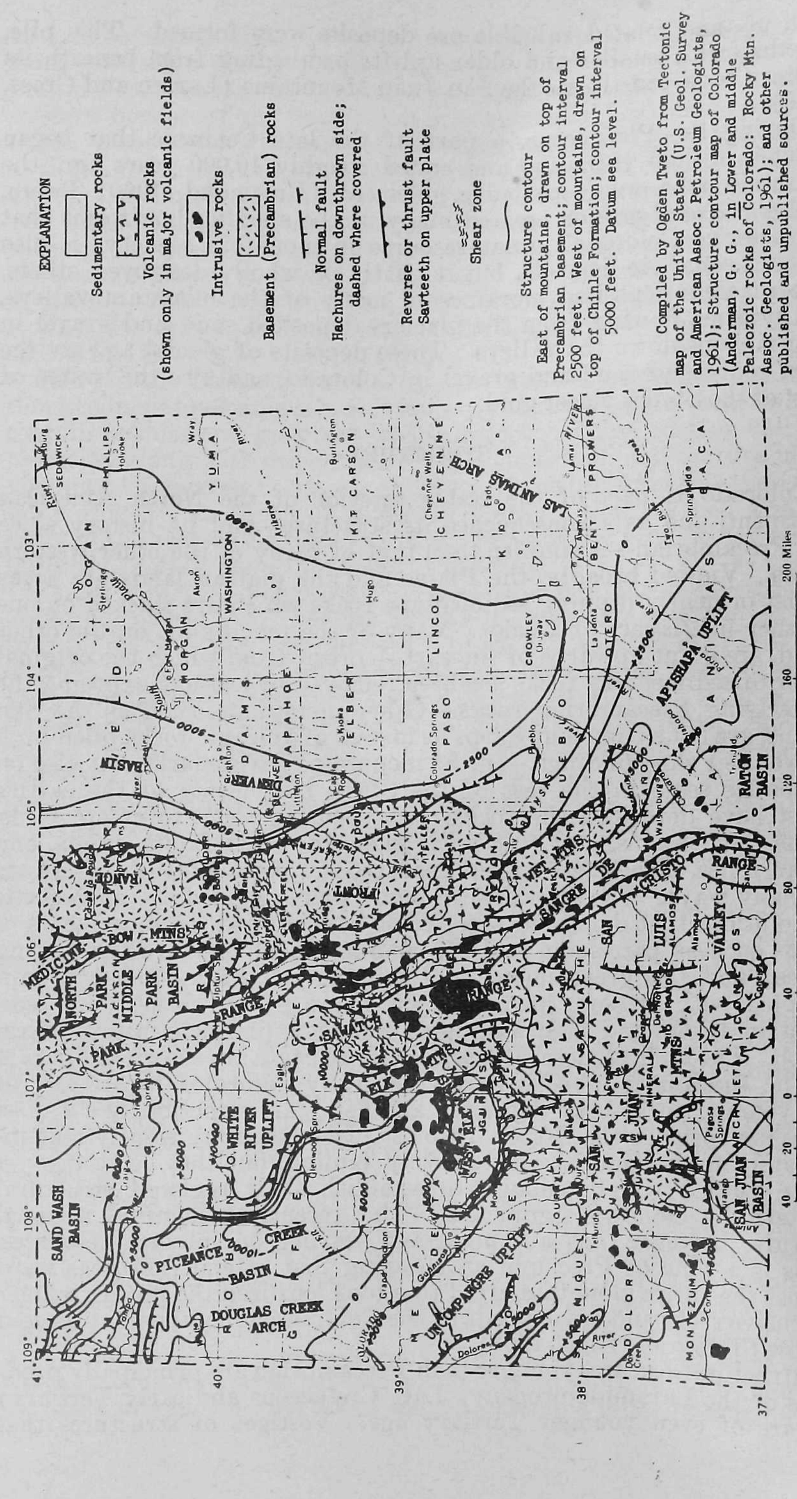

FIGURE 2.—Principal structural features of Colorado.

accompanied earlier mountains, such as those of the late Paleozoic, exist of course, but they are marked more by unconformities (i.e. erosion surfaces between formations) than by visible faults and folds.

In the plains area, the principal structural feature is the Denver basin, a broad asymmetric basin that occupies most of the area north of the Arkansas River and extends beyond the State border into Wyoming and Nebraska. The deepest part of this basin lies along an axis between Denver and Cheyenne, Wyo., where the top of the basement or Precambrian rocks is 5,000–6,000 feet below sea level. From the bottom of the basin, the basement rises gently to the east but steeply toward the mountains to the west. In southern Colorado, a gentle arch—the Apishapa uplift—complements the Denver basin. Both the basin and the arch are important to petroleum exploration and production.

In the mountain area, the Front Range is a broad, flat-topped arch or anticline, from which the sedimentary cover has been removed. The almost flat-lying rocks of the Plains turn up abruptly at the mountain front, where their eroded edges form a belt of hogbacks and strike valleys. In places along the front, the sedimentary rocks are faulted against the Precambrian rocks, but the front as a whole seems to be primarily a simple upfold. The western side of the range is more complicated, being bordered through much of its length by a line of echelon thrust faults. The Park Range, to the west, is in its northern half generally similar structurally to the Front Range, but its southern half is a fault-block range elevated on the east side of the Mosquito-Gore normal fault system. The Sawatch Range, farther west, is a huge upfold or anticline that has been stripped of its sedimentary cover, thus exposing the Precambrian rocks that make up most of the range. Small thrust faults border part of its western side. Other mountains of anticlinal or domal structure include the Uinta, White River, and the older or Needle Mountains part of the San Juan Mountains. Being volcanic, the main part of the San Juan Mountains is constructional rather than structural, but the volcanic rocks themselves contain many major caldera subsidence structures and fault blocks. The same is probably true of the little-studied West Elk Mountains to the north, although these mountains owe their relief to many large laccolithic intrusions.

Only two ranges in Colorado, the Sangre de Cristo and the Elk, are characterized by tightly folded and thrust-faulted sedimentary rocks (Burbank, 1933; Burbank and Goddard, 1937), but parts of even these ranges are domal, intrusive, or fault-block in character (Litsey, 1958; Vanderwilt, 1937).

In south-central Colorado, a belt of young faults of large displacement extends northward between some of the mountain ranges. The faults border a down-dropped block that is the northern extension of one that extends through the length of New Mexico, where it is known as the Rio Grande depression. In Colorado, the depressed block lies beneath—and is the cause of—the San Luis Valley and, farther north, the valley of the upper Arkansas River. In the San Luis Valley, one of the bordering faults forms the steep western face of the Sangre de Cristo Range. Along the Arkansas valley, the young faults slice almost lengthwise through the flank of the Sawatch anticline, separating the main body of the anticline core from the eastern limb, which lies in the Park Range. The young faults are of economic interest because there is some mineralization of the shallow, hot-spring or epithermal type along them.

In the plateau lands of western Colorado, the rocks dip very gently over wide areas, but they undulate broadly in basins and arches and locally bend abruptly along sharp monoclinal folds. The Piceance Creek basin, in Mesa, Garfield, and Rio Blanco counties, contains the great oil shale deposits of the Green River Formation, and is also of interest for petroleum in the underlying rocks. It is separated from another large basin to the west and principally in Utah—the Uinta Basin—by the Douglas Creek arch, on which is located Colorado's most productive oil field, at Rangely. Other broad basins of similar interest to the petroleum industry are the Sand Wash, at the Wyoming border, and the San Juan at the New Mexico border. Sharp monoclinal flexures, or upturns of the layered rocks, border the present-day Uncompahgre uplift (not to be confused with the older and much more extensive Uncompahgre Highland), which extends from near Ouray northwestward to the Utah border west of Grand Junction. The monocline on the northeastern side of the uplift is of interest not only for the striking scenery of the Colorado National Monument just west of Grand Junction but for ground-water behavior in this agriculturally productive area (Lohman, 1965). Just southwest of the uplift and parallel to it are large, complex salt-piercement anticlines (Cater and Elston, 1963), of interest to both the mining and the petroleum industries.

ECONOMIC GEOLOGY

Each of the minerals and rocks that constitute economic resources is the product of some specific geologic process or sequence of processes and thus is limited in occurrence to the places where those processes have operated. Some processes operated widely, and their products are therefore commonplace and generally cheap, but other processes were comparatively rare, and their products are correspondingly rare and dear. Some processes were primarily sedimentary in character, and their products are thus limited to sedimentary environments. The mineral fuels, for example, were derived from plant and animal life that under certain conditions was incorporated in sediments as they accumulated, and the search for coal, oil, and gas is thus made only in sedimentary rocks of certain kinds. Other processes were primarily igneous, that is, related to bodies of molten rock that existed at one time. Some igneous rocks, as perlite, pumice, and those used for stone, are valuable in themselves, and the search for them is naturally made in areas where igneous rocks are exposed. But a large class of more valuable materials, including ores of many kinds, are fugitive products of igneous bodies: They left such bodies, perhaps in water solutions or vapors, and came to rest elsewhere in other rocks. Many, and perhaps most, of the igneous bodies that gave rise to ore deposits are not exposed at the surface, but the geologic environments in which they might exist are recognizable, and the search for their products is therefore made mainly in those special environments.

Still other processes that produced materials of economic value are metamorphic, that is, related to transformations of materials within the earth, as, for example the change of limestone into marble, or of bituminous coal into anthracite. Finally, some mineral resources are partly or wholly products of the process of weathering, that is, either the mechanical breakdown or the chemical decay of rocks, as sands and gravels, gold placers, some iron and manganese deposits, and many clays.

Through process, mineral commodities are directly related to the character, origin, structure, and history of the rocks in any given area, and they thus vary with the geology. As Colorado is varied geologically, it has mineral resources in great variety, and these differ widely from area to area within the State.

On the Plains, where sedimentary rocks extend to great depth, oil and gas, principally from the Mesozoic rocks and in places from the Paleozoic rocks, are the major deep subsurface resources. At shallower depths, the gravels and sands are major resources, in part as construction materials, but especially as reservoirs for groundwater. Where Cretaceous shales are at or near the surface, they are potential sources of bentonite and raw material for lightweight aggregate, and the limey parts are important sources of cement rocks. Near the mountains, where the buried rock units of the Plains turn up to the surface, and where the rocks of latest Cretaceous and earliest Tertiary age are preserved, coal, fireclay, gypsum, and dimension stone are major resources, and groundwater is charged into some of the aquifers of the Plains.

In the mountains, where basement, igneous, and sedimentary rocks are all present and the structure is complex, the mineral resources are much more varied. Metals are the principal mineral resource, but many others exist also. Coal, oil, and gas exist in the sedimentary rocks of the intermontane basins; peat, for soil conditioning, comes from many high-altitude valleys; pumice, perlite, and scoria used in construction and for lightweight aggregate occur in the areas of volcanic rocks; building stone of many kinds, ranging from the hard Precambrian granites to the soft, decorative travertine of hot spring deposits, is widely available; gypsum, limestone, dolomite, and high-silica sandstone or quartzite occur in the areas of sedimentary rocks; vermiculite exists in the Precambrian rocks; a host of pegmatite minerals, including massive quartz, feldspars, micas, beryl, and many others are obtainable from some of the countless pegmatite bodies in the Precambrian rocks; fluorspar, barite, and alunite occur in various environments; and beryllium minerals and decorative, semiprecious, and precious stones occur principally with the Precambrian and younger igneous rocks.

Most of the metallic wealth of Colorado has come from the Colorado mineral belt, a long narrow belt that extends diagonally across the mountain province from the edge of the Plains in Boulder County to the southwest side of the San Juan Mountains. The only major metallic deposits known outside of this belt are the gold-silver deposits of the Cripple Creek and the Westcliffe-Silver Cliff volcanic centers, and the uranium-vanadium deposits near the western border of the State. Although important discoveries may be made outside the belt in the future, the major metallic resources almost certainly lie principally within the belt, just as the bulk of the past production has come from the belt.

The mineral belt is about 250 miles long and ranges from 15–30 miles wide in its northeastern part to as much as 60 miles wide in its southwestern part. Throughout its length, it is characterized by bodies of intrusive igneous rocks—called porphyries—of early and middle Tertiary age, and by related ore deposits (Burbank, 1933; Lovering, 1933; Tweto and Sims, 1963). As noted previously (p. 17), it is located along a belt of much older faults or shear zones of Precambrian age, and it cuts indiscriminately across mountain ranges and intervening valleys, no matter what their geology. In the Front Range, swarms of small faults, many of them mineralized and hence, veins, lie within the mineral belt and generally parallel to it, but elsewhere no such pattern is known. Mineralization is not continuous in the belt but is concentrated in local centers, some of which differ markedly from their neighbors in the character of their ore. Many of the districts, however, have mixed ores, valuable for gold, silver, copper, lead, and zinc in various proportions. Examples are the Ward-Gold Hill area in Boulder County, and, proceeding southwestward, the Blackhawk-Central City-Idaho Springs area, and the Georgetown-Silver Plume, Montezuma, and Breckenridge districts in the Front Range; the Alma, Kokomo, Leadville, and Gilman-Red Cliff districts in the Park Range; the St. Elmo, Monarch-Garfield, Aspen, and Pitkin-Tincup districts in the Sawatch Range; and the Ouray, Telluride, Silverton, Lake City, Creede, and Rico districts in the San Juan Mountains. Sprinkled among these complex-ore districts are districts that produce only one or two materials, as Jamestown (gold and fluorspar), Nederland (tungsten), Eldora (gold), Red Mountain (molybdenum), and Climax (molybdenum-tungsten). In addition, tungsten occurs with the sulfide ores of Alma and Silverton, tungsten and molybdenum at Pitkin-Tincup, and iron, manganese, and bismuth with the Leadville ores.

In the Plateau province, which consists principally of sedimentary rocks, the vast resources of oil shale in the Green River Formation overshadow all other mineral resources except water, but resources of many other kinds exist in quantity. Almost the entire area is in some degree geologically eligible for oil and gas; important coal deposits exist in the rocks of the Upper Cretaceous; major uranium and vanadium output has come from the Mesozoic rocks; salt (including some potash) and gypsum exist in abundance in the rocks of late Paleozoic age; and there are many potential sources of clays, building stone, limestone, and cement rock in formations of various ages, and of sand and gravel in deposits of relatively recent age.

In summary, the geology of each area imposes a general control on the kinds of resources that may exist there, but geologic factors more specific than those discussed above, along with economic considerations, determine whether a resource does in fact exist. These factors, along with other aspects of the geology of individual commodities, are discussed in sections that follow.

TOPOGRAPHIC AND GEOLOGIC MAPPING

The Topographic Division of the U.S. Geological Survey has the responsibility of preparing the National Topographic Map Series covering the United States and its possessions. Topographic mapping operations in Colorado are directed by the Rocky Mountain Region Engineer, whose offices are located at Building 25, Denver Federal Center, Denver, Colo. At the same address are the technical laboratories and map sales and distribution activities. A Public Inquiries Office is located at the New Customhouse in downtown Denver.

Topographic maps at the scale of 1: 250,000 are available for all of Colorado. Figure 3 shows areas covered by published topographic maps of quadrangles at scales of 1: 24,000 and 1: 62,500. As of April 1, 1964, there were 352 maps of 7½-minute quadrangles published at 1: 24,000, and 88 maps of 15-minute quadrangles published at 1: 62,500. Each of these quadrangle maps, as well as special maps of irregularly shaped areas, is outlined separately and named on the Index to topographic mapping in Colorado. This index is revised frequently and is available at no charge from the Geological Survey. In addition to the published maps, as of April 1, 1964, there were 355 maps of 7½-minute quadrangles in progress in various stages of preparation.

Information shown on topographic maps is intended to give as complete a picture of the terrain as the publication scale allows. The content of the map is useful to engineers, geologists, administrators, conservationists, foresters, economists, planners, and many others. These maps are essential to the comprehensive development of the economic and natural resources of the State. Although a large part of Colorado is now covered by detailed mapping, Colorado's expanding population and burgeoning industry are demanding more maps.

The mapping process also makes available at nominal cost the following byproducts of value to science and industry: (1) copies of aerial photographs from which the maps are made; (2) control data, consisting of horizontal positions in terms of latitude and longitude, and elevation of bench marks above sea level; and (3) copies of map manuscripts at each stage of completion. Anyone seeking more information regarding the topographic maps or the mapping program should contact Rocky Mountain Region Engineer, Building 25, Denver Federal Center, Denver, Colo.

A geologic map of the entire State, at the scale of 1: 500,000, was prepared and published in 1935 by the U.S. Geological Survey, in cooperation with the Colorado State Geological Survey Board and Colorado Metal Mining Fund. Geologic maps at larger scales have also been published for many parts of the State; figure 4 shows the areas covered by geologic maps published at the scale of 1: 63,360 or larger, and the areas covered by geologic maps published at scales between 1: 63,360 and 1: 250,000. For information regarding the exact area covered by each individual map, its scale, and publication source, the reader is referred to Boardman, Leona, 1954, Geologic map index of Colorado: U.S. Geological Survey index to geologic mapping in the United States.

Geologic maps are fundamental for intelligent exploration, development, and appraisal of mineral and water resources of a region, and they are being used increasingly in planning and engineering urban development and highway construction. Less than 50 percent of Colorado is covered by geologic mapping at scales adequate for most of these purposes.

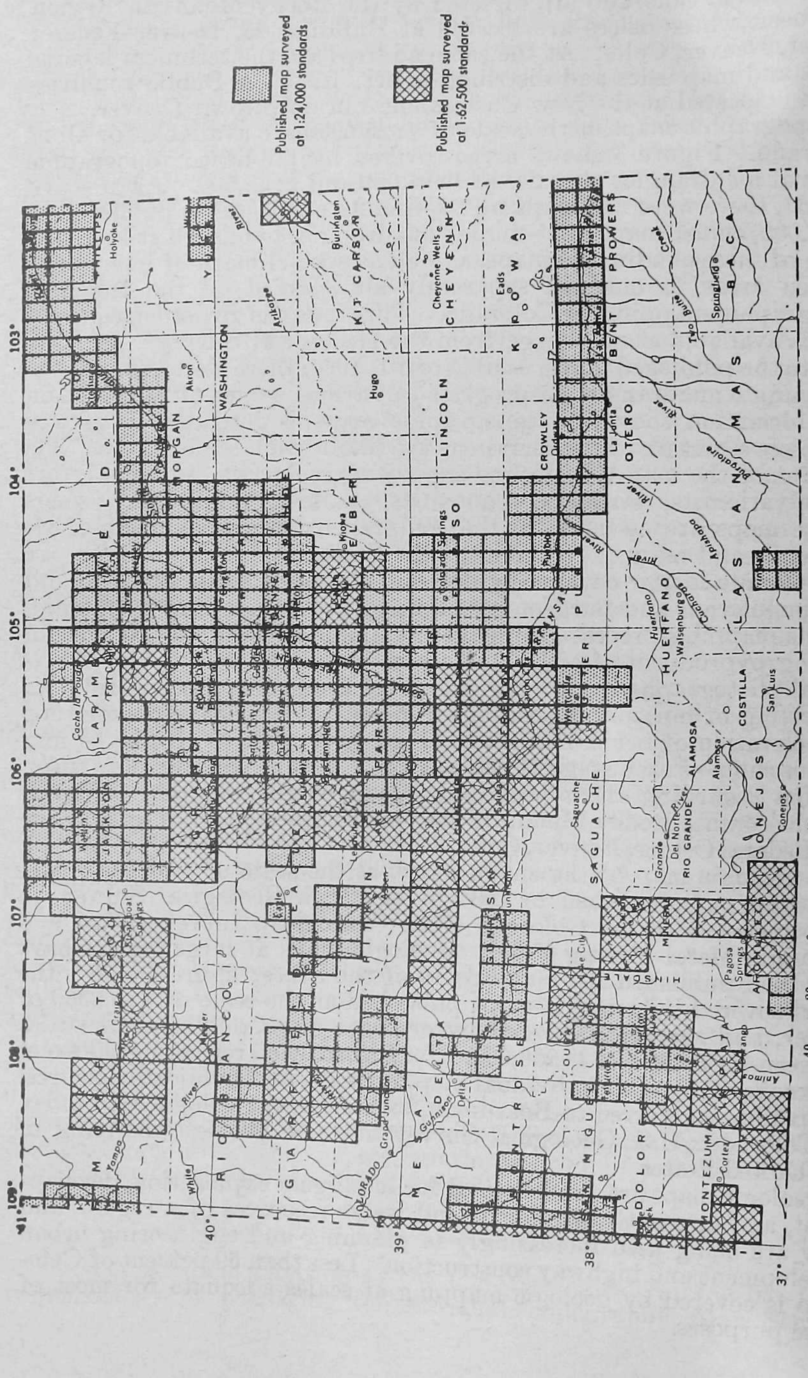

FIGURE 3.—Published topographic maps of quadrangles in Colorado.

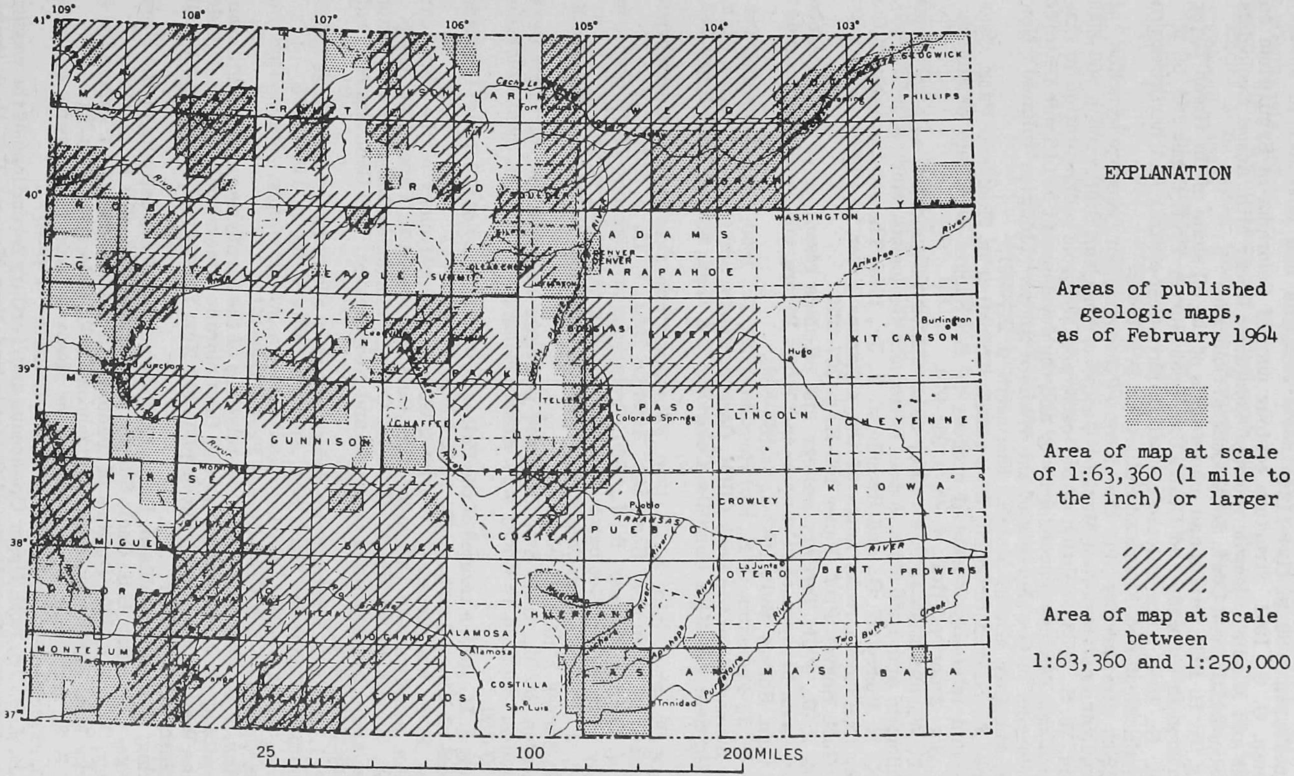

FIGURE 4.—Areas of published geologic maps in Colorado.

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THE MINERAL INDUSTRY IN COLORADO

Colorado possesses rich and varied mineral deposits, from which products valued at about $7 billion have been extracted. In the United States, Colorado ranks first in the production of molybdenum and vanadium, second in gold, and third in silver and tungsten. It has produced large amounts of lead, zinc, uranium, and copper, and moderate to small amounts of other metals. Colorado has also produced organic fuels—coal, oil, and natural gas—in large amounts. Supplies of construction materials, especially sand, gravel, clay, and cement rock, generally have been adequate for local needs. Figure 5 shows the yearly total dollar value of Colorado mineral production from 1868 through 1962 and the value of major groups of commodities by 5-year averages. Figure 6 shows the total value of the principal mineral commodities produced in Colorado and the percentage of total value represented by each.

The annual rate of mineral production of Colorado increased rather steadily from the 1860's to World War I. It declined slightly in the 1920's and sharply in the early 30's. From its low point in 1932 it increased at a strong rate through the 1940's and then increased spectacularly through the 1950's. During this 100-year history of mineral production in Colorado, several different commodities have successively dominated the output.

Gold, followed closely by silver, dominated Colorado's early mineral production. Gold was discovered near the site of Denver in 1858, precipitating a rush to the territory in 1859 and the early discoveries of placer and lode deposits in the nearby mountains. From this area prospectors spread into the other parts of central and western Colorado, and by 1900 discoveries had been made in all of the major precious- and base-metal mining camps in the State. The combined value of gold and silver production reached its peak in the early 1900's and has gradually declined since then, except for a minor reversal of this downward trend in the late 1930's (fig. 5).

Lead, zinc, and some copper are closely associated with the precious metals in many deposits in Colorado, and to such ore the term "complex ore" is commonly applied. Significant production of lead began with the discovery of the Leadville deposits in 1877. Significant production of zinc, on the other hand, began about 1900, not with the discovery of new deposits rich in this metal but rather as a result of the invention of concentrating devices, such as the Wilfley table, to separate zinc minerals from complex ores. Since then the yearly production rate of these two metals has been nearly parallel; it has fluctuated between sharp peaks and deep lows, but in general it was moderately high from 1900 to 1920 and from 1940 to 1960, and low in the 1930's. Since 1943 the combined value of lead and zinc produced in Colorado has exceeded that of gold and silver. Because Colorado contains very few deposits worked for copper alone, its copper output has come almost entirely from the complex ores. As a result the

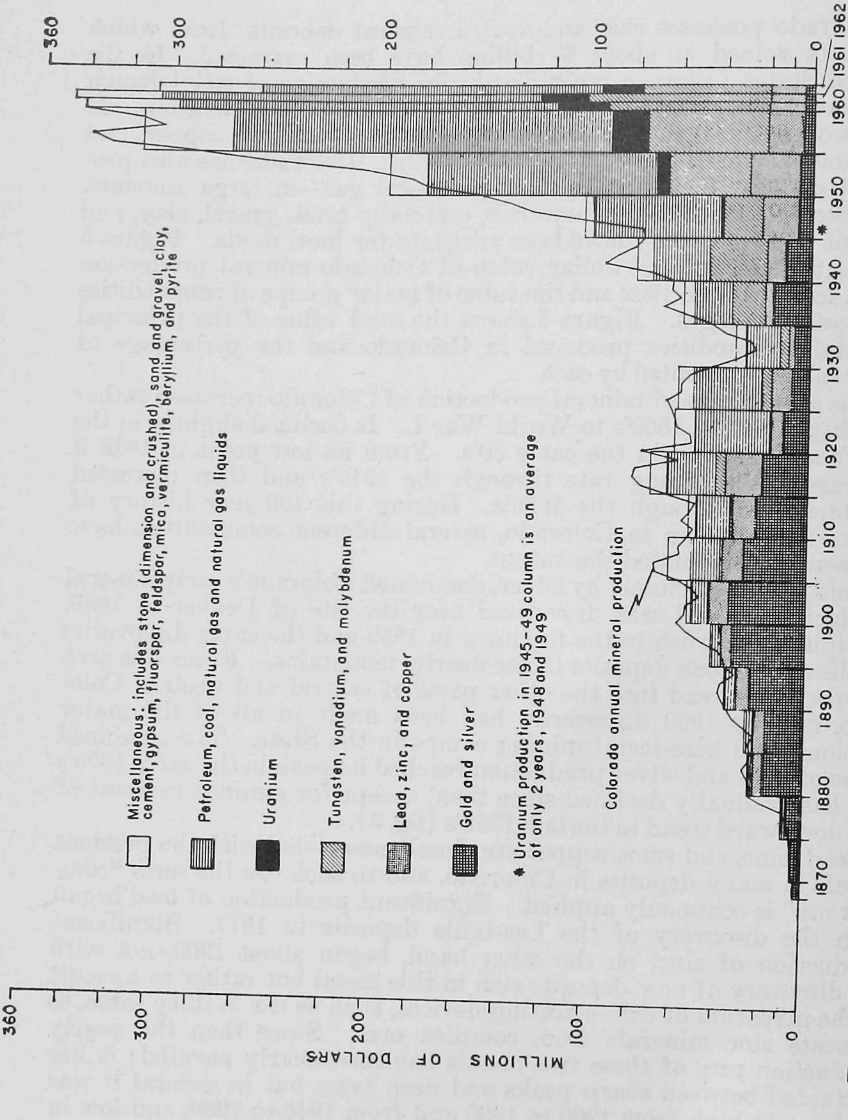

FIGURE 5.—Yearly total dollar value of mineral production in Colorado from 1868 through 1962; the values of major commodity groups and uranium are shown by 5-year averages, except for 1960–1962, where yearly values are shown. (Modified after Koschmann, 1962.)

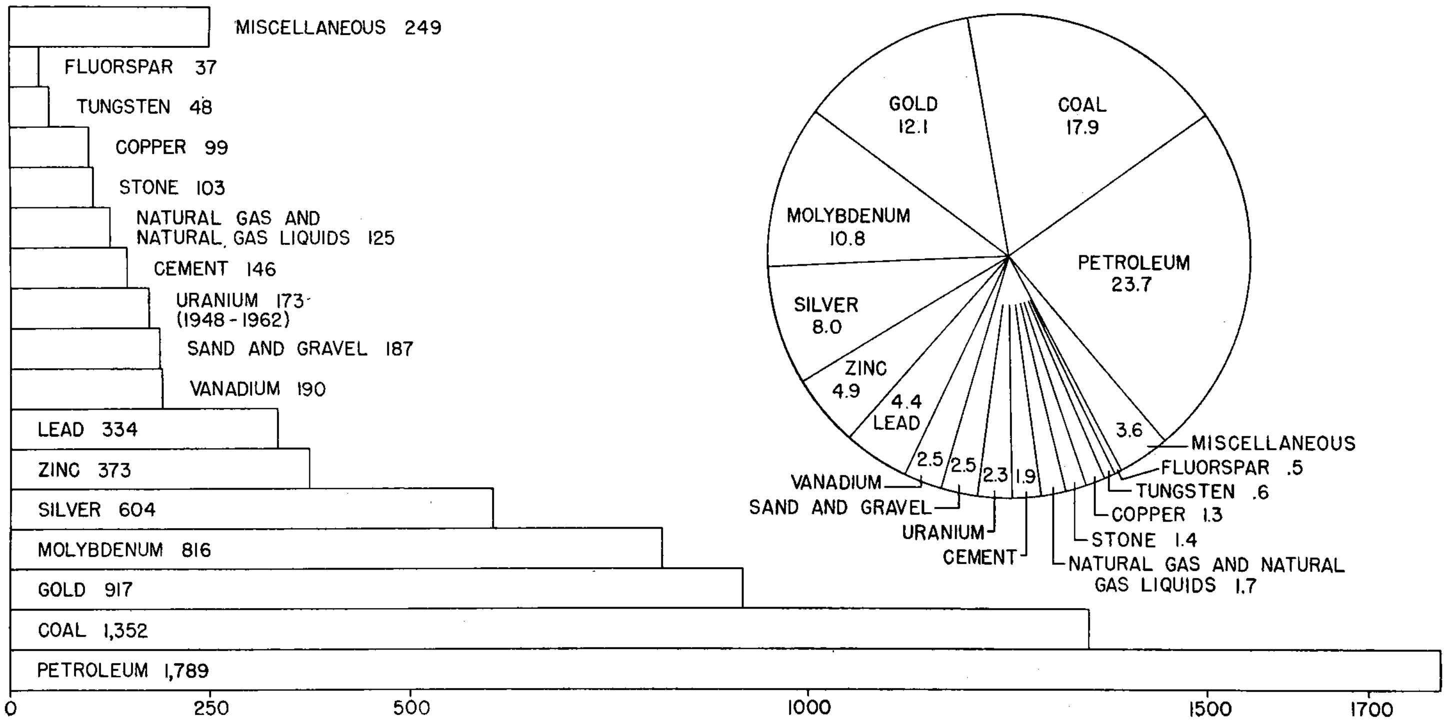

FIGURE 6.—Dollar values and percentages of total value of each principal mineral commodity produced in Colorado 1858 through 1962. (Modified after Koschmann, 1962.)

production rate of copper since about 1900 has fluctuated with that of lead and zinc, although at a much lower level except during the 1930's, when the copper production value exceeded the total of lead and zinc.

Very large supplies of two ferroalloy metals have been developed in Colorado. The State has furnished about 57 percent of the world's total production of molybdenum and about 48 percent of the world's vanadium. Significant production of molybdenum in Colorado began in the mid-1920's, and it has increased rather steadily since then. The value of the molybdenum output was $62 million in 1960, about equal to that of all other metals combined in Colorado. Vanadium production in Colorado began about 1910 and was important though modest through the 1940's. Production increased strongly during the 1950's, as a byproduct of the uranium-mining industry.

Colorado was the first State to produce uranium on a large scale, and although its uranium industry has been overshadowed by major discoveries made in other states since the late 1940's, in 1961 it produced uranium ore valued at $21.5 million and stood fourth among the uranium-producing States.

In recent years, the organic fuels have held first place in value among the mineral products of Colorado. Coal production began in the 1860's shortly after establishment of the earliest permanent settlements. Production increased gradually, and by 1917 the value of the annual output exceeded that of gold. In most years from 1917 to 1947, coal was Colorado's leading mineral commodity in dollar value. In 1947, petroleum passed coal in value of the annual output, and since then it has been Colorado's leading mineral product.

Information regarding the historic stages of the mineral industry in Colorado and much of the production data in the above paragraphs is taken largely from a paper by the late A. H. Koschmann (1962), U.S. Geological Survey. Readers interested in more information of this type are referred to Koschmann's paper and the references he cites.

Although historically Colorado is renowned for its mineral production, as its population grew the value of its agricultural and livestock production exceeded the value of its mineral products. In 1962 cash income from farm marketing, including crops and livestock and products totalled $624.8 million (preliminary figures, Colorado Dept. Agriculture and U.S. Dept. Agriculture, Bull. 63–1, p. 56). The value of all mineral products during 1962 was $308.1 million (U.S. Bureau Mines, Minerals Yearbook 1962, vol. 3, p. 227).

The mineral industry in Colorado employed 12,451 men in 1962. This total includes 88 men employed in placer mining and 5,065 men in other mining, 327 men in pits and quarries, 3,472 men on oil wells, and 3,499 men in mills, plants, and smelters (Colorado Bureau Mines Annual Report 1962, p. 58). According to the Colorado Department of Employment, the rates of wages and salaries paid in the mineral industry are the highest among the major industries in Colorado due to the skills required of labor and management in the mineral industry. In 1962 the total payroll in the mineral industry was about $80 million.

Figure 7 compares the number of men employed in the Colorado mineral industry with the total dollar value of mineral commodities produced for every fifth year from 1900 to 1960. The overall trend is that of decreasing employment relative to the total production value, but in detail this general trend breaks into three distinct periods—1900–1920, 1920–1945, and 1945–1960.

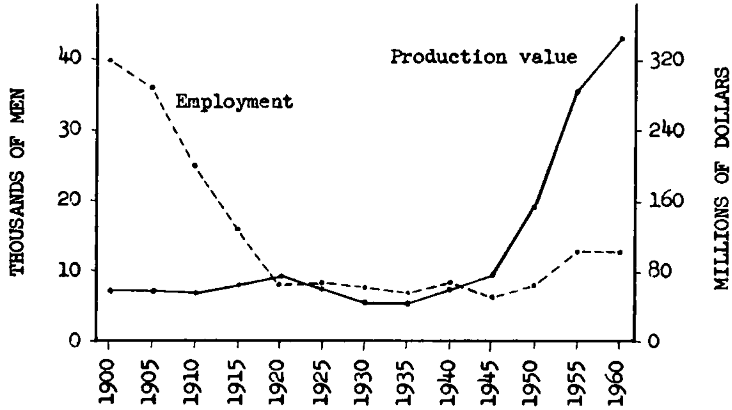

FIGURE 7.—Comparison of number of men employed with the dollar value of commodities produced in Colorado in every fifth year, 1900–1960.

The total output of the mineral industry in Colorado in 1900 was valued at about $60 million and nearly 40,000 men were employed. Output in 1920 amounted to nearly $80 million and about 8,000 men were employed. These changes result from the interplay of various factors, but two factors are most significant. First, during this period many small metal mines shut down and there was a gradual decrease in metal-mine output and an increase in the output of coal and construction materials, an overall shift toward opertions requiring less manpower per unit of production. And second, the introduction, improvement, and gradual increased use of mechanized equipment, such as pneumatic rock drills, gold dredges, and electric power, raised the output per man employed.

During the 1920–45 period, production and employment rates of the mineral industry were fairly stable, and they plot on figure 7 as nearly parallel lines. Since 1945 both employment and production value have increased, but the value has increased far more rapidly than employment, chiefly due to the growth of the oil industry, where the output value per man is large.

The long-range outlook for the mineral industry in Colorado is bright. The world's increasing population and rising standard of living will put additional requirements on the raw material resources of the State. The ultimate level of these demands and their sequence of development, however, can not be predicted accurately. They will depend upon the character of raw material supplies in Colorado and other parts of the world and their rate of discovery, upon the political and economic environment in Colorado and the rest of the world, and upon technological developments and the substitution of one commodity for another. Assuming no drastic changes in politics, economics, or technology, the general trends can be anticipated as listed below.

In recent years the value of petroleum and natural gas produced in Colorado has nearly equalled the total value of all other mineral commodities produced in the State. The production of these fuels will remain high for some years but will gradually decrease unless new oil and gas fields are found; there are potential areas for new fields in Colorado. Petroleum reserves in Colorado are moderately large, and the chances of finding new reserves are good. Nevertheless, the potential of both coal reserves and the shale oil resources are far greater than that of petroleum. Coal resources in Colorado are large, and the production of coal will probably remain at moderate levels or increase gradually. Oil will ultimately be recovered from the oil shales of Colorado, and once started, the production will probably be large. Thanks to its oil shale, Colorado may one day assume a prominent position in world oil production.

The raw material supplies of most construction materials in Colorado are generally adequate to satisfy the increasing demands of the growing population and industry of the State. Production of these materials will increase as needed, although, for some materials, sources more remote from centers of population will have to be tapped.

The production of precious and base metals dominated the early history of mining in Colorado, but the value of their output in recent years has been relatively small in comparison with commodities such as petroleum and molybdenum. Reserves and resources of the precious and base metals are adequate to sustain production at present rates for many years, but unless large new deposits of these metals are found, they are not likely to resume their once-dominant role in Colorado's mineral industry.

Among the ferrous and miscellaneous metals and the nonmetallic and industrial minerals, molybdenum, vanadium, and uranium have been the most important in total dollar value. Reserves and resources of molybdenum are large, and it is reasonable to expect its production to continue at a high level and perhaps even increase. The reserves of vanadium and uranium, on the other hand, are only moderate. Vanadium output in recent years has been a byproduct of uranium ore mining; its future will be influenced largely by the uranium industry, which will be regulated by government purchases until 1970. Beyond 1970 the outlook for vanadium and uranium production in Colorado will depend largely on the price paid for uranium for industrial use or by continued government purchases.

MINERAL FUELS AND ASSOCIATED RESOURCES

COAL

(By E. R. Landis, U.S. Geological Survey, Denver, Colo.)

Coal was third in value among the mineral products of Colorado in 1963, being exceeded only by crude petroleum and molybdenum. Production amounted to 3,707,440 tons of coal with a value of about $24 million and was obtained from 104 mines in 15 counties. Among the states, Colorado was eleventh in coal output and second among the states west of the Mississippi River.

Colorado's resources of coal are very large and are widely distributed over the State. About 29,600 square miles (28 percent) of Colorado is underlain by coal-bearing rocks. These rocks are all of Cretaceous and early Tertiary age, but they occur in several stratigraphic units—the Dakota Sandstone, the Mesaverde Group, and the Fruitland, Lance, Laramie, Vermejo, Raton, Denver, Dawson, Fort Union, and Coalmont Formations. Most of these units are present in only parts of the State, and not all of them are coal-bearing everywhere they are present. (For age, stratigraphic position, and approximate distribution of these units, see table 1.)

Coal originates mainly from vegetable matter that accumulated in swamps and was buried by younger sediments. Progressive changes in the physical and chemical properties occur after burial, mainly due to time and weight of the overlying sediments, but in places these changes are speeded by pressure from structural deformation or heat from intrusive igneous rocks. In general, the original moisture and volatile matter in coal decrease with these changes and the carbon content and heat value increase proportionately, commonly increasing the usability and value of the coal. Coal is ranked according to the progress of change, from lignite to bituminous and anthracite. Some coals have special characteristics that make them usable for specific purposes, such as some of the higher rank coals that can be used for making coke.

Colorado's coals are mostly bituminous and are mainly used for heat energy—about 40 percent of the coal produced in 1963 was used as heat energy in generating electric power and 20 to 25 percent was used for industrial and domestic heating. The rest of the coal produced was used in making coke for the steel industry; about half of this was consumed in Colorado and the rest shipped to other western states. Valuable byproducts are obtained during coking.

PRODUCTION

Coal production in Colorado was first recorded in 1864, when 500 tons of coal was produced, but mining began at least as early as 1860 and small amounts were probably mined prior to that date. Yearly production increased steadily with minor fluctuations until 1917, when

12,483,336 tons was produced. Since then production declined slowly and steadily although in the last ten years it seems to have stabilized at an average of about 3.35 million tons per year. Up to January 1, 1964, the recorded coal production of Colorado totaled about 520 million tons (table 2).

In 1963, coal was mined in 15 counties, but 61 percent was produced in three counties, Routt (786,815 tons), Las Animas (775,938 tons), and Weld (721,032 tons). Almost all the coal produced in Routt County comes from two large strip mines and is used for electric power generation; almost all the coal produced in Las Animas County comes from a single highly mechanized underground mine and is used to make coke for the steel industry; and the coal produced in Weld County comes from six mechanized underground mines and is used for electric power generation and industrial and domestic heating.

Though it is customary to tabulate coal production and related figures by counties, the areas in which coal is or has been mined generally are much smaller than counties, so that a county may include all or parts of several coal-producing areas, or the natural geologic and geographic boundaries of the coal-mining areas may lie across county boundaries. Because these natural boundaries also relate to many diverse factors, such as the type and quality of coal and availability and feasibility of transportation forms, it is common to evaluate resources by the geologic and geographic entities known, generally according to size or importance, as coal areas, districts, fields, and regions. The fields from which coal was produced in 1963 are listed in table 3, with production figures, number and types of mines, and percent of production attributable to each type of mine.

RESOURCES

Known coal resources can be defined as that part of the total amount in the ground (the total resources) that has been determined to be present by mapping and exploration and that can be quantitatively evaluated. The original known coal resources, that is, coal originally present in the ground before mining, were estimated by Landis (1959), using U.S. Geological Survey standard methods (Averitt, 1961, p. 14–22). The estimate was made on an individual-bed-basis in all parts of the State where it was feasible, and the resources were classified according to the characteristics of the coal and associated rocks and according to the abundance and reliability of the available information. The results of the quantitative evaluation were presented in tables with a total of 27 categories arranged by county and township and range. These data are summarized below, according to county and coal rank (table 4) and also by region or field and coal rank (table 5).

Although coal-bearing rocks underlie about 29,600 square miles of Colorado, the available information allowed a quantitative appraisal in only 5,276 square miles. In that area, 81,785 million tons of coal is estimated to have been present originally. Of this total, 0.11 percent, or about 90 million tons, is anthracite or semianthracite, 77.28 percent, or about 63 billion tons, is classed as bituminous; and 22.61 percent, or about 18.5 billion tons is subbituminous coal.

In the rest of Colorado that is underlain by coal-bearing rocks—approximately 24,000 square miles or about one quarter of the State—

TABLE 2.—*Short tons of coal produced in Colorado from 1864 to Jan. 1, 1964, by counties* [1]

Counties	Coal produced to Jan. 1, 1956	1956	1957	1958	1959	1960	1961	1962	1963	Total
Boulder	42, 265, 569	5, 419	------	160	------	------	------	------	------	42, 271, 148
Delta	3, 827, 471	60, 230	61, 697	50, 045	69, 551	69, 898	57, 044	66, 318	35, 043	4, 297, 297
El Paso	15, 134, 687	47, 185	44, 088	7, 600	4, 392	3, 883	3, 293	2, 286	1, 207	15, 248, 621
Fremont	34, 067, 861	241, 529	226, 468	250, 733	280, 976	300, 382	309, 354	334, 559	322, 387	36, 334, 249
Garfield	6, 965, 267	35, 851	38, 687	21, 633	17, 412	15, 290	16, 158	11, 910	8, 550	7, 130, 758
Gunnison	32, 501, 730	303, 859	291, 668	284, 268	263, 809	272, 286	269, 894	196, 309	163, 238	34, 547, 061
Huerfano	75, 920, 055	63, 680	70, 331	63, 530	60, 694	61, 188	49, 055	44, 644	43, 732	76, 376, 909
Jefferson	4, 920, 403	------	------	------	------	------	------	------	------	4, 920, 403
La Plata	5, 806, 064	55, 801	39, 814	33, 800	29, 465	32, 999	32, 771	30, 286	27, 748	6, 088, 748
Las Animas	154, 376, 851	1, 020, 875	1, 049, 568	773, 905	700, 150	705, 072	798, 065	684, 357	775, 938	160, 884, 781
Mesa	5, 892, 749	71, 563	77, 339	85, 304	90, 126	107, 209	124, 214	112, 857	79, 319	6, 640, 680
Moffat	1, 882, 512	96, 461	108, 025	117, 855	120, 463	125, 805	117, 257	128, 381	158, 298	2, 855, 057
Montezuma	126, 952	941	1, 035	268	------	------	------	------	------	129, 196
Pitkin	7, 555, 893	154, 081	219, 642	272, 063	323, 435	457, 524	582, 319	414, 687	499, 252	10, 478, 896
Rio Blanco	651, 576	18, 728	12, 902	11, 250	10, 841	11, 484	10, 643	8, 296	6, 587	742, 307
Routt	37, 081, 502	484, 034	458, 964	386, 635	389, 695	469, 325	446, 355	488, 105	786, 815	40, 991, 430
Weld	54, 384, 119	638, 393	621, 103	580, 012	781, 811	741, 506	794, 443	786, 457	721, 032	60, 048, 876
Other counties	[2] 894, 048	[3] 5, 031	[4] 3, 456	[5] 33, 130	[5] 150, 866	[5] 250, 721	[6] 89, 827	[6] 83, 118	[6] 78, 294	[2] 1, 588, 491
Total	[7] 492, 989, 721	3, 303, 661	3, 324, 787	2, 972, 191	3, 293, 686	3, 624, 572	3, 700, 692	3, 392, 570	3, 707, 440	[7] 520, 309, 320

[1] From Landis (1959, tables 5 and 6); Colorado State Inspector of Coal Mines, Reports; and Colorado Bureau of Mines, Annual Reports.

[2] Includes, at various times, Adams, Archuleta, Arapahoe, Douglas, Dolores, Elbert, El Paso, Jackson, Jefferson, Larimer, Moffat, Montezuma, Montrose, Ouray, Park, Pitkin, Rio Blanco, and San Miguel Counties.

[3] Includes Archuleta, Jackson, Montrose, and San Miguel Counties.

[4] Includes Jackson, Montrose, and San Miguel Counties.

[5] Includes Jackson and Montrose Counties.

[6] Montrose County.

[7] Includes 8,734,412 tons not otherwise assigned.

TABLE 3.—*Coal production in Colorado in 1963, by region and field, with number and type of mines and percentage of production by type*

Region and field	Number of mines		Percentage of production		Production (short tons)
	Underground	Strip	Underground	Strip	
Green River region: Yampa field	8	2	22.0	78.0	945,113
Uinta region:					
Book Cliffs field	7	1	93.0	7.0	79,319
Grand Mesa field	4		100.0		13,354
Somerset field	7		100.0		166,312
Crested Butte field	3		100.0		18,615
Carbondale field	5		100.0		501,782
Grand Hogback field	3		100.0		6,020
Danforth Hills field	1		100.0		3,792
Lower White River field	1		100.0		2,795
Subtotal	31	1	99.3	.7	791,989
San Juan River region: Durango field	10		100.0		27,748
Raton Mesa region:					
Walsenburg field	6		100.0		43,732
Trinidad field	16		100.0		775,938
Subtotal	22		100.0		819,670
Denver region:					
Boulder-Weld field	6		100.0		721,032
Colorado Springs field		1		100.0	1,207
Subtotal	6	1	99.8	.2	722,239
Canon City field	18	4	90.0	10.0	322,387
Nucla-Naturita field		1		100.0	78,294
Total	95	9	77.0	23.0	3,707,440

TABLE 4.—*Original known coal resources of Colorado, by county and rank, under less than 3,000 feet of overburden*

[In millions of short tons]

County	Square miles included in estimate	Rank of coal		County total
		Subbituminous	Bituminous	
Adams	26	335.28		335.28
Arapahoe	40	271.69		271.69
Archuleta	47		455.30	455.30
Boulder	58	465.14		465.14
Delta	86	1,306.35	362.48	1,668.83
Douglas	12	186.73		186.73
Elbert	152	787.75		787.75
El Paso	123	571.96		571.96
Fremont	36		295.34	295.34
Garfield	151		2,267.65	2,267.65
Gunnison [1]	162	306.88	3,201.53	3,598.79
Huerfano	172		1,190.44	1,190.44
Jackson	102	3,735.13		3,735.13
Jefferson	78	806.62		806.62
La Plata	608		7,912.94	7,912.94
Larimer	12	78.16		78.16
Las Animas	872		11,483.97	11,483.97
Mesa	187	123.61	1,300.33	1,423.94
Moffat	511	4,391.11	15,780.90	20,172.01
Montezuma	293		1,277.91	1,277.91
Montrose	40	1,029.26	114.34	1,143.60
Ouray	22	1,018.80		1,018.80
Park	8		92.25	92.25
Pitkin	17		412.52	412.52
Rio Blanco	711		9,852.90	9,852.90
Routt	415	1,320.38	7,201.85	8,522.23
Weld	335	1,756.75		1,756.75
Total	5,276	18,491.60	63,202.65	81,784.63

[1] Gunnison County had original known resources of 90.38 millions of short tons of anthracitic coal.

TABLE 5.—*Original known coal resources of Colorado, by region or field and by rank, under less than 3,000 feet of overburden*

[In millions of short tons]

Region or field	Square miles included in estimate	Rank of coal		Region or field total
		Subbituminous	Bituminous	
Green River region	828	5,711.49	17,896.07	23,607.56
Uinta region [1]	1,401	1,429.96	22,484.09	24,004.43
San Juan River region	946		9,633.85	9,633.85
Raton Mesa region	1,044		12,674.41	12,674.41
Denver region	836	5,260.08		5,260.08
Canon City field	36		295.34	295.34
Nucla-Naturita field	15		114.34	114.34
Pagosa Springs field	1		10.10	10.10
Tongue Mesa field	58	2,354.94		2,354.94
North Park field	102	3,735.13		3,735.13
South Park field	8		92.25	92.25
Cortez area	1		2.20	2.20
Total	5,276	18,491.60	63,202.65	81,784.63

[1] The Uinta region had original known resources of 90.38 millions of short tons of anthracite coal.

known coal resources have not been estimated because information regarding these coal-bearing rocks is too scant. It is reasonable to expect, however, that these 24,000 square miles will contain 3 to 5 times as much coal as the total estimated known resources.

COAL REGIONS AND FIELDS

The coal resources of Colorado are in five large regions and seven smaller individual fields and areas, which are shown on figure 8 and identified by name. They are described briefly below. For more detailed description, see Landis (1959), Vanderwilt (1947, p. 266–278), and Yingst (1960).

Green River region.—The Green River region of Colorado and Wyoming contains large resources of coal ranging in rank from subbituminous to bituminous. All the estimated known coal resources are in the Yampa field (No. 1, fig. 8), in Moffat and Routt Counties. Most of the coal is of high-volatile C bituminous rank, with the coal near the eastern edge of the field being of higher rank. Anthracite occurs in a few small areas near intrusive igneous rocks. The higher rank bituminous coals occur in the Iles and the lower part of the Williams Fork Formations of the Mesaverde Group. The coal in the upper part of the Williams Fork and in the younger Lance and Fort Union Formations is of subbituminous rank. Most of the coal currently produced comes from large strip mines working coal beds as much as 30 feet thick; almost all of the coal is used for electric power generation. For 1963 production data and information regarding operating mines in this field and those described below, the reader is referred to table 3.

Uinta region.—The Colorado part of the Uinta region of Colorado and Utah includes coal beds ranging in rank from subbituminous to anthracite, and from nearly flat-lying to steeply dipping and complexly faulted. Coal has been produced from eight fields. All the coal occurs in the Mesaverde Group, which crops out around the periphery of the region.

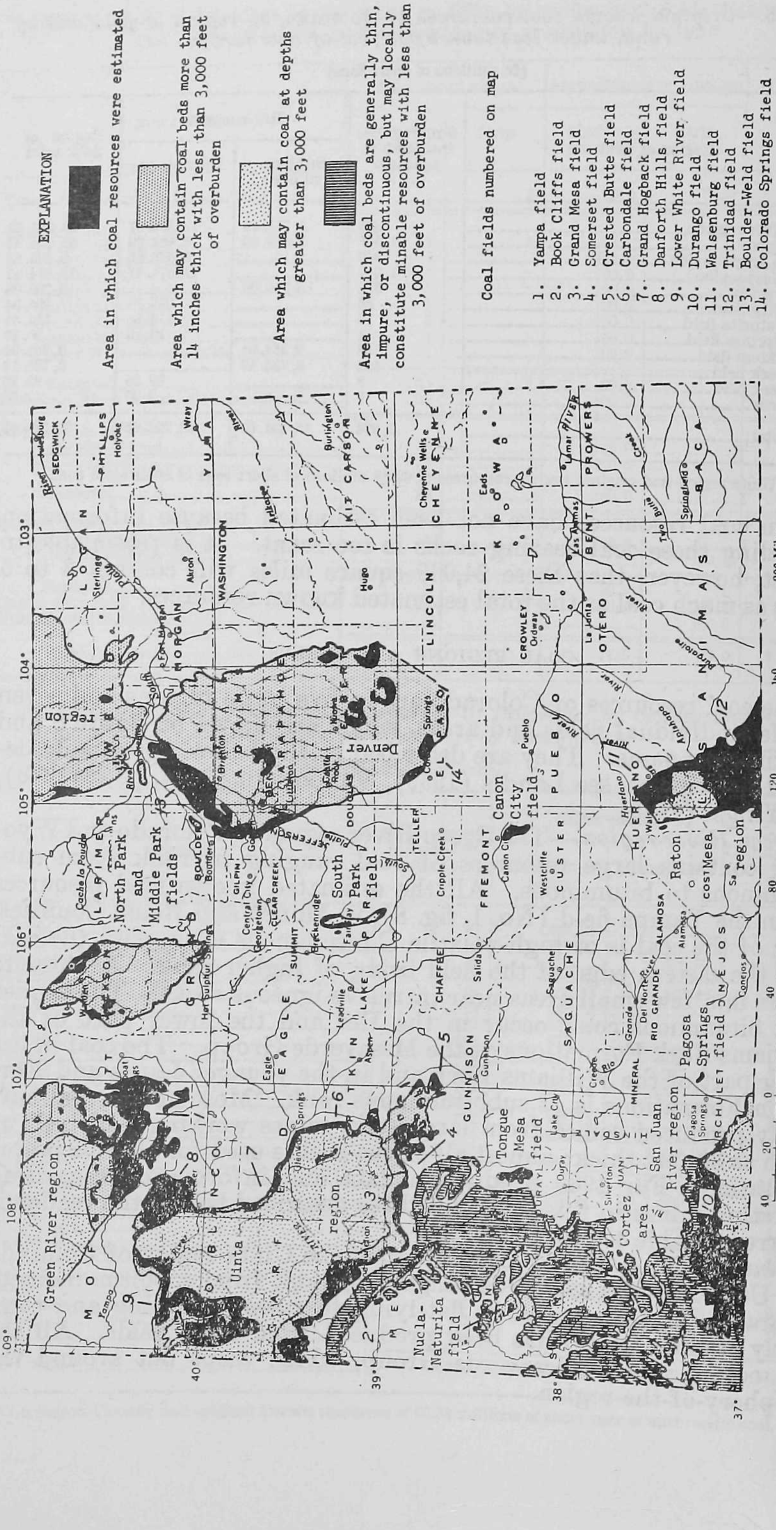

FIGURE 8.—Coal regions and fields in Colorado.

The Book Cliffs field (No. 2) of western Garfield and northern Mesa Counties contains mostly high-volatile C bituminous coal. A small amount of high-volatile B is also present. Most of the coal beds that have been and are being mined are in the lower 450 feet of the Mount Garfield Formation of the Mesaverde Group. Eight mines have been recently active in the field but most of the coal mined at present comes from one mine in the eastern part of the field and is used for electric power generation.

The Grand Mesa field (No. 3) of southeastern Mesa and northern Delta Counties contains coal beds ranging in rank from subbituminous A to high-volatile C bituminous. As many as five coal beds more than 14 inches thick are present in parts of the field, but, in general, no more than three are present in any one area. The coal beds near the base of the coal-bearing sequence have been the most productive. All the coal mined in the field is used for industrial and domestic heating.

The Somerset field (No. 4) of eastern Delta and western Gunnison Counties contains large resources of high-volatile C and B bituminous coal, a large part of which is moderately to strongly coking. In the western part of the field there are 5 to 8 thick beds and in the eastern part there are commonly only two thick beds. In the eastern part of the field the beds have been locally metamorphosed to higher ranks by igneous intrusions. The coal produced in this field is used almost entirely for making coke for the steel industry.

The coal-bearing rocks of the Crested Butte field (No. 5) of Gunnison County in the southeastern corner of the Uinta region have been subjected to greater amounts of deformation and igneous intrusion than those elsewhere in the region, and consequently the coal ranges widely in rank, with transitions in short distances. In general, however, the coal in the northern and western parts of the field is semi-anthracite and anthracite and the coal in the southern part of the field is high-volatile C and B bituminous coal, some of which has coking properties. The number of coal beds in various parts of the field range from one to as many as five.

The Carbondale field (No. 6) of eastern Garfield, western Pitkin, and northern Gunnison Counties lies north of the Crested Butte field along the eastern edge of the Uinta region. The coals range in rank from high-volatile C bituminous coal to anthracite. In the northern part of the field the coal is mainly high-volatile B bituminous; in the southern part it is mainly high-volatile A and medium-volatile bituminous. Most of the bituminous coal in the southern part of the field is moderately to strongly coking; but the coal in the northern part of the field is mainly non-coking. Though there are several groups of coal beds in the coal-bearing sequence, the beds in the lower part are generally of better quality and have been mined the most. Almost all the coal produced in the field is used to make coke for the steel industry. At least 50 percent of the coal in the field is bituminous coal with moderate to strong coking properties and about 7 percent is anthracite or semi-anthracite. The field ranked fourth in coal production in the State in 1963 (table 3).

The Grand Hogback field (No. 7) of Garfield and Rio Blanco Counties forms a large part of the eastern edge of the Uinta region. The Mesaverde Group in this field comprises, in ascending order, the Iles and Williams Fork Formations. Both formations contain coal but the beds in the Iles are thin, impure, and lenticular. Nine or more coal beds are present in the lower 2,500 feet of the Williams Fork Formation and have been the source of most of the coal produced in the field. A higher group of coal beds, numbering as many as four, are present in the upper part of the Williams Fork but these beds have not been explored or developed as much as the lower beds. The coal in the southern part of the field is mainly high-volatile B bituminous and is noncoking. The coal in the northern part of the field is mainly high-volatile C bituminous. Coal mined in the field is used almost entirely for local domestic heating.

The Danforth Hills field (No. 8) is in the northeastern part of the Uinta region of Colorado in northern Rio Blanco and southern Moffat Counties. Five groups of coal beds are present in the coal-bearing sequence, three in the Williams Fork Formation and two in the Iles Formation. Individual coal beds are lenticular and correlation of beds within the coal groups is difficult. The coal is mostly high-volatile C bituminous but some subbituminous coal may be present in the upper part of the Williams Fork Formation in the northern part of the field. Comparatively little mining has been done in the field, despite the large number of thick coal beds.

The Lower White River field (No. 9) includes the area along the northern edge of the Uinta region in southern Moffat and western Rio Blanco Counties. All the known coal resources of the field are in the Williams Fork Formation of the Mesaverde Group. Detailed information is lacking on the rank of the coal and on the thickness, persistence, and lateral correlation of the coal beds, but the information available suggests the presence of large resources of high-volatile C bituminous coal.

San Juan River region.—The San Juan River region in Archuleta, La Plata, and Montezuma Counties comprises the Colorado portion of the San Juan Basin of New Mexico and Colorado. Coal is present in three different formations. The lowest coal beds are in the Dakota Sandstone and are generally thin and discontinuous. The middle set of coal beds are in the Menefee Formation of the Mesaverde Group. They are of high-volatile A, B, and C bituminous rank and have coking properties in the Durango Field (No. 10) in the northern part of the region. The uppermost coal beds are in the Fruitland Formation; they are generally thicker and of slightly lower quality and rank than those in the Menefee Formation. In general, most of the coal mined in the area comes from the Menefee, but considerable quantities have also been mined from the Fruitland. At present, mining activity is concentrated in the Durango field.

Raton Mesa region.—The Colorado part of the Raton Mesa region of Colorado and New Mexico consists of two fields, the Walsenburg field (No. 11) of Huerfano County and the Trinidad field (No. 12) of Las Animas County. The coal beds of the region are present in two rock units, the Vermejo Formation and the overlying Raton Formation. Though most of the mining in the region has been in beds of the Vermejo Formation, large quantities of coal have been and are being produced from beds of the Raton Formation.

The coal of the Walsenburg field is mostly high-volatile C bituminous coal and is noncoking. The Raton Formation is thin or absent in parts of the field and practically all mining has been in beds of the Vermejo Formation.

The Trinidad field contains bituminous coal that ranges in rank from high-volatile A to high-volatile B and possesses coking properties. In this field, as in the Walsenburg field, the beds of the Vermejo Formation have been mined much more than those of the Raton Formation, but considerable quantities of coal have been produced from some beds of the Raton Formation. Most of the coal mined at present comes from one underground mine working a bed in the Raton Formation and is used to make coke for the steel industry.

Denver region.—The Denver region is in parts of El Paso, Douglas, Elbert, Arapahoe, Jefferson, Denver, Adams, Boulder, Morgan, Weld, and Larimer Counties. It comprises a large area in eastern Colorado, east of the Front Range and north of the Arkansas River, underlain by the coal-bearing Laramie Formation. In the southeastern and central parts of the region thick but discontinuous coal beds are present in those parts of the Dawson and Denver Formations that are of early Tertiary age.

The coal ranges in rank from subbituminous B to subbituminous C and some of the younger coals may be lignitic. In general, coal in the more highly deformed western and northern parts of the region is of higher rank than coal in the eastern and southern part. Coal has been mined at many places in the region but at present mining is largely concentrated in the southwestern part of Weld County, part of the Boulder-Weld field (No. 13). In that area the coal occurs in the Laramie Formation and is mainly subbituminous B in rank. A substantial percentage of the coal produced is used for electric power generation. The field is the only area in the State where shaft mining predominates over other mining methods.

A strip mine in the Colorado Springs field (No. 14) was active in 1963.

Canon City field.—The Canon City field, in southeastern Fremont County, contains as many as 16 coal beds but many of the beds are thin, lenticular, and of uncertain correlation.

The coal, which occurs in the Vermejo Formation, is mainly of high-volatile C bituminous rank and is noncoking. The coal beds crop out around the edges of an asymmetric synclinal basin that is bounded by a thrust fault on one side. Mines in the field are largely underground but in recent years strip mines have increased in number and importance.

Nucla-Naturita field.—The Dakota Sandstone is coal-bearing in many localities in southwestern Colorado, but only in the Nucla-Naturita field of Montrose County is the coal being mined at present. At least three coal beds are present in parts of the field, the middle bed of these exceeds 4 feet in thickness at some points. The coal is high-volatile B bituminous in rank and is used locally for electric power generation.

Other fields.—Coal has been mined in the past from the Pagosa Springs, Tongue Mesa, North Park, and South Park fields, but these fields were inactive in 1963. The coal possibilities of the Middle Park field cannot be evaluated because the available information is inadequate.

The Pagosa Springs field of northeastern Archuleta County contains as many as three coal beds, one of which is reported to be as much as 10½ feet thick. The coal-bearing rocks may be correlatives

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of the Fruitland Formation of Late Cretaceous age, and the coal is probably of high-volatile bituminous C rank similar to the coal of the Fruitland in the nearby San Juan River region.

The Tongue Mesa field in Gunnison, Ouray, and Montrose Counties is underlain by coal-bearing rocks of the Mesaverde Group. The coal-bearing strata are concealed by landslides, talus from the overlying volcanic rocks of Tertiary age, and glacial deposits of Quaternary age. Several coal beds as much as 40 feet thick have been reported in the field. The coal is subbituminous B in rank.

In the North Park field of Jackson County the Coalmont Formation contains as many as five coal beds. The maximum coal bed thickness reported is 66 feet. The available information indicates that the beds, though thick, are very lenticular and, in some cases, are podlike. Large quantities of coal were produced from the field during the late 1950's but no production has been reported since 1960.

In the South Park field, Park County, coal is present in the Laramie Formation, but there have been no active mines in the field for many years. As many as three beds are reportedly present in parts of the field and coal of both subbituminous and bituminous rank may be present.

In addition to the Nucla-Naturita field, coal resources are known to be present in the Dakota Sandstone in two other areas, the Cortez area of Montezuma County and along the northern edge of the San Juan River region in La Plata County. Estimated known resources of the Cortez area are listed on table 4; those in La Plata County are included with the estimated known resources of the San Juan River region. The Dakota Sandstone is present at depths of less than 3,000 feet over an area of more than 5,000 square miles in southwestern Colorado but the available information shows that the coal beds are generally of relatively poor quality, thin, discontinuous, and may be completely absent in large parts of the area underlain by the Dakota.

MINING METHODS

In 1963, a total of 104 mines, 95 underground and 9 strip, operated in Colorado. In recent years, the number of underground mines in the State has decreased steadily while the number of strip mines has remained nearly constant. Not only is the number of underground mines decreasing, but the relative proportion of total production mined underground has also decreased; in 1955 about 89 percent of the coal mined during the year came from 143 underground mines, and 7 strip mines produced the remainder; in 1963 about 77 percent of the coal came from 95 underground mines and 9 strip mines produced the remainder. Stated another way; in 1955 about 4.66 percent of the mines were strip mines and produced about 11 percent of the State's total, but in 1963 about 8.7 percent of the mines were strip mines and produced about 23 percent of the State's total. This trend of increasing proportion of total production from strip mines probably will continue.

OUTLOOK

Almost half of the coal produced in the United States in recent years was used to generate electricity, but only about 40 percent of Colorado's production was used for this purpose. However, the amount of coal used by the electric utilities in the Rocky Mountain region has increased greatly in recent years, and within the next decade at least 50 percent, and possibly as much as 75 percent, of the coal mined in Colorado will probably be used to generate electricity. If the amount of coal used by the steel industry and for industrial and domestic heating remains constant or nearly so, total coal production should increase significantly in the foreseeable future.

As the energy demands of the western United States increase, the large amount of readily available heat energy represented by the coal resources of the State should become a larger factor in the economy of Colorado than it is in 1964.

OIL AND GAS

(By N. W. Bass, U.S. Geological Survey, Denver, Colo.)

INTRODUCTION

The total value of petroleum, including crude oil, natural gas, liquid petroleum gases, and natural gasoline produced in Colorado in 1963 was $131,100,000. It is noteworthy that the total value of petroleum amounted to 41 percent of the total value ($318,608,000) of all minerals produced in the State in 1963 (Mullen, 1964). The value of petroleum is less than it was in 1962, however, when it amounted to $142,383,000. The reduced value is due mainly to the fact that 4,277,000 fewer barrels of crude oil were produced in Colorado in 1963 than in 1962. As pointed out by Mullen (1964) the reduced production of crude oil was caused by (1) a continued decline in production of many of the older fields in the State, (2) a decrease in the rate of production in the Rangely field (the largest field in the State) because the field's production rate is controlled as a unit through secondary recovery operations in order to obtain maximum ultimate recovery, and (3) the failure to discover new fields whose total yield might offset the loss caused by items 1 and 2. The discovery of new fields may be related to the number of wildcat wells drilled; only 287 wildcat wells were drilled in Colorado in 1963, which is 95 fewer than in 1962, and is only 35 percent of the number drilled in 1955 when 811 wildcat wells were drilled in the State. Of the 287 wildcats drilled in 1963, 13 were completed as oil wells, 12 were completed as gas wells, and 262 were dry holes. Moreover, only 600 wells, including the wildcats and all development wells, were drilled in 1963, which is 158 fewer than in 1962. The number of wells completed in Colorado has declined each year since 1955 when 1,509 wells were drilled (Oil and Gas Journal, Jan. 27, 1964, p. 149).

Colorado had estimated proved recoverable reserves on January 1, 1964 of 302,800,000 barrels of crude oil (table 6, col. 1), 2,093 billion cubic feet of natural gas (col. 6), and 22,000,000 barrels of natural gas liquids, including condensate, natural gasoline, and liquified pertoleum gases (col. 8). Colorado ranks 14th among the States in estimated proved reserves of crude oil (col. 1), 12th in estimated reserves of natural gas (col. 6), 13th in estimated reserves

TABLE 6.—*United States oil and gas production and reserve data by States*

[Compiled from Oil and Gas Journal, v. 62, no. 4, Jan. 27, 1964, p. 153–158]

Rank	(1) Estimated proved recoverable reserves of crude oil, Jan. 1, 1964			(2) Daily production of crude oil and condensate		(3) Total production of crude oil and condensate, 1859–1963		(4) Daily average yield of oil per well	
	State	Thousand barrels	Percent United States	State	Barrels	State	Thousand barrels	State	Barrels
1	Texas	14,205,750	41.1	Texas	2,655,000	Texas	26,679,873	Alaska	491.7
2	Louisiana	7,137,500	20.6	Louisiana	1,434,000	California	12,924,868	Florida	106.2
3	California	3,775,499	10.9	California	825,000	Oklahoma	8,822,729	Utah	103.9
4	Oklahoma	2,098,000	6.1	Oklahoma	549,000	Louisiana	6,940,968	Mississippi	62.0
5	Wyoming	1,260,500	3.7	Wyoming	397,000	Kansas	3,645,750	Wyoming	52.6
6	New Mexico	1,025,000	3.0	Kansas	301,000	Illinois	2,458,013	Louisiana	51.1
7	Kansas	896,500	2.6	New Mexico	298,000	Wyoming	2,342,063	Alabama	49.2
8	Utah	618,750	1.8	Illinois	204,000	New Mexico	1,846,393	**Colorado**	48.5
9	Mississippi	536,000	1.6	Mississippi	162,000	Pennsylvania	1,237,351	North Dakota	36.8
10	Illinois	510,000	1.5	**Colorado**	105,000	Arkansas	1,172,628	Nebraska	33.9
11	North Dakota	394,000	1.1	Utah	92,000	Mississippi	854,492	Montana	24.0
12	Montana	356,000	1.0	Montana	85,000	**Colorado**	722,518	California	20.3
13	Arkansas	309,500	.9	Arkansas	75,000	Ohio	684,173	New Mexico	17.9
14	**Colorado**	302,800	.9	North Dakota	68,000	Michigan	493,558	Texas	13.3
15	Alaska	296,500	.9	Nebraska	60,000	West Virginia	475,168	Arkansas	12.6
16	Kentucky	187,500	.5	Kentucky	52,000	Kentucky	472,257	Michigan	10.2
17	Nebraska	152,000	.3	Michigan	44,000	Montana	458,996	Illinois	6.7
18	Michigan	116,100	.3	Indiana	32,000	Indiana	353,982	Oklahoma	6.7
19	Pennsylvania	98,250	.3	Alaska	30,000	Utah	217,629	Kansas	6.5
20	Ohio	81,800	.2	Alabama	25,000	Nebraska	210,555	Indiana	5.7
21	Indiana	62,000	.2	Ohio	15,000	New York	201,164	Kentucky	2.7
22	Alabama	61,150	.2	Pennsylvania	14,000	North Dakota	178,445	Ohio	.9
23	West Virginia	47,100	.1	West Virginia	9,000	Alabama	60,493	West Virginia	.7
24	New York	31,389	.1	New York	5,000	Alaska	28,101	New York	.4
25				Florida	1,000	Florida	7,788	Pennsylvania	.2
	Others [1]	33,166	.1	Others	1,000	Others	5,112		
	Total, United States.	34,592,754		Total, United States.	7,538,000	Total, United States.	73,495,067	Average for United States.	12.6

[1] Arizona, Florida, Maryland, Missouri, Nevada, South Dakota, Tennessee, and Virginia.

Rank	(5) Wells producing oil in 1963		(6) Estimated natural gas reserves, Jan. 1, 1964		(7) Total liquid reserves, Jan. 1, 1964		(8) Estimated proved reserves natural gas liquids (includes condensate, natural gasoline, and liquefied petroleum gases), Jan. 1, 1964		(9) Marketed production of natural gas in 1963	
	State	Number of wells	State	Billion cubic feet	State	Million barrels	State	Thousand barrels	State	Million cubic feet
1	Texas	198,841	Texas	127,341	Texas	18,046.3	Texas	3,840,500	Texas	6,192,000
2	Oklahoma	81,952	Louisiana	73,860	Louisiana	8,946.5	Louisiana	1,809,000	Louisiana	3,888,300
3	Pennsylvania	56,213	Oklahoma	19,067	California	4,025.0	New Mexico	524,500	Oklahoma	956,900
4	Kansas	45,987	Kansas	18,035	Oklahoma	2,451.0	Oklahoma	353,000	New Mexico	810,800
5	California	40,556	New Mexico	14,640	New Mexico	1,549.5	California	249,500	Kansas	743,500
6	Illinois	30,544	California	9,102	Wyoming	1,358.9	Kansas	173,300	California	635,500
7	Louisiana	28,052	Wyoming	4,025	Kansas	1,069.8	Wyoming	98,400	West Virginia	217,100
8	Kentucky	19,115	Alaska	3,895	Utah	660.5	North Dakota	76,800	Mississippi	202,100
9	Ohio	16,930	Mississippi	3,037	Mississippi	572.4	West Virginia	58,000	Wyoming	184,200
10	New Mexico	16,648	West Virginia	2,598	Illinois	512.0	Kentucky	50,000	**Colorado**	**115,000**
11	New York	13,103	Utah	2,320	North Dakota	470.8	Utah	41,800	Pennsylvania	93,200
12	West Virginia	13,087	**Colorado**	**2,093**	Montana	366.0	Mississippi	36,400	Utah	87,400
13	Wyoming	7,554	Arkansas	1,677	Arkansas	326.6	**Colorado**	**22,000**	Arkansas	77,200
14	Arkansas	6,005	Pennsylvania	1,210	**Colorado**	**324.8**	Arkansas	17,150	Kentucky	75,700
15	Indiana	5,628	Kentucky	1,082	Kentucky	237.5	Montana	10,050	Ohio	37,000
16	Michigan	4,307	North Dakota	798	Nebraska	155.0	Michigan	6,500	Montana	31,200
17	Montana	3,534	Michigan	678	Michigan	122.6	Nebraska	3,000	Michigan	27,300
18	Mississippi	2,605	Montana	591	West Virginia	105.1	Illinois	2,000	North Dakota	26,550
19	**Colorado**	**2,166**	Illinois	119	Pennsylvania	100.0	Pennsylvania	1,800	Nebraska	14,320
20	North Dakota	1,852	Nebraska	84	Indiana	62.1	Indiana	84	Illinois	10,200
21	Nebraska	1,763	Indiana	29					New York	4,480
22	Utah	886							Maryland	1,725
23	Alabama	515								
24	Alaska	60								
25	Florida	12								
	Others	169	Others	1,480	Others	504.2	Others	20	Others	3,510
	Total, United States	598,084	Total, United States	287,761	Total, United States	41,966.6	Total, United States	7,373,804	Total, United States	14,435,185

of natural gas liquids (col. 8). Colorado ranks 10th among the States in the daily production of crude oil and condensate (col. 2), 12th in the total production of crude oil from 1859 to 1963 (col. 3), 8th in the daily average yield of oil per well (col. 4), 19th in the number of oil-producing wells in 1963 (col. 5), and 10th in the total natural gas marketed in 1963 (col. 9).

HOW OIL AND GAS POOLS OCCUR

Most oil and gas pools are in marine rocks and there is much geologic evidence that plant and animal life buried in the marine sediments was the source of most oil and gas. There are exceptions, however, for some oil and gas pools are in rocks of continental origin, and the evidence appears to indicate that the oil and gas were derived from plant and animal life indigenous to these rocks. Most of Colorado's oil and gas pools are in marine rocks but several, including the Powder Wash and Hiawatha fields and the Piceance Creek pool and others near it in the northwestern part of the State, are in continental rocks.

The composition of crude oils varies from pool to pool and the variation is particularly pronounced in rocks of different geologic age. The crude oil from the Weber Sandstone of Pennsylvania and Permian age in the Rangely oil field in northwestern Colorado is unlike the crude oil from sands of Jurassic age in the Wilson Creek and Maudlin Gulch fields 40 miles east of Rangely, and the oil in these Jurassic sands is unlike oil in the Dakota Sandstone and Mancos Shale of Cretaceous age in nearby fields. On the other hand, crude oil from the Weber Sandstone in the Rangely field and in several other fields is similar even though the fields are many miles apart. Oil is produced from rocks of Pennsylvanian and Permian age, Triassic age, and Cretaceous age within the Rangely field, the three oil pools being separated vertically by several hundred feet of strata, and chemical analyses show that crude oils in the three zones are dissimilar. The fact that crude oils from separate horizons are somewhat different in composition and that oils at the same stratigraphic horizon in a given region are similar suggests that the plant and animal life in the geologic past varied sufficiently from one age to another to give rise to crude oils of different compositions (Bass, 1963, p. 2044).

Oil and gas accumulations, called pools, fields, or reservoirs, occur in porous beds which are overlain and underlain by rocks that are virtually impervious. The source beds for most oil and gas pools interfinger with or lie directly above or below the reservoir beds in the area close by the pools. Oil and gas migrate more readily laterally through the rocks at the horizons of the reservoirs than vertically across the beds because sedimentary rocks are more permeable laterally than vertically. The accumulation of oil and gas into pools takes place where the beds are folded into an anticlinal fold, known as a structural trap, or where the reservoir bed lenses out into impervious shale or other rock, or where the permeability of the reservoir bed terminates laterally because of a filling of its pores with impermeable cementing material, known as a stratigraphic trap. The fractured reservoir trap is a variant of the structural trap and is of considerable importance in Colorado. In this type of trap, impermeable rocks such as shale, limy shale, or limestone have been fractured by structural movements and rendered porous.

Except for some fractured reservoir traps, the reservoir beds in most fields contain water, oil, and gas, and a natural separation of these substances has taken place because of their different specific gravities. The water in the porous bed is low on the flanks of the anticline or in the structurally low end of a stratigraphic trap, the oil is above the water, and gas occupies the highest part. The Rangely, Wilson Creek, Thornburg, Moffat, and several other fields in northwestern Colorado and the Wellington, Fort Collins, Pierce, and Black Hollow fields in the northeastern part of the State are examples of fields on anticlines. Most of the oil and gas fields in the Denver basin in northeastern Colorado, several of the gas fields in southeastern Colorado, the gas fields southwest of the Piceance Creek field in Rio Blanco County and the gas fields in Mesa County southwest of the Divide Creek field are examples of stratigraphic trap fields. The Florence-Canon City field in southeastern Colorado and the Tow Creek field and the Mancos Shale pool in the Rangely field in northwestern Colorado are important examples of fractured reservoir traps.

The gas in most of Colorado's gas pools is composed of hydrocarbon gases, chiefly methane, like that commonly present in gas pools elsewhere. The gas in the Mesaverde Group of the Ignacio-Blanco field, in the Entrada Sandstone of the Thornburg field, in the Wasatch Formation of the Hiawatha field, and in the Dakota Sandstone—J sand in a wildcat well in Morgan County, a few miles northwest of the Sand River field, whose analyses are shown in table 7, are representative of the most common types of gas. As such gas is marketed chiefly for fuel for domestic and commercial uses, its heating value, expressed in British thermal units (Btu) in the analyses, is important to the consumer. Gas from any one of these fields will produce more heat per thousand cubic feet than gas from the Greenwood Extension field, for example, which has a heating value of only 940 Btu.

The gas from the Greenwood Extension field has a high content of nitrogen and an appreciable content of helium, two noninflammable gases which reduce the heating value of the gas. Although the helium content is not a large percent of the gas, it is so much larger than the percent contained in the gas of most gas fields that it is an important constitutent. The helium in the Keyes gas field of Oklahoma, directly south of the Greenwood Extension field, and in the gas fields near Amarillo, which are supplying most of the helium for the United States today, constitutes less than one percent of the gas. The helium in the Keyes field is being extracted from the gas as it leaves the field and before it enters the trunk lines that carry the gas to markets. It is apparent that the total reserve of helium in the Greenwood Extension field is very large because the field covers a very large area and the reservoir pressure is about 435 pounds per square inch, but here the field gas containing helium passes directly into the trunk lines and the helium is lost forever.

The gas in the McElmo (represented by a well near the field) and North McCallum fields is unusual in that it is composed chiefly of carbon dioxide (table 7). The gas will not burn and so is useless for fuel, but at McElmo it is used for the manufacture of dry ice, as is gas from the small Nina View field in Las Animas County. Gas from the North McCallum field was used formerly to repressure their reservoir sand and more recently as an additive to the fluid used in the process of fracturing oil sands. The carbon dioxide gas goes into solution in the oil and it is claimed that this modified "frac" fluid

TABLE 7.—*Analyses of gas from a few gas fields in Colorado (Anderson and Hinson, 1951, p. 52–55; Boone, 1958, p. 25–29)*

County	Field	Location			Depth to gas sand in feet	Stratigraphic position		Analysis (in percent)							Heating value (Btu per cu. ft.)
		Sec.	T.	R.		System or series	Formation	Methane	Ethane	Propane	Nitrogen	Oxygen	Carbon dioxide	Helium	
La Plata	Ignacio-Blanco	15	32 N.	[1] 11 W.	4,530	Cretaceous	Mesaverde Group.	85.8	7.8	2.9	0.5	Tr.	1.2	0.01	1,152
Moffat	Thornburg	16	3 N.	91 W.	2,525	Jurassic	Entrada Sandstone.	99.5	0	------	0	0.3	.2	0	1,008
Do	Hiawatha	19	12 N.	100 W.	1,520	Eocene	Wasatch Formation.	86.7	7.0	------	5.6	.5	.2	.03	1,004
Morgan	Wildcat, near Sand River.	7	1 N.	56 W.	5,313	Cretaceous	Dakota Sandstone J sand.	88.2	5.8	.4	3.3	0	.7	.04	1,060
Baca	Greenwood extension.	18	32 S.	41 W.	3,150	Pennsylvanian	Shawnee Group	64.5	6.3	3.6	22.8	0	.1	.56	940
Jackson	North McCallum	12	9 N.	79 W.	5,113	Cretaceous	Dakota Sandstone.	2.8	1.9	------	2.9	.6	91.8	.13	------
Montezuma	Wildcat, near McElmo.	27	37 N.	[1] 17 W.	7,768	Mississippian	Leadville Limestone.	.1	.1	0	1.9	.1	97.7	.10	3
Las Animas	Model	35	29 S.	60 W.	941	Permian	Lyons Sandstone	.1	0	------	76.1	1.6	14.3	7.93	------

[1] New Mexico principal meridian.

under pressure will penetrate the sand farther than the fluid that is ordinarily used.

The most unusual gas in the State is in the Model field in Las Animas County. The gas contains no hydrocarbons and so won't burn, but it contains an unusually large percent of helium—7.93 percent. The entire gas deposit is owned by the United States Government as a helium reserve. The total reserve is very large even though the pressure at the well heads is only 11 pounds per square inch, for the gas reservoir sand is about 200 feet thick and is gas bearing in a large area.

Oil or gas, or both, are produced in Colorado from no less than 25 formations or groups distributed stratigraphically between rocks of Devonian age to those of Tertiary age. By far the most pools are in the Dakota Sandstone of Cretaceous age but the yield of oil and gas from the Weber Sandstone of Pennsylvanian and Permian age in the Rangely field is so large that the Weber ranks first in total yield.

The total yield of oil and gas by the end of 1962 from several formations is shown below:

	Oil		Gas (billion cubic feet)
	Million barrels	Percent of Colorado total	
Weber Sandstone (Pennsylvanian and Permian)	326.0	45	497
Dakota Sandstone (Cretaceous)	231.6	32	454
Entrada Sandstone and Morrison Formation (Jurassic)	71.0	10	122
Pierre Shale (Cretaceous)	14.4	2	
Lyons Sandstone (Permian)	10.0	1	
Wasatch Formation (Tertiary)	6.0	1	148
Mesaverde Group (Cretaceous)			101
Total	659.0	91	1,322

Much of the statistical data in this entire report was obtained from Colorado Oil and Gas Statistics for 1962 compiled by the Oil and Gas Conservation Commission of the State of Colorado, and much geologic information was obtained from Jensen and others (1954) and Colorado-Nebraska oil and gas field volume 1961, Rocky Mountain Association of Geologists (Parker, 1962).

HISTORY OF OIL AND GAS EXPLORATION

Oil was discovered in Colorado in 1862 by A. M. Cassedy in a well 50 feet deep near an oil seep on Oil Creek in T. 17 S., R. 70 W., about 6 miles north of Canon City, Fremont County, according to Brainerd and Van Tuyl (1954), after whom this chapter is taken. The discovery was made only about 2½ years after the Drake well in Pennsylvania, which is accepted as the earliest discovery of oil by a well drilled for oil in the United States. Five or six wells were drilled north of Canon City near the discovery well to depths ranging between 50 and 90 feet. Gasoline, kerosene, and fuel oil were refined from the crude oil by a crudely built refinery. The gasoline was discarded and the kerosene and fuel oil were marketed in Denver and in mining camps until about 1870.

Additional drilling was carried on in 1876 several miles southeast of the original Cassedy well, near the present site of Florence in T. 19 S., R. 69 W. Oil was discovered in fractured shale beds of the Pierre Shale at a depth of 1,187 feet. This well was the discovery well in the Florence field and this was the only producing oil field in the State from 1876 to 1902. Well no. 42, which was drilled in April 1889, is still producing and produced 1,000 barrels of oil in 1963, according to records of the Colorado Oil and Gas Conservation Commission.

Although a few discoveries of oil and gas were made between 1902 and 1923, there were no discoveries of large reserves. A gas well was discovered in November 1923 in the Dakota Sandstone at Wellington, Larimer County, on the west margin of the Denver basin. An oil well whose flow was rated at 4,560 barrels a day was discovered in March 1924 in the Dakota Sandstone in the Moffat field, Moffat County. Soon there were 100 wells being drilled in the State and several fields were discovered, including Garmesa in Garfield County in 1925, and North McCallum in Jackson County and Hiawatha in Moffat County in 1926. Oil was discovered in 1927 in the Morrison Formation in the Iles field, Moffat County. This discovery was particularly important to oil prospectors because it was the first large pool found in rocks older than the Dakota Sandstone.

Helium-rich gas was discovered at Model in Las Animas County in 1929 and oil was found in the Dakota Sandstone in the Greasewood field in southeastern Weld County in the Denver basin. Several dry holes at Greasewood and the fact that northeastern Colorado was remote from trunk pipeline systems retarded prospecting in the general area.

Oil was discovered in the Weber Sandstone at Rangely, Rio Blanco County, in 1933, 31 years after the discovery of a shallow oil pool in 1902. The lack of a market for the oil, however, prevented the development at Rangely until the second World War created a demand.

The important Wilson Creek Field, Rio Blanco County, was discovered in 1937. Oil in the Dakota Sandstone was discovered in 1949 on the east flank of the Denver basin in Cheyenne County, Nebraska, a few miles north of the Colorado boundary. Immediately following this discovery, millions of acres were leased in northeastern Colorado and seismograph surveying parties by the score were put to work in the area. The first discovery in the D and J sands of the Dakota was made in Logan County in 1950 and wildcat drilling and discoveries followed at a terrific pace, reaching the peak of activity in 1955 when 1,273 wells were drilled in the State. Oil in the Lyons Sandstone was discovered in 1953 in the Black Hollow field in the western part of Weld County near the deepest part of the Denver basin. There were 326 pools in the Denver basin alone in 1964.

Much of the prospecting and discoveries of gas pools in the southern part of northwestern Colorado occurred between 1955 and 1961, following the building of gas pipelines from the fields to markets. The development drilling of the Ignacio-Blanco and Barker Creek gas fields, La Plata County, was done in the early 1950's, because of the construction of pipelines there.

The peak of oil production in Colorado was reached in 1956 when 58,537,662 barrels of oil were produced; the peak of gas production was reached in 1961 when 209,571,505 Mcf [1] were produced. Colorado's annual oil production from 1887 to 1963 is shown on figure 9.

OIL AND GAS FIELDS

The oil and gas fields of Colorado are readily grouped into five regions, northeastern, northwestern, southwestern, southeastern, and North Park. The northeastern and southeastern regions are in the Great Plains physiographic province, the northwestern and southwestern regions are in the Plateau province, and North Park is in the Mountain province (p. 11). The northeastern region includes most of the Colorado portion of the Denver basin in which a few hundred oil and gas fields are present and where most exploration is being carried on. The northwestern region includes the Piceance Creek and Sand Wash basins, each of which contains many oil and gas fields. This region is second only to the northeastern region in exploration activity. The southwestern region includes small portions of the San Juan Basin of New Mexico and the Paradox basin of Utah and contains only a few oil and gas fields, although considerable exploration for oil and gas is in progress. The southeastern region includes the southern part of the Denver basin, the northern part of the Raton basin of New Mexico and Colorado, and the westernmost part of the Hugoton embayment of the Anadarko basin of Kansas and Oklahoma. The region contains relatively few oil and gas fields and only a few exploratory wells are being drilled. North Park, which embraces the North Park basin in the north-central part of the State, contains only a few fields and only a little exploratory drilling is being carried on.

Northeastern region.—The northeastern region includes all but the southern part of the Colorado portion of the Denver basin (fig. 10).

The oil and gas fields in the northeastern region had yielded 237,181,017 barrels of oil and 311,599,278 Mcf of gas by the end of 1962, which was 34.4 percent of the total oil produced and 16.6 percent of the total gas produced in Colorado, according to the Oil and Gas Conservation Commission of Colorado. It is noteworthy that

[1] Natural gas is commonly measured and marketed in units of 1,000 cubic feet, a term that is abbreviated to Mcf.

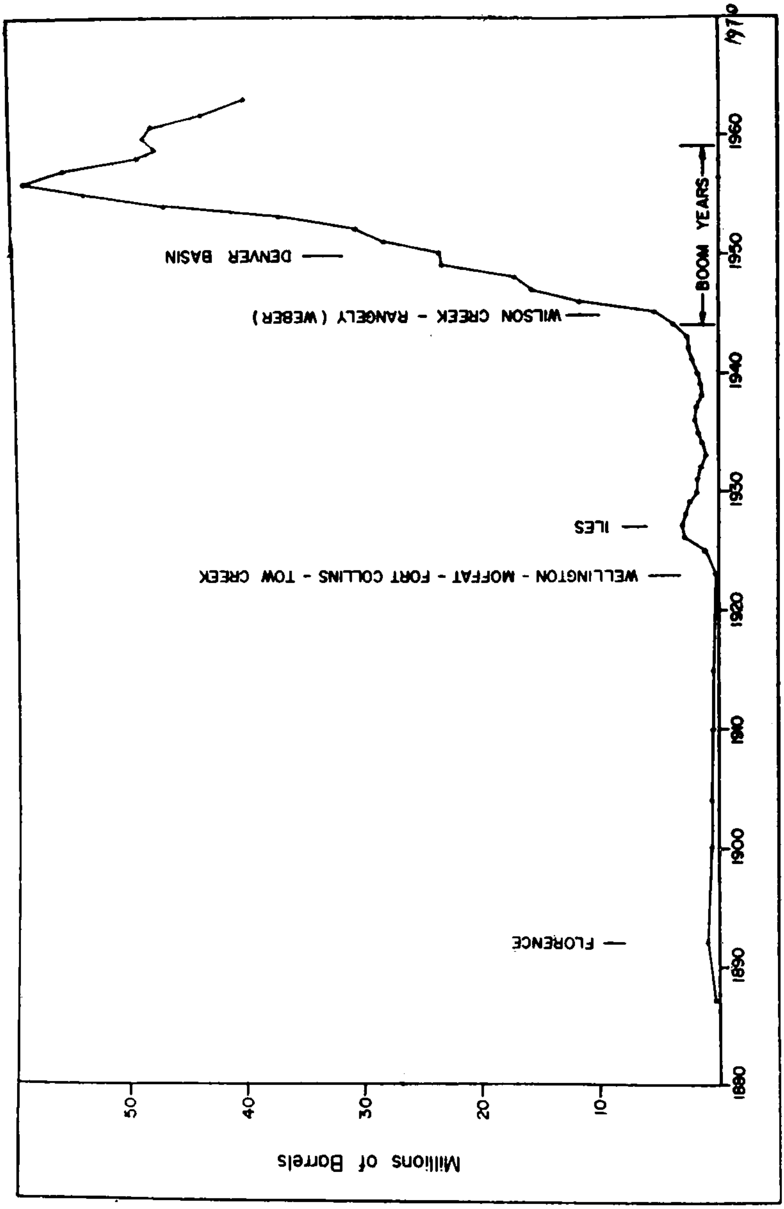

FIGURE 9.—Curve showing Colorado's annual oil production from 1887 to 1963 (1887–1959 after Van Tuyl and Brainerd, 1960, p. 503; 1960–1963 from Colorado oil and gas statistics, yearly reports, by Colorado Oil and Gas Conservation Commission).

about 96 percent of the oil came from the Dakota Sandstone and about 4 percent from the Lyons Sandstone. All but about 0.5 percent of the total gas came from the Dakota Sandstone.

In the Denver basin, the Dakota Sandstone ranges from about 350 to 600 feet in thickness, and consists of a sequence of interbedded units of sandstone and shale of Early Cretaceous age. In the oil fields area the formation generally contains three or more sandstone units, known in descending order as the D, J, and M sands, and locally the O sand, separated by units of dark-gray to black marine shale. The oil and gas pools in the D and J sands throughout the main part of the Denver basin are in stratigraphic traps consisting of porous lenses of sandstone which pinch out laterally into relatively impervious sandy shale and shale. Prominent anticlines are absent in most of these oil and gas fields. The oil- and gas-bearing sand lenses in parts of the basin are systematically arranged in narrow belts corresponding to ancient shore lines, examples of which are in the southwestern part of Washington County and extending into eastern Adams County. The porous sand lenses appear to have no systematic arrangement, however, in the large oil- and gas-producing area in the western part of Logan County. The discovery of oil- and gas-bearing sand lenses is particularly difficult because their presence is not predictable from surface features and rarely in the subsurface except at the site of the pool. Hoping to find new fields, geologists project data obtained from the records of producing wells and dry holes into undrilled areas by theoretical sand distribution patterns. Only one well in 10 to 20 is successful in discovering a new pool.

By the end of 1962 the D sand had yielded 86 million barrels of oil and 154 billion cubic feet of gas, and the J sand had yielded 126 million barrels of oil and 135.7 billion cubic feet of gas; the O sand had yielded only .9 million barrels of oil and 101 million cubic feet of gas. It is noteworthy that the Adena pool alone accounted for 50 million barrels of oil yielded from the J sand. Table 8 lists many of the oil pools in the Denver basin in order of their total oil yield and the principal oil-producing sand.

TABLE 8.—*Major oil- and gas-producing fields in northeastern Colorado and the principal oil-producing sands in the Dakota Sandstone*

Field and location	Barrels of oil produced through 1963	Principal producing sand	Remarks
Adena, Tps. 1–2 N., Rs. 57–58 W	52,721,021	J	2,560,648 barrels from D sand.
Little Beaver, Tps. 1–2 S., R. 56 W	13,677,448	D	2,742,128 barrels from J sand.
Plum Bush Creek, T. 2 S., Rs. 55–56 W	11,924,397	J	
Yenter, T. 8 N., R. 54 W	8,354,306	J	
Graylin, N.W., Tps. 8–9 N., Rs. 53–54 W	7,945,854	D	
Big Beaver, T. 3 S., R. 56 W	7,746,431	J	
Bobcat, T. 1 S., R. 56 W	5,647,381	D	1,295 barrels from J sand.
Badger Creek, T. 2 S., R. 57 W	5,145,917	D	1,005,190 barrels from J sand.
Mount Hope, T. 9 N., Rs. 53–54 W	4,849,084	D	87,692 barrels from J sand.
Cliff, Tps. 11–12 N., R. 54 W	4,685,305	D	
Lewis Creek, T. 11 N., Rs. 52–53 W	4,191,937	J	
Merino, T. 6 N., R. 54 W	3,270,785	J	
Little Beaver, East, Tps. 1–2 S., R. 56 W	3,141,321	D	243,519 barrels from J sand.
Sand River, T. 1 N., R. 56 W	2,689,467	D	
Luft, T. 8 N., Rs. 53–54 W	2,350,711	D	
Kejr, T. 2 S., R. 56 W	2,115,499	D	394,669 barrels from J sand.

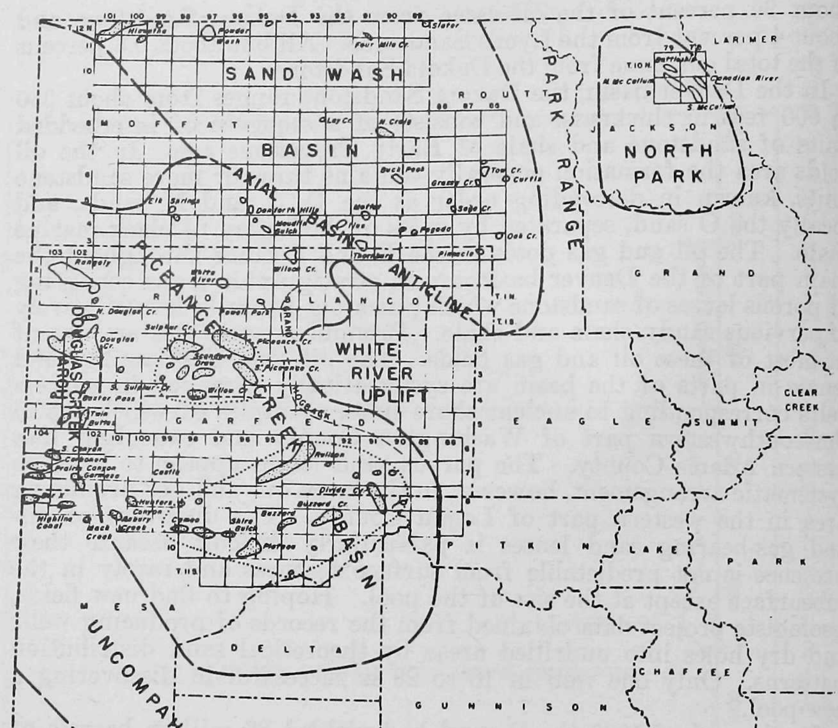

Figure 10.—Colorado oil and gas fields.

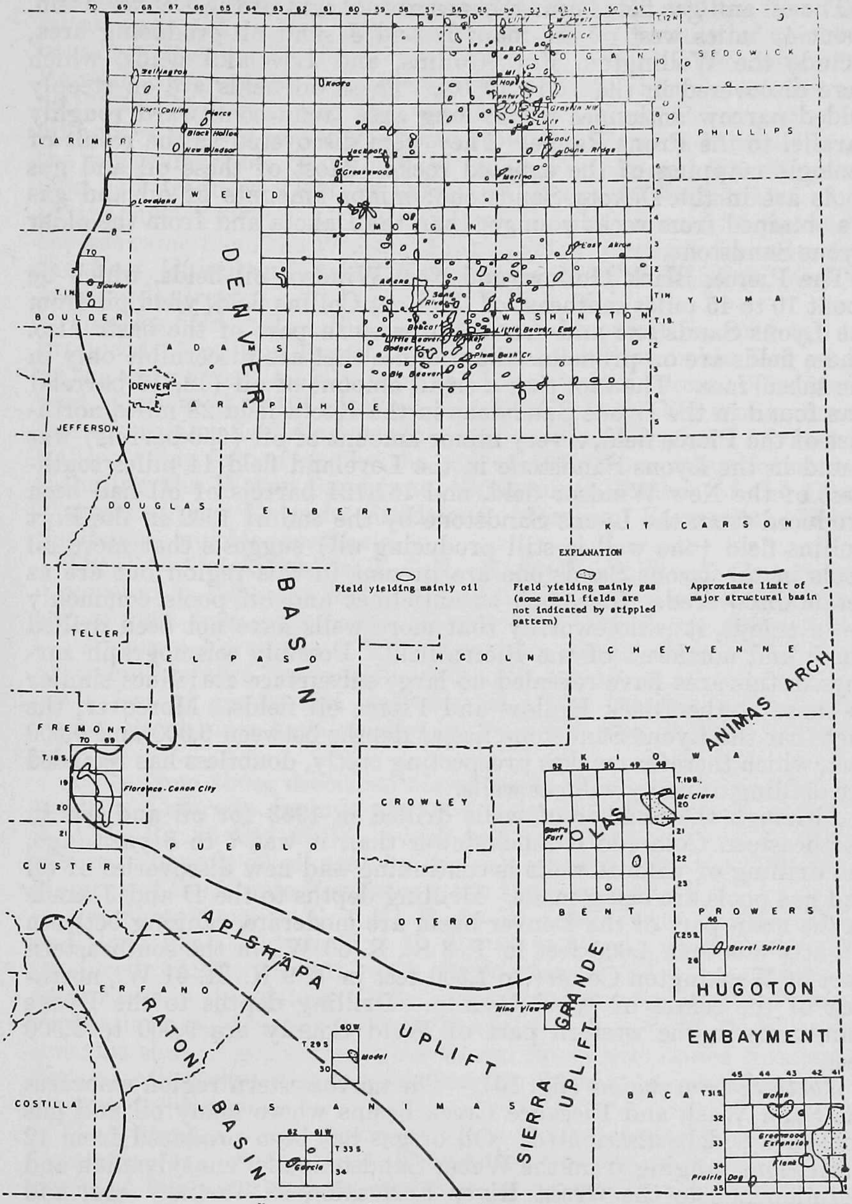

FIGURE 10.—Colorado oil and gas fields.

The oil and gas fields near the western margin of the Denver basin, about 45 miles west of the main D and J sand oil-producing area, include the Wellington, Fort Collins, and Loveland fields, which were discovered in the early 1920's. These oil fields are on steeply folded narrow anticlines whose long axes trend southward roughly parallel to the Front Range. They were discovered as the result of geologic mapping of the exposed rocks. Most of these oil and gas pools are in the Dakota Sandstone; minor amounts of oil and gas are obtained from rocks younger than the Dakota and from the older Lyons Sandstone.

The Pierce, Black Hollow, and New Windsor oil fields, which lie about 10 to 15 miles southeast of the Fort Collins field, yield oil from the Lyons Sandstone and are in the western part of the basin also. These fields are on pronounced anticlines that are discernible only in the subsurface. The fact that a small amount of oil (12,816 barrels) was found in the Lyons Sandstone in the Keota field 28 miles northeast of the Pierce field, a very minor amount of oil (650 barrels) was found in the Lyons Sandstone in the Loveland field 14 miles southwest of the New Windsor field, and 151,124 barrels of oil had been produced from the Lyons Sandstone by the end of 1962 in the Fort Collins field (one well is still producing oil) suggests that more oil pools in the Lyons Sandstone are present in this region but are as yet undiscovered. Inasmuch as anticlines and oil pools commonly lie in trends, it is noteworthy that more wells have not been drilled north and northeast of the Pierce field. Possibly seismograph surveys in this area have revealed no large subsurface anticlines similar to those at the Black Hollow and Pierce oil fields. Moreover, the fact that the Lyons Sandstone lies at depths between 9,000 and 9,500 feet, which therefore makes prospecting costly, doubtless has retarded the drilling of many wildcat wells.

Although the number of wells drilled in 1963 for oil and gas in northeastern Colorado is much fewer than it was 7 to 8 years ago, the drilling of wildcat wells is continuing and new discoveries of oil and gas pools are being made. Drilling depths to the D and J sands in the main part of the Denver basin are moderate, ranging between slightly less than 4,000 feet in T. 3 S., R. 50 W., in the southeastern part of Washington County to 7,300 feet in T. 9 N., R. 61 W., northeast of the center of Weld County. Drilling depths to the Lyons Sandstone in the western part of Weld County are 9,000 to 9,500 feet.

Northwestern region (fig. 10).—The northwestern region embraces the Sand Wash and Piceance Creek basins where many oil and gas pools are widely distributed. Oil or gas has been produced from 12 formations ranging from the Weber Sandstone of Pennsylvanian and Permian age to the Green River Formation of Tertiary age, and including rocks of Triassic, Jurassic, and Cretaceous ages. (For age and stratigraphic position of the stratigraphic units mentioned in the following paragraphs, see table 1.)

A relatively large part of northwestern Colorado is occupied by the Sand Wash basin. Oil and gas has been produced from many fields which are widely spaced in the basin but most of the oil and gas has been produced from only a very few fields.

The Powder Wash oil and gas field in R. 97 W. and the Hiawatha oil and gas field in Rs. 100 and 101 W., directly south of the State boundary, were discovered in 1931 and 1926, respectively. The Powder Wash field had produced 3,224,004 barrels of oil and 55,175,440 Mcf of gas by the end of 1962. About 95 percent of the oil and 86 percent of the gas came from the Wasatch Formation and the remainder came from the Fort Union Formation. The Hiawatha field had produced 2,886,686 barrels of oil and 97,681,683 Mcf of gas by the end of 1962. All but 2 percent of the oil and 35 percent of the gas came from the Wasatch Formation; the remainder came from the Fort Union and Lance Formations, the Lewis Shale, and the Mesaverde Group.

The Iles field in T. 4 N., R. 92 W., was discovered in 1924 and had produced 15 million barrels of oil and 1.9 billion cubic feet of gas by the end of 1962, mainly from the Entrada Sandstone. The Moffat field, discovered in 1924 in Tps. 4 and 5 N., R. 91 W., 4 miles northeast of the Iles field, had produced 8.6 million barrels of oil and 175 million cubic feet of gas by the end of 1962 from many formations, including the Weber Sandstone, Shinarump Member of the Chinle Formation, the Entrada Sandstone, Morrison Formation, Dakota Sandstone, and Mancos Shale.

The Tow Creek field in T. 6 N., R. 86 W., in Routt County, was discovered in 1924 and had produced 2.7 million barrels of oil by the end of 1962 from beds in the Mancos Shale which are equivalent to the Niobrara Formation. The Thornburg field in T. 3 N., R. 91 W., discovered in 1925, had produced 753,686 barrels of oil and 10 billion cubic feet of gas by the end of 1962. The Dakota, Entrada, and Weber Sandstones have yielded gas but only the Weber has yielded oil.

Aside from those described above, small oil or gas fields in northwestern Colorado include the Pinnacle and Oak Creek fields in T. 3 N., Rs. 86 and 87 W., which had produced between 50 and 80 thousand barrels of oil each by the end of 1962 from the Shinarump Member of the Chinle Formation; the Pagoda gas field, a shut-in field in the Shinarump in T. 4 N., R. 89 W.; the Curtis, Grassy Creek, and Buck Peak fields in T. 6 N., Rs. 85 to 87 and 90 W., which had produced 62,271, 139,961, and 73,366 barrels of oil, respectively, from rocks in the Mancos Shale which are equivalent to the Niobrara Formation; and the North Craig gas field in T. 8 N., R. 90 W., which contains shut-in gas pools in the Lewis Shale and Lance Formation. Several other shut-in gas pools having from 1 to 2 wells each are present in the region.

The Piceance Creek basin occupies a large area in west-central Colorado. It is really the southeastern extension of the large Uinta Basin of Utah and is separated from it by the Douglas Creek arch, a northward-trending structural feature whose axis lies 12 to 15 miles east of the Colorado-Utah boundary. The Piceance Creek basin is separated from the Sand Wash basin on the northeast by the Axial Basin anticline, a northwestward-trending feature in Moffat and Rio Blanco Counties.

The Piceance Creek basin contains many oil and gas fields, including the Rangely field, which is the largest producing oil field in the State. The Rangely oil field in Tps. 1 and 2 N., Rs. 101 to 103 W., is on a prominent anticline that trends northwest and is more than 20 miles long. A total of 8,602,701 barrels of oil had been produced from the Mancos Shale, 2,471 barrels from the Morrison Formation, 212,087 barrels from the Shinarump Member of the Chinle Formation, and 324,407,041 barrels from the Weber Sandstone by the end of 1962. The total production of the field, from all reservoirs, was 349,051,000 barrels of oil at the end of 1963.

The Wilson Creek field in Tps. 2 and 3 N., R. 94 W., on the northeast margin of the Piceance Creek basin, was discovered in 1938 and by the end of 1963 had produced 52 million barrels and 24½ billion cubic feet of gas from the Entrada Sandstone and the Morrison Formation. The field produced 2,265,230 barrels of oil in 1962 and 2,382,000 barrels of oil in 1963. The oil field is on a prominent dome on the Danforth Hills anticline, which trends northwesterly for more than 25 miles and includes several smaller domes, some of which contain oil fields. Among these is the Maudlin Gulch field, which had produced 1,283,562 barrels of oil by the end of 1962. Except for 6,337 barrels of oil from the Weber Sandstone, the entire yield of oil at Maudlin Gulch came from the Entrada Sandstone and the Morrison Formation. The Danforth Hills oil field is 5 miles farther northwest along the Danforth Hills anticline. It had produced 1,837,118 barrels of oil from the Entrada Sandstone and Morrison Formation by the end of 1962.

The North Douglas Creek field in T. 1 S., Rs. 101 and 102 W., about 6 miles south of Rangely, had produced 5 million cubic feet of gas from a sand in the upper part of the Mancos Shale, and 14,725 barrels of oil from the Weber Sandstone by the end of 1962.

Gas was discovered in 1943 in sec. 5, T. 3 S., R. 101 W., in the Dakota Sandstone on the Douglas Creek arch. This discovery led to the development of a large gas field, chiefly in sands in the Mancos Shale and in the Dakota Sandstone in parts of T. 2 S., Rs. 101 to 103 W., and T. 3 S., Rs. 101 and 102 W. More than 40 gas wells have been completed, but most wells are shut-in By the end of 1962, nearly 8 billion cubic feet of gas had been produced from the Dakota Sandstone and half a billion cubic feet had been produced from the Mancos Shale.

Several gas fields are present in an area 10 to 30 miles wide extending southward for 40 miles from the Douglas Creek field. The gas wells are widely spaced in the area. The gas is present in the Entrada Sandstone, Morrison Formation, Burro Canyon Formation, Dakota Sandstone, and sandstones in the upper part of the Mancos Shale. The gas fields include Baxter Pass, Twin Buttes, South Canyon, Carbonera, Prairie Canyon, Garmesa, Bar X, Highline Canal, Hunters Canyon, Asbury Creek, and Mack Creek. Some of the fields are shut-in. The total yield of the seven fields that are connected to a pipe line was 11,255,620 Mcf of gas by the end of 1962.

A slightly elliptical area 15 miles wide and 25 miles long in south-central Rio Blanco County, Tps. 2 to 4 S., Rs. 95 to 99 W., contains the Piceance Creek, Sulphur Creek, South Sulphur Creek, Scandard Draw, and Willow Creek gas fields. Most of the wells yield gas from the Green River or Wasatch Formations; a very few yield oil. Two or more wells yield gas from the Mesaverde Group. Gas was discovered in 1930 by a well on the northeast flank of the Piceance Creek anticline, a large asymmetric fold in the northeastern part of this large gas-bearing area. The fold has a structural closure of about 800 feet on beds in the Green River Formation. The initial daily yield of the gas wells in the Piceance Creek field ranged between less than a million to 9.8 million cubic feet. The gas accumulation in the South Piceance Creek field is due to the presence of lenticular beds of sandstone in the Green River Formation which pinch out laterally into shale. The initial yield of the wells ranged between less than a million to 5 million cubic feet of gas. Two wells yield a small amount of oil. The Scandard Draw field, discovered in 1958 contains a few widely spaced wells which yield small flows of gas from sands in the Mesaverde Group. The Sulphur Creek field, discovered in 1958, yields gas from the Green River Formation in several wells, from the Wasatch Formation in a few wells, from the Mesaverde Group in one well, and some oil from the Green River Formation in two wells. The initial yield of the gas wells ranged between less than a million to 9 million cubic feet a day. The wells are shut-in. The South Sulphur Creek and Willow Creek gas pools are several miles southwest of the other pools. Each pool contains only a few wells in either the Green River, Wasatch, or Mesaverde. The initial daily yield of the wells ranged between ½ million to 4 million cubic feet of gas.

Another area about 25 miles wide and 50 miles long, tending northeastward, mostly in southeastern Garfield and northeastern Mesa Counties, contains several gas fields. Most wells here yield gas from the Mesaverde Group; a few yield gas from the Dakota Sandstone. The gas-bearing sands of the Mesaverde are distributed through a thick sequence of rocks in parts of the area but in other parts two units called the Cozette and Corcoran sands are the gas reservoirs. These two sands are separated from the overlying main body of the Mesaverde by a unit of shale several hundred feet thick whose lithology is similar to the Mancos Shale. Accordingly, some geologists consider these two sands as members of the Mancos Shale. Others consider them as members of the Mesaverde Group because they can be correlated with sandstone units in the basal part of the Mesaverde on the outcrop along the Grand Hogback several miles northeast of the gas fields.

The Rulison gas field in Garfield County in the north part of the 25- by 50-mile area was discovered in 1956. The gas is chiefly from a zone 1,500 to 2,000 feet thick in the Mesaverde Group. The field extends southwestward from Rifle for about 20 miles. The initial daily yield of most wells was a little more than 1 million cubic feet; the initial daily yield of one well was 4.3 million cubic feet. The accumulation of the gas is believed to be due to pinch outs of porosity in the sands. The total yield of the field by the end of 1962 was 378,-282 Mcf.

The Buzzard Creek field, discovered in 1955, the Buzzard field, discovered in 1958, and the Plateau field, discovered in 1958, in Mesa County in the south part of the 25- by 50-mile area, yield gas chiefly from the Cozette and Corcoran sands. Some wells are shut-in; others produce at relatively small rates. The total yield by the end of 1962 was 950,062 Mcf. It is reported that the yield of the wells in these fields is maintained longer than that of the wells in the Rulison field.

The Divide Creek gas field, discovered in 1956, is on a steeply folded anticline that trends northwest. Gas is present in sands in the Measverde Group in about a dozen wells. The initial daily yield of the wells ranged from less than a million to 15.9 million cubic feet a day. Only a few wells are being produced. The total yield for the field by the end of 1962 was 851,186 Mcf.

A few wells, notably four widely separated wells in T. 10 S., R. 97 W., T. 9 S., Rs. 98 and 99 W., and T. 8 S., R. 98 W., at the southwest end of the 25- by 50-mile area yield gas from the Dakota Sandstone. The initial daily yield of these wells ranged from 1.7 to 5.2 million cubic feet.

Southwestern region.—Only a few oil and gas fields are present in southwestern Colorado and of these the two largest are on the State boundary and those parts in Colorado constitute minor parts of much larger fields in adjacent states.

The northern margin of the unusually large Ignacio-Blanco gas field in New Mexico projects 12 miles into the southeastern part of La Plata County, Colo. The gas field lies in the northern part of the San Juan Basin, most of which is in New Mexico. In Colorado, gas occurs chiefly in the Dakota Sandstone, the Mesaverde Group, the Pictured Cliffs Sandstone, and the Fruitland Formation.

The Dakota Sandstone gas pool is in the lower, middle, and upper sandstone units of the Dakota. The wells producing from the Dakota are restricted to parts of T. 32 N., Rs. 6, 7, and 11 W., T. 33 N., Rs. 7 to 11 W., and T. 34 N, R. 10 W. Most wells are on the Bondad-Ignacio anticline, northwest- and west-trending structural feature, but others are far down the flank of the anticline or in a syncline. The accumulation of gas in places away from the anticline appears to be controlled by the lenticular character of the reservoir sands. The total production of gas from the Dakota Sandstone by the end of 1962 was 34,115,133 Mcf.

The Mesaverde Group yields gas throughout the field, both on the main anticline and low on its south flank. Gas wells producing from the Mesaverde Group are distributed through an area 36 miles long along the State boundary and extending 12 miles north at the widest place. The gas-bearing sands appear to be coalescing lenses of highly permeable sand that are in parallel belts trending northwest. The belts of permeable sand represent shoreline deposits that formed during times when the shore remained relatively stationary for long periods, during which the very fine sediment was winnowed out of the beach sand by wave action, resulting in a well-sorted permeable thick lens of sand. Later, the shoreline moved rapidly seaward or landward and another period of stability took place. Hollenshead and Pritchard (1961) have shown that the shoreline moved generally northeastward (seaward) in early Mesaverde time and southwestward (landward) in late Mesaverde time.

The northwest trend of a permeable sand belt can be demonstrated by the initial daily yield of the gas wells. A belt about 2 miles wide in which all wells had an initial daily yield of more than 4 million cubic feet trends northwest from the north-central part of T. 32 N., R. 7 W., across T. 33 N., R. 8 W., the north part of T. 33 N., R. 9 W., and into the southeasternmost part of T. 34 N., R. 10 W. This belt is flanked on both sides by wells whose initial daily yield was much less than 4 million cubic feet. Undoubtedly, this narrow belt containing large initial-yield wells coincides with an elongate narrow belt of well-sorted clean sand with large porosity and large permeability. The sand belt represents a period during Mesaverde time when the shoreline remained relatively fixed and a clean sand beach was formed. It is noteworthy that the belt does not coincide with the axis of the principal anticline; rather, the belt's southeast half is on the southwest flank of the anticline and farther northwest the belt passes diagonally across the axis of the anticline and down the north flank.

The total production of gas from the Mesaverde Group by the end of 1962 was 99,235,149 Mcf.

The Fruitland Formation yields gas on the anticline that extends from the northwestern part of T. 32 N., R. 6 W., northwestward to sec. 12, T. 33 N., R. 8 W, thence westward across T. 33 N., R. 8 W., and most of T. 33 N., R. 9 W. All wells are on the anticline and most of those with large initial daily yield are near the crest of the anticline The total production of gas from the Fruitland Formation by the end of 1962 was 31,424,015 Mcf.

The total production of gas from all sands for the Colorado portion of the Ignacio-Blanco field was 164,774,297 Mcf by the end of 1962.

The Fladine Park oil pool in T. 35 N., R. 20 W., adjacent to the Colorado-Utah boundary, is the eastern margin of the Ismay oil field of Utah. Six wells in Colorado yield oil from the Ismay zone of dolomite and limestone at the base of the upper member of the Hermosa Formation. The accumulation of oil is probably in a stratigraphic trap due to lithologic changes in the reservoir rock rather than to the attitude of the beds. The total production was 505,289 barrels of oil by the end of 1962.

The Red Mesa field, largely in T. 33 N., R. 12 W., yields a small amount of oil from many wells in the Dakota Sandstone and sandstones in the Mancos Shale. The field's total production of oil by the end of 1962 was 183,950 barrels. Nearby, the Alkali Gulch gas field in T. 34 N., R. 12 W., had yielded 12,948,025 Mcf of gas by the end of 1962 from three wells in the Paradox Member of the Hermosa Formation.

The north portion of the Barker Creek gas field of New Mexico projects into T. 32 N., R. 14 W., Colorado. Here, four wells had yielded 68,690,568 Mcf of gas from the Paradox Member of the Hermosa Formation by the end of 1962.

The Gramps oil field, chiefly in sec. 24, T. 33 N., R. 2 E., Archuleta County, was discovered in 1935. The oil pool in the Dakota Sandstone is on an anticline whose crest is in the SE¼ sec. 24. The oil-bearing sand is offset, down 300 to 1,100 feet on the north, along an east-west fault. The field had produced 5,176,106 barrels of oil by the end of 1962 when 23 wells were producing.

Three wells in the Dove Creek pool in Tps. 38 and 39 N., R. 19 W., had produced 65,847 barrels of oil and 583,672 Mcf of gas from the Paradox Member of the Hermosa Formation by the end of 1962. The field was discovered in 1948.

The McElmo field in T. 36 N., R. 18 W., had yielded 759,529 Mcf of carbon dioxide gas by the end of 1962, largely from the Shinarump Member of the Chinle Formation and from the Leadville Limestone. The gas is used in the manufacture of dry ice. An analysis of gas from the Shinarump Member shows it contains 1.12 percent helium (Boone, 1958, p. 26–27).

The Southeast Lisbon field in T. 44 N., R. 19 W., contains shut-in gas wells in secs. 5, 8, and 16. The wells in secs. 5 and 16 have a potential yield of 3.4 million and 6.3 million cubic feet of gas a day from rocks of Mississippian age and the well in sec. 8 has a potential yield of 6.7 million cubic feet of gas a day from the Ouray Limestone of Devonian age. A well in sec. 30 has a potential yield of 11.7 million cubic feet a day from Mississippian rocks.

A few other pools in southwestern Colorado have had small yields of oil and gas.

Southeastern region.—Southeastern Colorado contains the southern part of the Denver basin, the northern part of the Raton basin, and the westernmost part of the Hugoton embayment. The Apishapa uplift, a broad southeastward-trending feature that has persisted as a positive area since at least early Paleozoic time, separates the Denver and Raton basins. The Sierra Grande uplift, which projects into Colorado from New Mexico and the Las Animas arch form an indefinite boundary between the Hugoton embayment and the Denver basin. A relatively few oil and gas fields have been discovered in southeastern Colorado. The largest gas fields in the region are those in Baca, Bent, and Kiowa Counties, where the gas reservoirs are due to stratigraphic traps in Pennsylvanian limestones and sandstones. Smaller fields are in Prowers and Las Animas Counties.

Gas is present in many wells in the Greenwood Extension and Walsh fields, an area of about 300 square miles in southeastern Baca County, including parts of Tps. 32 to 35 S., R. 41 W., Tps. 32 to 34 S., R. 42 W., T. 31 S., R. 43 W., and T. 32 S., Rs. 43 and 44 W. The potential yields of the wells range between less than a million to 13.5 million cubic feet of gas a day. The main gas-yielding zone in most wells is a unit of oolitic fossiliferous limestone about 20 feet thick near the middle of the Shawnee Group of Pennsylvanian age (table 9). The regional dip of the rocks here is northeastward away from the Sierra Grande uplift (Maher and Collins, 1949, fig. 2). The gas trap appears to be an updip pinch out of the porous zones. Only eight wells are producing; they had yielded 2,864,291 Mcf of gas by the end of 1962.

The Flank field, which is mainly in the northwestern part of T. 34 S., R. 42 W., yields gas in some wells and oil and gas in other wells from a sandstone in the Morrow Series. The initial daily yield of the gas wells ranged between less than a million to 7.3 million cubic feet. Six wells in the pool had produced a total of 238,044 barrels of oil and 89,682 Mcf of gas by the end of 1962.

A single well in sec. 6, T. 35 S., R. 44 W., in the Prairie Dog field yielded 358,607 Mcf of gas from the Cherokee Group by the end of 1962.

A sand lens in the lower part of the Morrow Series yields gas in more than 20 wells in the McClave field, T. 20 S., R. 48 W., and

TABLE 9.—*Nomenclature of principal Paleozoic rock units in the subsurface in the southern part of the Great Plains province, Colorado, and equivalent formations exposed at the margin of the Mountain province (after Maher, 1950)*

Geologic time units	Subsurface southeastern and eastern Colorado	Margin of Mountain province
Permian	Nippewalla Group Blaine Formation Sumner Group Chase Group Council Grove Group Admire Group	Fountain Formation.
Pennsylvania	Wabaunsee Group Shawnee Group Douglas Group Lansing and Kansas City Groups Marmaton Group Cherokee Group Atoka Series Morrow Series	
Mississippian	Ste. Genevieve Limestone St. Louis Limestone Salem and Warsaw Limestones Keokuk and Burlington Limestones Kinderhook Series	Leadville Limestone.
Devonian	Absent in much of region	Chaffee Formation.
Silurian	Absent	Absent.
Ordovician	Viola Limestone Simpson Group	Fremont Limestone. Harding Sandstone. Manitou Formation.
Cambrian	Arbuckle Group Bonneterre Dolomite Lamotte Sandstone	Peerless Formation. Sawatch Quartzite.

parts of adjacent townships, and two wells yielded a small amount of oil. The initial daily yield of the gas wells ranged from less than a million to 10 million cubic feet. The reservoir is a stratigraphic trap in which the gas-bearing sand has a maximum thickness of 28 feet and pinches out laterally into shale. The sand, named the McClave sand, is in the Morrow Series about 150 feet above the top of the Ste. Genevieve Limestone. Most wells are shut-in. A total of 44,357 Mcf of gas and 15,015 barrels of oil had been produced by the end of 1962.

Bent's Fort field in T. 21 S., R. 51 W., contains two small gas wells and a small oil well which are shut-in. The oil- and gas-bearing zones are in the Atoka and Morrow Series. The Barrel Springs pool in Tps. 25 and 26 S., R. 46 W., contains two wells that had yielded a total of 3,638 barrels of oil and 14,866 Mcf of gas from the Morrow Series by the end of 1962.

The Model gas field in Tps. 29 and 30 S., R. 60 W., is on an anticline on the crest of the Apishapa uplift, and it contains several shut-in gas wells in the Lyons Sandstone, which lies at a depth of about 900 feet (Bass and others, 1947). The gas is unique in that it is composed of nitrogen, carbon dioxide, helium, and oxygen and contains almost no hydrocarbon gases (table 7). The Model gas field is owned by the Federal government and constitutes a large helium reserve.

Many wells have been drilled for gas in the Garcia field in Tps. 33 and 34 S., Rs. 61 and 62 W., over the past 65 years or more. Small flows of gas were found in many wells in the Niobrara Formation and in a few wells in the Greenhorn Limestone. The gas was used domestically on nearby ranches.

The Florence-Canon City field is in the Canon City embayment, a structural depression on the southwestern margin of the Denver basin. The oil field trends northwesterly and is about 15 miles long and 3 miles wide. The oil occurs in fractures at many horizons in the Pierre Shale; the Tepee Buttes zone, which is about 600 feet thick and contains many lenses of fossiliferous limestone, is the most prolific oil-bearing zone. The field contains an unusually large number of dry holes because many wells failed to encounter a fractured zone and therefore failed to produce oil. More than 1,300 wells have been drilled in the field. The field had yielded 14,392,-140 barrels of oil by the end of 1962; the total yield for 1962 was 29,041 barrels.

North Park.—North Park is a north-trending intermountain basin about 60 miles long and 35 miles wide. It contains four oil or gas fields in Jackson County.

The North McCallum oil and gas field is on an asymmetric faulted anticline which trends northwest across parts of T. 9 N., Rs. 78 and 79 W., and T. 10 N., R. 79 W. Carbon dioxide gas associated with condensate in the Dakota Sandstone was discovered by drilling in 1926 as the result of geologic mapping of the exposed rocks. Later, other sands in the Dakota Sandstone, Lakota and Morrison Formations, and Entrada Sandstone were found to be productive of oil or condensate. The total production of the field by the end of 1962 was 4,388,915 barrels of oil and 396,825,550 Mcf of gas.

The South McCallum field, T. 9 N., R. 78 W., is on a faulted asymmetric anticline on which gas and condensate were discovered in 1958. Sands in the Dakota Sandstone and the Lakota Formation (of petroleum geologists) produce condensate. The total yield by the end of 1962 was 656,355 barrels of oil and 101,499,354 Mcf of gas.

The Canadian River field was discovered in 1956 by a combination of photogeology and seismograph surveys. The total yield of the field by the end of 1962 was 407,852 barrels of oil and 2,916,559 Mcf of gas. Of this total, most of the oil, except 2,111 barrels from the Niobrara Formation, and all of the gas came from the Dakota Sandstone and the Lakota Formation.

The Battleship oil field in T. 10 N., R. 79 W., is on a northwest-trending anticline that was mapped on the exposed rocks. The rocks are cut by a reverse fault trending northwest on the northeast flank of the anticline. The main oil-bearing sandstone in the Lakota Formation is displaced vertically nearly 700 feet. The total yield of the field by the end of 1962 was 1,865,583 barrels of oil, 1,789,186 barrels of which were produced from the Lakota Formation and 76,397 barrels from the Dakota Sandstone.

RESERVES AND OUTLOOK

The annual additions to Colorado's oil and gas reserves by discoveries of new pools and by expansion of old pools have failed to equal the amounts produced annually for the past several years (table 10). The peak for both oil and gas reserves was reached on Jan. 1, 1960 when the reserves of crude oil were 401,000 thousand barrels and the reserves of gas were 2,496 billion cubic feet. The proved reserves of crude oil on Jan. 1, 1964 were 90,200 thousand barrels less than on Jan. 1, 1957. This is an average annual reduction in reserves of 12,886 thousand barrels but the State had an

TABLE 10.—*Estimated proved reserves of crude oil and gas and annual production of oil and gas in Colorado*

Crude oil				Gas			
Estimated proved reserves		Produced		Estimated proved reserves		Produced	
Jan. 1—	Thousand barrels	Year	Thousand barrels	Jan. 1—	Billion cubic feet at 60° F., and 14.65 psia	Year	Million cubic feet
1964	302,800			1964	2,093		
1963	333,800	1963	38,500	1963	2,060	1963	115,000
1962	362,000	1962	42,432	1962	2,020	1962	101,826
1961	398,000	1961	46,756	1961	2,043	1961	108,142
1960	401,000	1960	47,207	1960	2,496	1960	107,404
1959	355,000	1959	47,000	1959	2,349	1959	99,899
1958	384,000	1958	48,535	1958	2,381	1958	97,000
1957	393,000	1957	54,834	1957	2,423	1957	95,259
Total			325,264				724,530

Source: Oil and Gas Journal, Forecast and Annual Review numbers, January 1958–1964.

average annual production during this period of 46,466 thousand barrels, or a total production of 325,264 thousand barrels. The proved reserves of gas on Jan. 1, 1964 were 330 billion cubic feet less than on Jan. 1, 1957. This is an average annual reduction in reserves of about 47 billion cubic feet, but the State had an average annual production during this period of 103,504 million cubic feet or a total production of 724,530 million cubic feet. These data show that discoveries of oil pools and gas pools and expansions of old pools through this seven-year period has yielded a relatively small net loss in reserves of oil and gas.

The discovery of a few large pools would reverse this trend, however. An oil and gas field similar to Rangely may be discovered in the Piceance Creek basin by the drilling of prospect holes in the deeper part of the basin where the Weber Sandstone may lie at depths of 18,000 to 20,000 feet. The drilling of many exploratory wells is continuing in the Denver basin for oil and gas in the D and J sands. The discovery of another pool of similar size to Adena or the discovery of several pools of similar size to Little Beaver or Plum Bush Creek or pools with smaller reserves than these may take place in the future. The drilling of deep wells to the Lyons Sandstone in the western part of the Denver basin may discover large oil and gas pools. Large areas such as the Sand Wash basin in northwestern Colorado, the Paradox basin in southwestern Colorado, Middle and South Parks in central Colorado south of North Park, and the Raton basin and the Hugoton embayment in southeastern Colorado are not fully explored and wildcat drilling in these areas may result in discoveries.

OIL SHALE

(By J. R. Donnell, U.S. Geological Survey, Denver, Colo.)

The term oil shale is applied to any fine-grained sedimentary rock with a higher than average percentage of organic matter that contains no free oil and which will yield little or no oil when treated with the ordinary petroleum solvents, but which will yield varying amounts of oil when subjected to destructive distillation in a closed retort. Sedimentary rocks highest in organic material are normally fissile, dark-brown to black, marine or lacustrine shales, but the term oil shale is also applied to any argillaceous, carbonate, and siliceous rocks that will yield oil upon destructive distillation.

Oil-shale deposits of varying size and value are present in many countries of the world. Some of the thickest, richest, and most extensive deposits are in the United States. The Devonian Chattanooga Shale and its correlatives that underlie thousands of square miles in eastern and central United States average about 40 feet in thickness and will yield an average of about 5 gallons of oil per ton (Swanson, 1960).

However, by far the richest and thickest known oil shales in the world occur in the Green River Formation, which was deposited in Eocene time in three large lakes in Utah, Wyoming, and Colorado. All three of these lake basins contain potentially commercial deposits of oil shale, but the Piceance Creek basin, which covers an area of over 2,000 square miles in Rio Blanco, Garfield, Mesa, and Delta Counties, in northwestern Colorado, has the greatest resource of oil shale (fig. 11). The richest and thickest part of the deposit underlies 1,400 square miles of area between the Colorado River and White River.

Because some of the asphaltic deposits in Colorado are in close proximity to the area of the oil shales, figure 11 also shows the distribution of asphaltic deposits in Colorado.

The Green River Formation in Colorado consists of several members of which four are of interest here. These are, in ascending order, the Douglas Creek, Garden Gulch, Parachute Creek, and Evacuation Creek Members. The Douglas Creek and Evacuation Creek Members consist largely of sandstone, with minor amounts of oolitic sandstone and limestone, algal limestone, low-grade oil shale, and barren marlstone. The Parachute Creek and Garden Gulch Members contain virtually all of the oil-shale beds of potential commercial importance (fig. 12). Where exposed, the Garden Gulch Member consists dominantly of low-grade oil shale with minor amounts of thin rich oil shale, algal and oolitic limestone, and sandstone. Toward the center of the Piceance Creek basin, the sandstones and limestones in the Garden Gulch Member grade into finer clastics and the low-grade oil-shale beds become thicker and richer. The Parachute Creek Member at the type area north and west of Rifle, Colo., has an almost continuous sequence of oil shale more than 1,000 feet thick that may be mapped as two oil-shale zones. The lower oil-shale zone ranges from 500 to 800 feet in thickness; its base is at the upper contact of the Garden Gulch Member, and its top is at the base of a zone of lean oil shale or barren marlstone called "B" Groove. The upper oil-shale zone is 300 to 500 feet thick; its base is at the top of the "B" Groove and its top is at the basal contact of the Evacuation Creek Member. Toward the margins of the basin, the lower oil-shale zone thins to a wedge edge and toward the center of the basin the oil shales thicken and increase in oil content similar to those in the Garden Gulch Member (fig. 13). The lower part of the upper oil-shale zone forms a prominent ledge

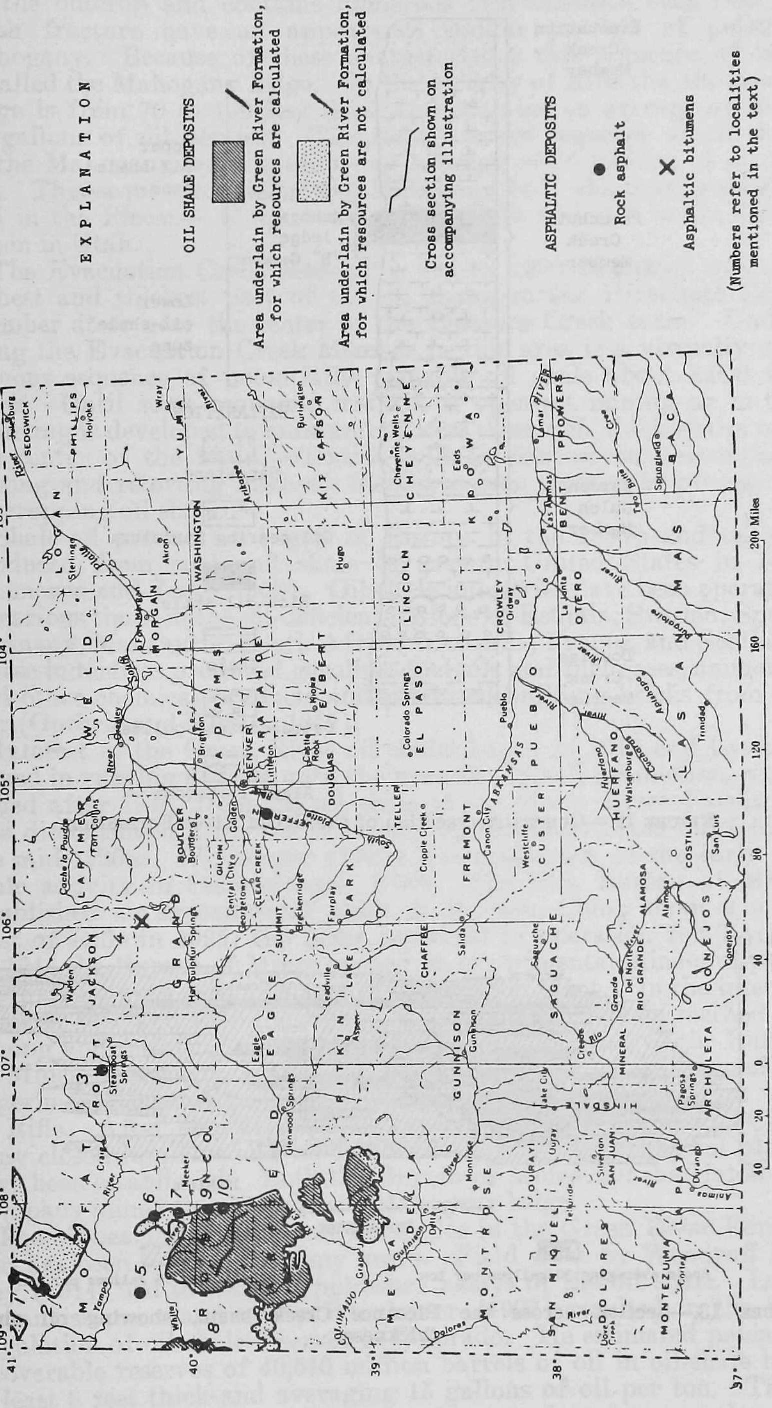

FIGURE 11.—Oil-shale and asphaltic deposits in Colorado.

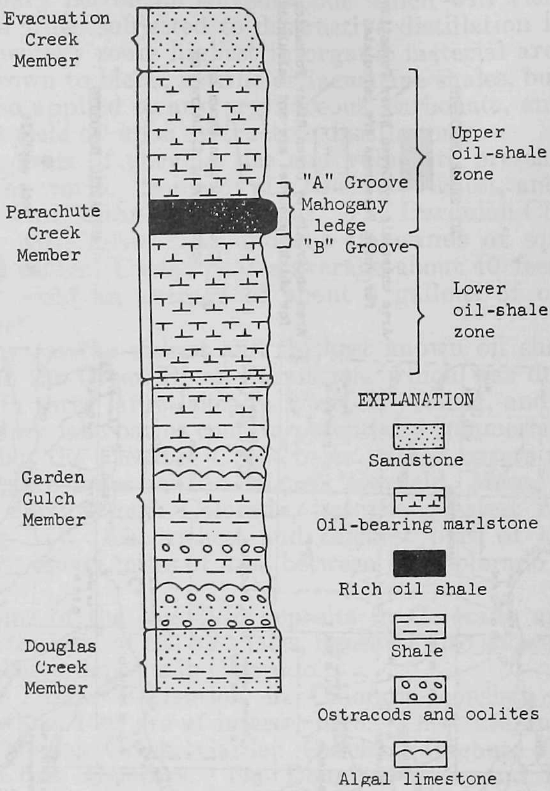

FIGURE 12.—Generalized section of the Green River Formation.

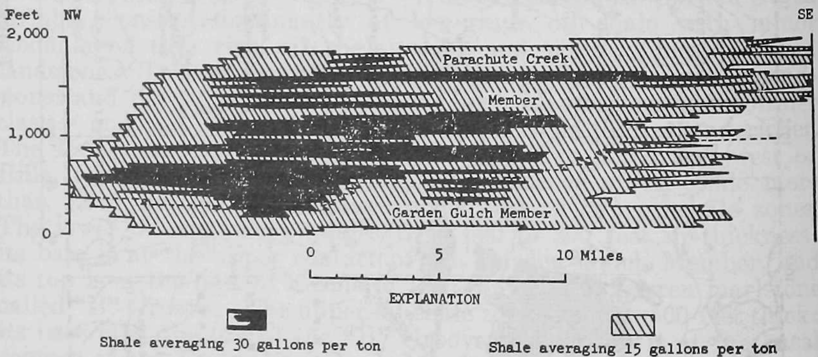

FIGURE 13.—Section across the Piceance Creek basin, showing oil shale thickness.

on the outcrop and contains numerous rich oil-shale beds that on fresh fracture have an appearance similar to that of polished mahogany. Because of these characteristics this sequence of beds is called the Mahogany ledge. In the vicinity of Rifle the Mahogany ledge is from 70 to 100 feet thick and contains an average of 25 to 30 gallons of oil per ton. The richest 5-foot sequence of oil shale in the Mahogany ledge contains an average of 60 gallons of oil per ton. This sequence is called the Mahogany bed—the most persistent bed in the Piceance Creek basin in Colorado and also in the Uinta Basin in Utah.

The Evacuation Creek Member is 300 to 1,000 feet thick over the richest and thickest part of the oil shales in the Parachute Creek Member at or near the center of the Piceance Creek basin. Underlying the Evacuation Creek Member in this area is a virtually continuous sequence of potentially valuable oil shale about 2,000 feet thick. Until some economic method of open-pit mining or in situ retorting is developed to mine and process these rich, thick shales near the center of the basin, attention will be focused on conventional mining and retorting methods that have been devised to process the outcropping oil shale.

Shale-oil production began in Europe in the 1830's and oil was produced from coal and shale in eastern United States in 1860 (Cameron and Jones, 1963). Oil-shale industries have been operative at various times in the oil-deficient nations of Estonia, Sweden, Spain, Germany, Manchuria, South Africa, Australia, France, and Scotland. These industries produced gasoline, fuel oils and fuel gases, ammonia, and other chemical products and produced building bricks from the ash (Guthrie and Klosky, 1951).

Interest in the Green River oil shales began in 1916 and has continued in varying degrees until the present. Small production, established after 1916, from the oil shale of the Green River Formation was discontinued after the discovery of the East Texas oil field in the mid-1920's. Winchester (1923) discusses much of the early oil-shale activity in Colorado and Utah. The U.S. Bureau of Mines established an experimental plant at Rulison, Colo., about 9 miles west of Rifle in 1925; the plant remained in operation for 2 years. In 1945 the Bureau of Mines opened an experimental mine and plant at Anvil Points a few miles east of the Rulison plant. In the interval between 1945 and 1955 the Bureau developed and refined methods of mining and retorting oil shale. About at the cessation of the Bureau of Mines operations, Union Oil Company of California began an experimental operation on their land about 20 miles north and west of Rifle. After several years of experimentation, Union Oil Company closed its plant and no further large-scale experimental plants have been established. Both the Bureau of Mines and the Union Oil Company mined the shales in the Mahogany ledge.

The oil-bearing potential of the shales in the Green River Formation has been known for many years. Field work by Woodruff and Day (1914) led to the first published assays of the oil shale. Later reconnaissance mapping by Winchester (1923) resulted in the first calculation of oil-shale reserves in Colorado. He estimated potential recoverable reserves of 40,640 million barrels of oil in oil-shale beds at least 3 feet thick and averaging 15 gallons of oil per ton. These estimates were based on his numerous assays of surface samples and on the assays made earlier by Woodruff and Day. Belser (1951) on the basis of 45 assays of surface sections, cores, and rotary cuttings from wells drilled for oil and gas, estimated a total oil content of 493,716 million barrels for shales with an average yield of 15 gallons of oil per ton. Detailed geologic mapping in conjunction with additional assay information resulted in a further upgrading of resources of 15-gallon per ton oil shale to 959,000 million barrels (Donnell, 1961).

To date the U.S. Navy, many oil companies, and individuals have drilled more than 100 core holes to evaluate the oil shales. Most of these core holes are clustered in an area of about 500 square miles immediately north of the Colorado River; several were drilled along the western margin and one in the northeast corner of the Piceance Basin. In addition, more than 100 wells were drilled for oil and gas near the center of the basin in areas remote from core drilling. The U.S. Bureau of Mines oil-shale laboratory at Laramie, Wyo., assayed the cores and rotary cuttings and these assay results were used with older assays in the resource computation given below. Assays of rotary cuttings are at best only indicative of the general value of the oil shale. Varying sampling techniques, contamination from cavings, and sample lag are three of many factors to be taken into consideration in the evaluation of assays from rotary cuttings.

Based on the abundance of additional information, new resources were calculated for thicknesses of shale containing an average of 30, 25, and 15 gallons of oil per ton. The 30- and 25-gallon shale resource figures are contained in the 15-gallon figure and the 30-gallon resource figure is contained in the 25-gallon figure.

An area of 1,300 square miles in Colorado is underlain by oil shale that contains 400 billion barrels of oil in beds 15 or more feet thick that will yield an average of 30 gallons of oil per ton. An area of 1,350 square miles in Colorado is underlain by oil shale that contains 600 billion barrels of oil in beds 15 or more feet thick that will yield an average of 25 gallons of oil per ton. An area of 1,700 square miles in Colorado is underlain by oil shale that contains one and a quarter trillion barrels of oil in beds 15 or more feet thick that will yield an average of 15 gallons of oil per ton. Presumably 25 to 50 percent of the oil contained in the shales would be lost in mining and retorting. Resource summaries are given by county in table 11.

TABLE 11.—*Shale-oil resources in Colorado*

Location	Area underlain by oil shale (square miles)	Yield in gallons of oil per ton of shale	Contained shale oil (million barrels) [1]
Garfield County	390 427 527	30 25 15	33,800 50,900 225,500
Rio Blanco County	901 902 925	30 25 15	407,200 555,400 975,800
Mesa County	18 26 191	30 25 15	568 1,036 11,213
Delta County	50	15	1,670
Total, Colorado	1,309 1,355 1,693	30 25 15	441,568 607,336 1,214,183

[1] The 30- and 25-gallon shale resource figures are contained in the 15-gallon figure and the 30-gallon figures are contained in the 25- and 15-gallon figures.

In addition to the areas for which resources were tabulated above, several hundred square miles of land in Moffat and Rio Blanco Counties are underlain by oil shale of unknown thickness and value (fig. 11).

The detailed mapping and the density of sampling has established two parameters that will remain virtually unchanged. The area underlain by and the thickness of the deposit (total volume of rock) is well delineated. The remaining parameter is the estimate of the oil content of the shale which may vary with more and better samples. Nevertheless, sufficient information is now available to determine, in general, the content of the oil shale throughout the greater part of the Piceance Creek basin. Thus any future calculation of the oil-shale resources of 15-gallon or more per ton shale in the Piceance Creek basin will only slightly modify the present figure of 1¼ trillion barrels.

ROCK ASPHALT AND SOLID ASPHALTIC BITUMENS

(By K. G. Bell, U.S. Geological Survey, Denver, Colo.)

Rock asphalt is rock, sediment, or soil at or near the earth's surface that is impregnated by viscous fluid asphaltic bitumen that does not flow freely through the host material at atmospheric temperatures and pressures. Such deposits also are known as bituminous sand, oil sand, or tar sand. Asphaltic bitumens are fluid and solid substances, some of which are petroleums, some of which are derived from petroleums, and others are derived from the kerogen of oil shale. Gilsonite and grahamite are varieties of solid asphaltic bitumens.

Rock asphalt is found in sedimentary terranes that include petroleum-bearing formations. All the petroliferous regions of the world either contain known rock asphalt deposits or are favorable areas in which additional discoveries might be made. Solid asphaltic bitumens occur in petroliferous regions and also are associated with oil shales.

Because some of the asphaltic deposits in Colorado are in close proximity to the area of oil shales, the asphaltic deposits in Colorado are shown on the map with oil shale (fig. 11).

Rock asphalt and solid asphaltic bitumens have been used by man since prehistoric times. They have been sources of bitumen used for impregnating and waterproofing various objects, and for use as a binder, lubricant, illuminating fuel, and roofing. Rock asphalt has been used as quarried, or mixed with sand, crushed rock, or other aggregates to make pavements and roads. A historical summary of the uses of rock asphalts and solid asphaltic bitumens and the terminology associated with these substances has been compiled by Abraham (1960, v. 1, chaps. 1 and 2).

Large industries based upon rock asphalts and solid asphaltic bitumens have existed in many countries. Some of the largest operations have been in France, Italy, Venezuela, Trinidad, and the United States. Most of the material produced was used to make pavements and roofs.

During the period from about 1900 to 1930 rock asphalts were mined in the United States in rather large quantities, especially in Kentucky, Alabama, Oklahoma, Texas, Utah, and California. Smaller operations existed in other states. Rock asphalt production reached its peak in the 1920's and then declined rapidly because of being displaced on the market by residual asphalts from petroleum refineries. The latter materials are shipped in an easily handled fluid form and are mixed with aggregate on the job.

Very little use is now being made of rock asphalts in the United States. Recent production has been only a few thousand tons per year and has been used only locally and almost wholly for road repair and paving. Some of the larger deposits are being investigated by the petroleum industry with the viewpoint of ultimately using the contained bitumen as a source of liquid and gaseous fuel.

Most of the known rock asphalt deposits in Colorado (fig. 11) are along the margins of sedimentary basins of Tertiary age in the northwestern part of the State. Asphaltic rocks crop out intermittently along the northeast side of the Gray Hills (Nos. 6 and 7, fig. 11) and the east side of the Petrolite Hills (Nos. 9 and 10, fig. 11) in Moffat and Rio Blanco Counties. These deposits are in sandstone beds near the base of the Green River Formation. The beds dip westward into the Piceance Creek basin. There is a deposit of asphalt-impregnated sand resting upon the Wasatch Formation near the Hiawatha gas and oil field (No. 1, fig. 11) in T. 12 N., R. 100 W., Moffat County (Barb, 1944, p. 19). Another deposit, probably in the Browns Park Formation, is in sec. 1, T. 9 N., R. 101 W., in a gulch tributary to Vermillion Creek (No. 2, fig. 11) in Moffat County (Barb, 1944, p. 19–20). Other deposits (No. 5, fig. 11) crop out in Tps. 4 and 5 N., Rs. 100 to 103 W., in Moffat County; these deposits are in formations of Mesozoic age (Barb, 1944, p. 22). None of these deposits have been thoroughly explored. Those in the Gray Hills and the Petrolite Hills probably are the largest.

There has been no significant production of rock asphalt or of solid asphaltic bitumens in Colorado. Very small quantities of rock asphalt have been mined from deposits near Morrison (No. 11, fig. 11) in Jefferson County, Hiawatha in Moffat County, and the Petrolite Hills in Rio Blanco County, and the material was used by local residents. An attempt was made to extract oil from a small deposit of rock asphalt cropping out near the forks of Tow Creek (No. 3, fig. 11) in Routt County (Crawford, Willson, and Perini, 1920). A small quantity of grahamite, a solid asphaltic bitumen, was mined from the deposit near the headwaters of Willow Creek (No. 4, fig. 11) in Grand County; only a few tons of this material were sold (Lee, 1899).

The Weber Sandstone, which is the principal productive unit in the Rangely oil field, crops out around the western end of the White River uplift. At many places its outcrop is stained by a dry petroliferous residue. Test wells drilled down dip from the outcrop have encountered showings of petroleum but not in producible quantities. There may be deposits of asphalt-impregnated rock down dip from the Weber outcrop. Such deposits probably will be under a substantial overburden of soil and bedrock and perhaps too costly to search for and mine.

A gilsonite vein (No. 8, fig. 11), about 4 miles in length on the Colorado side of the State line and probably not exceeding 2 feet in width, is in the basal sandstone of the Green River Formation in T. 1 S., Rs. 103 and 104 W., Rio Blanco County. There has been no production of gilsonite from this vein. The small vein of grahamite near the head of Willow Creek, Grand County, is in sandstone of Tertiary age; this deposit probably has been almost completely mined out.

Inasmuch as the known rock asphalt and solid asphaltic bitumen deposits of Colorado are unexplored, no quantitative resource estimate can be made. The resources seem to be small compared to those in several other States.

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METALLIC MINERAL RESOURCES

PRECIOUS AND BASE METALS—GOLD, SILVER, ZINC, LEAD, AND COPPER

Historically, Colorado is renowned for its output of precious and base metals, especially gold, silver, zinc, and lead; its copper yield has been moderate. The following figures and ranks are from published and unpublished data of the U.S. Bureau of Mines:

Between 1858 and 1962, Colorado produced $917,081,000 in gold, $604,301,000 in silver, $373,026,000 in zinc, $334,151,000 in lead, and $99,367,000 in copper. Among the States, Colorado ranks second in the total production of gold, third in silver, fourth in zinc, fourth in lead, and ninth in copper.

Although in recent years the production of gold and silver has declined appreciably, the yield of zinc, lead, and copper has remained fairly steady and the State has sustained its historic rank in these metals. In 1962, Colorado was seventh in the output of gold, fifth in silver, fourth in zinc, fourth in lead, and eighth in copper.

The production trends of the precious and base metals are described briefly on page 29 and shown by 5-year averages on figure 5.

Most of the silver, zinc, lead, and copper produced in Colorado, and part of the gold, comes from ores containing two or more metals, or from mining districts that contain more than one kind of metal deposit. The term "complex" is applied to these ores, deposits, and districts, in part because of the actual physical mixture of minerals and attendant problems in separating them, and in part because of the close association of deposits of different kinds. These mining districts or deposits are discussed below under the heading complex precious-and base-metal deposits. The locations of the principal districts are shown on figure 14.

One major district, Cripple Creek, contains no recoverable base metals. It is primarily a gold district and has yielded nearly half of Colorado's gold, along with a little silver. It is described separately below, but it is shown on figure 14.

Placer gold deposits also are described separately. Although some of these deposits occur within lode mining districts, many are outside the districts, and some are far removed from other metal mining operations. Locations of productive and potentially productive gold-placer deposits are shown on figure 16.

COMPLEX PRECIOUS- AND BASE-METAL DEPOSITS

(By M. H. Bergendahl, U.S. Geological Survey, Denver, Colo.)

Complex ores have been obtained from sources ranging in size from major mining districts down to small isolated mines and prospects. Mining districts that have yielded more than $500,000 worth of complex ores are shown on figure 14, and data regarding them are sum-

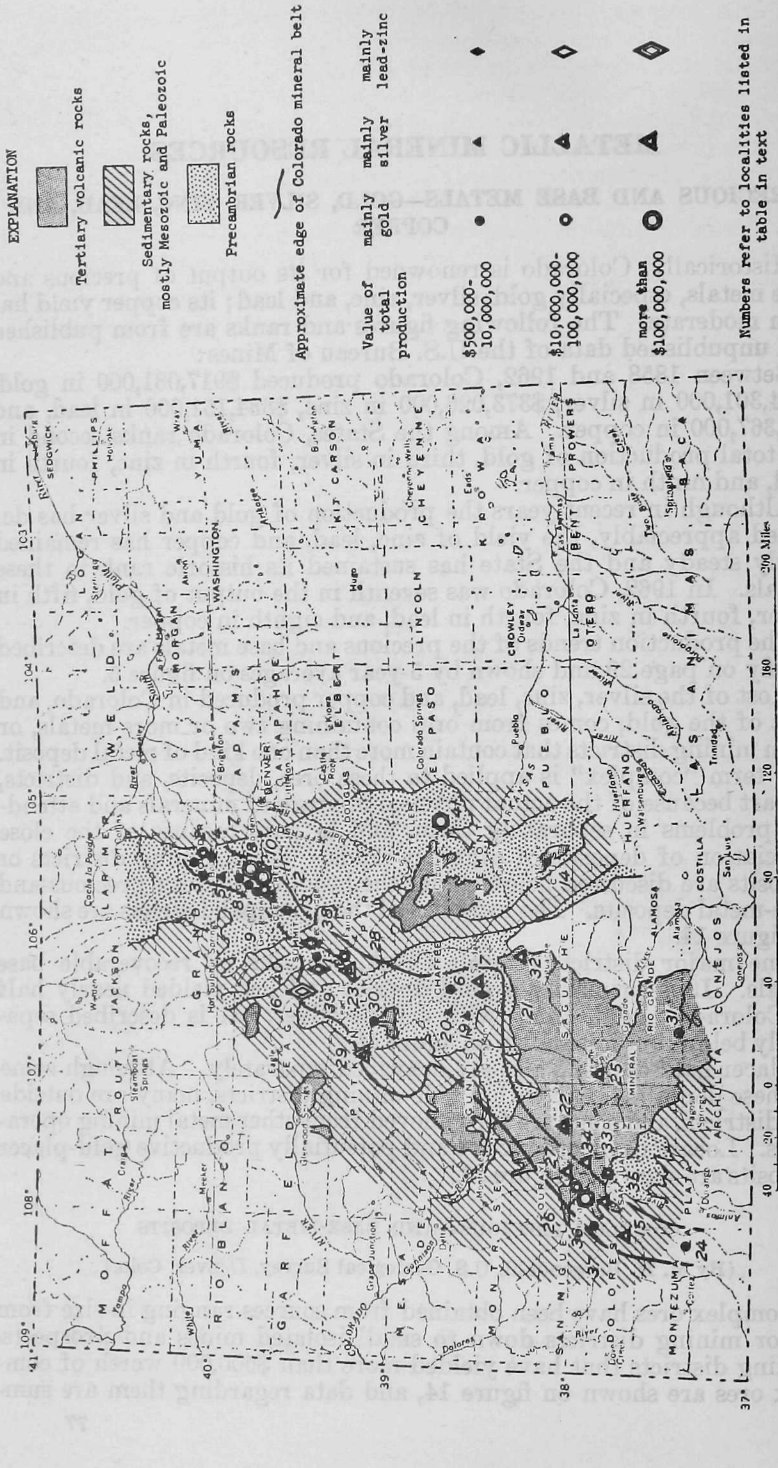

Figure 14.—Principal precious- and base-metal mining districts in Colorado. Numbered localities identified in table 12.

marized in table 12, which is keyed to the map by numbers. Most of these ore deposits are in the Colorado mineral belt, extending from Boulder County southwest to the San Juan Mountains. A few productive districts such as Westcliffe-Silver Cliff and Cripple Creek are southeast of the mineral belt, and numerous small districts, mines, and prospects occur in outlying areas in the northwestern and southern parts of the State. Readers interested in a more detailed map showing the distribution of all metalic mineral deposits in Colorado are referred to a map prepared by Fischer and others (1946), which was reproduced also in a report by Vanderwilt and others (1947).

TABLE 12.—*Major precious- and base-metal districts of Colorado*

Map location (fig. 14)	County, district, and total production through 1962 (placers excluded)	Commodities listed in order of production value; geologic type of occurrence	References
1	Boulder; Jamestown ($7,407,000).	Gold, silver, lead; fissure veins in Precambrian rocks near Tertiary porphyry intrusive.	Lovering and Goddard, 1950, p. 255–279.
2	Boulder; Gold Hill-Sugarloaf ($12,000,000).	Gold, silver, lead; fissure veins in Precambrian rocks.	Goddard, 1940.
3	Boulder; Ward ($3,000,000 to $9,000,000).	Gold, silver, lead; fissure veins and chimney-like bodies in Precambrian rocks near Tertiary dikes.	Lovering and Goddard, 1950, p. 203–213.
4	Boulder; Magnolia ($3,000,000).	Gold; telluride veins in Precambrian rocks.	Lovering and Goddard, 1950, p. 227–234.
5	Boulder; Grand Island-Caribou ($6,000,000).	Silver, lead, gold; veins in a stock that intruded Precambrian rocks.	Moore, Cavender, and Kaiser, 1957.
6	Chaffee; Chalk Creek ($5,930,000).	Gold, silver, lead, copper, zinc; veins in large Tertiary intrusive.	Dings and Robinson, 1957, p. 95–104.
7	Chaffee; Monarch ($13,195,000).	Silver, gold, lead, zinc, copper; replacement bodies in Paleozoic carbonate rocks near large Tertiary intrusive.	Dings and Robinson, 1957, p. 81–95.
8	Clear Creek; Alice ($550,000)	Gold, silver; stockwork in Tertiary intrusive.	Lovering and Goddard, 1950, p. 164–167.
9	Clear Creek; Empire ($5,037,000).	Gold, silver; veins in Precambrian granite near a Tertiary intrusive.	Lovering and Goddard, 1950, p. 156–161.
10	Clear Creek; Idaho Springs ($100,000,000 to $150,000,000).	Gold, silver, lead, zinc, copper; four mineralogic types of veins arranged in a zonal pattern in Precambrian rocks that are cut by Tertiary intrusives.	Lovering and Goddard, 1950, p. 167–191.
11	Clear Creek; Freeland-Lamartine ($18,000,000).	Gold, silver, lead, zinc, copper; veins in Precambrian rocks in vicinity of Tertiary intrusive bodies.	Harrison and Wells, 1956.
12	Clear Creek; Georgetown-Silver Plume ($31,450,000).	Silver, gold, lead, zinc; veins in Precambrian rocks and Tertiary intrusive bodies.	Lovering and Goddard, 1950, p. 138–156.
13	Clear Creek; Argentine-Montezuma ($6,450,000).	Lead, silver, gold, zinc; veins in Precambrian rocks that are cut by Tertiary dikes and small masses.	Lovering, 1935.
14	Custer; Westcliffe-Silver Cliff (9,600,000).	Silver, lead, gold; shells of ore minerals on rock fragments in volcanic pipes.	Cross, 1896; Emmons, 1896.
15	Dolores; Rico ($44,745,000)	Silver, zinc, lead, gold, copper; mineralized solution breccia in sedimentary gypsum beds, replacement bodies in Paleozoic carbonate rocks, fissure veins.	Cross and Ransome, 1905; Varnes, 1947b, p. 414–416.
16	Eagle; Gilman (Red Cliff) ($236,743,000).	Zinc, silver, lead, gold, copper; chimney-shaped replacement bodies in Paleozoic carbonate rocks, manto deposits.	Tweto and Lovering, 1947.
17	Gilpin; Northern Gilpin ($1,000,000).	Gold, silver, copper; veins in Precambrian rocks that are cut by small bodies of Tertiary intrusive rock.	Lovering and Goddard, 1950, p. 193–196.

TABLE 12.—*Major precious- and base-metal districts of Colorado*—Continued

Map location (fig. 14)	County, district, and total production through 1962 (placers excluded)	Commodities listed in order of production value; geologic type of occurrence	References
18	Gilpin; Central City ($100,000,000).	Gold, silver, copper, lead, zinc; four mineralogic types of veins in a zonal pattern in Precambrian rocks cut by Tertiary igneous bodies; a mineralized pipe has also been productive.	Sims, Drake, and Tooker, 1963.
19	Gunnison; Gold Brick-Quartz Creek ($626,000).	Silver, lead, gold; veins in Precambrian rocks; replacement bodies in Paleozoic carbonate rocks are of minor importance.	Dings and Robinson, 1957, p. 62–67; Crawford and Worcester, 1916.
20	Gunnison; Tincup ($3,056,000).	Silver, lead, gold; replacement bodies in Paleozoic carbonate rocks; veins in Precambrian rocks.	Dings and Robinson, 1957, p. 57–62; Goddard, 1936, p. 551–595.
21	Gunnison; Tomichi ($6,637,000).	Lead, zinc, silver, copper, gold; replacement deposits in Paleozoic carbonate rocks; a few veins in Tertiary intrusive rock.	Dings and Robinson, 1957, p. 67–81.
22	Hinsdale; Lake City ($11,200,000).	Silver, lead, gold, copper, zinc; three mineralogic types of veins in Tertiary volcanic rocks related to Lake City caldera.	Burbank, 1947a.
23	Lake; Leadville ($507,048,000).	Silver, lead, zinc, gold, copper; replacement deposits in Paleozoic carbonate rocks, veins in Paleozoic sedimentary rocks.	Loughlin and Behre, 1947; Emmons, Irving and Loughlin, 1927.
24	La Plata; La Plata ($6,092,000)	Gold, silver, lead, copper; veins and replacement deposits associated with Tertiary intrusive masses.	Eckel, 1949.
25	Mineral; Creede ($56,928,000)	Silver, lead, zinc, gold; veins in a down-faulted block of volcanic rocks associated with the Creede caldera.	Steven and Ratté, 1960a.
26	Ouray; Sneffels-Red Mountain ($92,719,000).	Gold, silver, lead, copper, zinc; veins and chimney deposits in Tertiary volcanic rocks on margin of Silverton volcanic basin.	Burbank, 1941 and 1947b.
27	Ouray; Uncompahgre (Ouray) ($12,703,000).	Silver, gold, lead, copper, zinc; fissure veins and replacement deposits in Paleozoic and Mesozoic sedimentary rocks near Tertiary intrusive rocks.	Luedke and Burbank, 1962.
28	Park; Alma ($36,154,000)	Gold, silver, lead, copper, zinc; veins and replacement deposits mostly in Paleozoic sedimentary rocks, associated with large faults.	Singewald and Butler, 1941.
29	Pitkin; Aspen ($100,490,000)	Silver, lead, zinc; veins in Paleozoic sedimentary rocks.	Vanderwilt, 1947, p. 180–182; Spurr, 1898.
30	Pitkin; Independence Pass ($500,000).	Gold; veins in Precambrian gneiss and Tertiary granite.	Vanderwilt and Koschmann, 1932.
31	Rio Grande; Summitville ($7,430,000).	Gold, silver, copper, lead: pipes and veinlike masses in Tertiary volcanic rocks.	Steven and Ratté, 1960b.
32	Saguache; Bonanza ($10,800,000).	Silver, lead, zinc, copper, gold; fissure veins in Tertiary volcanic rocks.	Burbank, 1932.
33	San Juan; Silverton ($80,935,000).	Gold, lead, silver, copper, zinc; fissure veins radial to Silverton caldera.	Varnes, 1963; Burbank, 1933.
34	San Juan; Eureka ($53,600,000)	Silver, gold, lead, zinc; fissure veins in a down-faulted block of Tertiary volcanic rocks near edge of Silverton caldera.	Burbank, 1947c; Varnes and Burbank, 1947.
35	San Miguel; Ophir ($11,525,000).	Silver, gold, lead; fissure veins in Tertiary volcanic rocks on west side of Silverton caldera.	Varnes, 1947a; Vhay, 1963.
36	San Miguel; Telluride ($229,000,000).	Gold, silver, lead, copper, zinc; fissure veins in Tertiary volcanic rocks on northwest side of Silverton caldera.	Burbank, 1941.

TABLE 12.—*Major precious- and base-metal districts of Colorado*—Continued

Map location (fig. 14)	County, district, and total production through 1962 (placers excluded)	Commodities listed in order of production value; geologic type of occurrence	References
37	San Miguel; Mount Wilson ($750,000).	Gold. silver, lead, copper, zinc; veins in and near a Tertiary intrusive mass.	Purington, 1898.
38	Summit; Breckenridge ($30,000,000).	Zinc, lead, gold, silver; veins and stockworks in Paleozoic and Mesozoic sedimentary rocks and Tertiary intrusive rocks.	Lovering, 1934.
39	Summit; Tenmile (Kokomo) ($27,621,000).	Lead, silver, zinc, gold, copper; replacement bodies in Paleozoic carbonate rocks; veins in Precambrian and Paleozoic rocks.	Koschmann and Wells, 1946.
40	Summit; Upper Blue River ($750,000 to $1,500,000).	Gold, silver, lead; veins in Precambrian metasedimentary and Paleozoic sedimentary rocks.	Singewald, 1951.
41	Teller; Cripple Creek ($426,043,000).	Gold, silver; veins in fractures in Tertiary volcanic rocks in Cripple Creek caldera.	Koschmann, 1949.

The complex precious- and base-metal deposits are varied both mineralogically and geologically. They occur in many different kinds of host rocks, and they have been localized by many different types of geologic structures; hence they assume numerous shapes and forms. The most abundant form is the vein, which is a tabular, generally steep, deposit occupying a fracture in the rocks. In some cases ore solutions passing through the fracture simply deposited ore minerals in open spaces, forming fissure veins; in others, they attacked rock on either side of the fracture and substituted ore minerals for rock minerals, forming replacement veins. Both processes went on in many veins. Some deposits are in zones of crushed rock impregnated with ore minerals rather than in clear-cut fractures and are known as mineralized shear zones. Others are interlacing networks of veinlets in a mass of rock and are known as stockworks.

A second major type of ore deposit is the replacement deposit, generally found in sedimentary rocks, and particularly in limestone or dolomite, but also found locally in metamorphic and igneous rocks. Such deposits generally lie parallel to the bedding, although they cut across it in places. If irregular or more or less equidimensional in plan view they are generally known as blanket deposits, but if elongated in plan view, they are known as mantos. Replacement deposits of more or less circular form that cut steeply across the bedding are known as chimneys, although this term is applied also to other bodies of this geometry, such as breccia pipes. Such pipes may result from explosive volcanic activity, which sometimes creates roughly vertical circular openings that are filled with loose material that has fallen or was washed back. These form excellent environments for ore deposition.

Most of the gold in the complex ores of Colorado occurs in its native state, but in some deposits in north-central Colorado and in the San Juan Mountains, gold telluride minerals are important. Silver occurs for the most part in sulfide minerals of other metals—mainly in galena, the lead sulfide—though in many deposits some silver is in amalgam with native gold, and in oxidized deposits mined in the past, silver minerals were prominent. The lead and zinc minerals commonly occur together—zinc as sphalerite and lead as galena. On oxidation, especially in a limestone host rock, these two sulfide minerals commonly alter to secondary carbonate minerals of lead and zinc. Copper in the form of sulfide minerals is widely distributed in the complex ores of Colorado, but generally it is present only in small amounts, and hence is only a minor byproduct of the ores. The largest single source of copper in Colorado is Gilman or Red Cliff district (No. 16, fig. 14), where certain ore bodies were rich in copper sulfides. Colorado contains no known disseminated or "porphyry type" copper deposits of the kind that supplies most the world's output of copper.

Deposits in the Front Range.—Deposits in the Front Range, in the northeast part of the mineral belt, are mainly in metamorphic and igneous rocks of Precambrian age, where these rocks are cut by small masses of porphyritic intrusive rock of Tertiary age. Almost all deposits are in the form of veins, which although numerous, are short and rather narrow.

Gold is the principal metal of value in these deposits; however, variable amounts of silver, lead, zinc, and copper are present in almost all districts. Vein mineralogy includes a wide variety of sulfides, sulfo-salts, and tellurides. Native gold occurs in some deposits, and in others, gold occurs in pyrite, chalcopyrite, and other sulfides. Galena and sphalerite contain silver in many districts. Locally, as in the Argentine district (No. 13), ruby silver minerals are common. The veins in the northeastern end of the mineral belt, in Boulder County, are characterized by tungsten minerals and a wide variety of gold, silver, lead, and mercury tellurides.

Some districts contain several vein systems, each characterized by a distinctive mineral assemblage. In the Central City district (No. 18), for example, the veins have been classified into two main types—pyrite veins and galena-sphalerite veins—and several variant types characterized by tellurides, enargite, fluorite, or uranium (Sims, Drake, and Tooker, 1963, p. 33–38). Ransome (1911, p. 124–157) recognized three major types of veins in the Breckenridge district (No. 38) : zinc-lead-silver-gold veins, gold-silver-lead stockworks and veins, and the wire and leaf gold veins of Farncomb Hill.

Deposits in the Park and Sawatch Ranges.—A considerable portion of Colorado's silver, lead, and zinc has been mined from large replacement bodies in the Leadville (No. 23), Gilman (No. 16), and Aspen (No. 29) districts, the three largest districts in the central part of the mineral belt.

The country rock in this region consists of Precambrian metamorphic and igneous rocks, Paleozoic and Mesozoic sedimentary rocks, and Tertiary intrusive rocks. The most valuable ore deposits are replacement bodies in carbonate sedimentary rocks near Tertiary intrusive masses. Veins in Precambrian and younger rocks have also been productive on a smaller scale.

The replacement bodies in the Leadville district are in dolomite that is interleaved with sheets of intrusive rock generally at or near the contact between the two kinds of rock. The largest bodies are in the top of the Leadville Limestone, just beneath shale of the overlying Belden Formation, or beneath a sill of porphyry in the shale (Ogden Tweto, written communication, 1964). Some of the replacement bodies are as much as 2,000 feet long, 800 feet wide, and 200 feet thick (Loughlin and Behre, 1947, p. 362–364).

The mixed sulfide replacement bodies at Leadville consist principally of pyrite, sphalerite, and galena. They generally contain a few ounces of silver and a few hundredths of an ounce of gold to the ton, as well as a little copper, but bodies rich in silver, gold, copper, or even bismuth occur locally. In these precious metal-rich bodies the silver is in the silver mineral argentite, in silver-bearing galena, or in the copper minerals tetrahedrite and chalcopyrite. Gold is generally in the chalcopyrite, but some is native.

Much of the ore at Leadville has been oxidized or transformed by weathering processes from sulfide minerals to carbonate or oxide minerals. In this process the metals originally intimately mixed in the sulfide ores were partially segregated, forming the very rich bonanza bodies of ore mined in the early days. Gold, being nearly insoluble, is generally unaffected by this process, and some of it at the surface finds its way into stream gravels, such as the placers of California Gulch.

Most production in the Gilman district has come from replacement bodies in the Leadville Limestone and the Dyer Dolomite Member of the Chaffee Formation. The deposits are in long mantos of zinc ore and in chimneys of pyritic lead-silver-copper-gold ore.

The manto deposits are in the Leadville Limestone and range from 50 to 300 feet in width, 5 to 150 feet in thickness, and as much as 4,000 feet in length (Tweto and Lovering, 1947, p. 381–385). The chimneys are downward tapering pipes that extend from the ends of mantos in the Leadville Limestone downward into the Parting Quartzite Member of the Chaffee Formation. The chimneys are roughly circular or elliptical and are as much as 300 feet in diameter at the top.

There is no physical break between the two types of ore bodies but there is a pronounced mineralogical difference. The chimney ore consists of a core of pyrite containing minor quantities of other minerals rich in silver, copper, and gold. This core is surrounded by a discontinuous shell of sphalerite and a fairly continuous outer shell of manganosiderite. The manto ore bodies consist of masses of minerals valued for zinc, lead, and silver (Tweto and Lovering, 1947, p. 384–385).

Deposits in the San Juan Mountains.—The outpourings of volcanic material that make up the San Juan Mountains issued from a number of centers, around which are clustered most of the major deposits of the southwestern part of the mineral belt. The deposits are primarily in Tertiary volcanic rocks, although some are in the underlying sedimentary rocks. Most of the deposits are genetically related to volcanism and occur in veins along faults associated with subsidence structures. The deposits at Summitville (No. 31), however are pipes and veinlike masses and those at Red Mountain (No. 26) are chimney deposits and breccia pipes. The veins in this region are larger and deeper than most other veins in the State. They are valued principally for gold, though important amounts of silver, lead, copper, and zinc are present in most districts.

The mineralogy of the deposits is fairly complex, and nearly every district has species that are not commonly found throughout the entire area. For example, argentite (silver sulfide) formed rich ore locally in the Silverton (No. 33) and Uncompahgre or Ouray (No. 27) districts; tetrahedrite (copper-iron sulfantimonide) was abundant in the Silverton, Telluride (No. 36), and Ouray districts; ruby silver minerals occurred in ore bodies in the Ouray, Red Mountain, and Telluride districts; and telluride minerals were reported from the Silverton district (Eckel, 1961, p. 59, 60, 261, 319, 328, 329).

Resources and outlook.—Except for a few isolated large operations, Colorado's base- and precious-metal industry has been in a general decline since the end of World War II. The shutdown of the mines of Leadville in 1957 and in Cripple Creek at the end of 1961 left only a few active districts. The Gilman district, whose output in 1962 was valued at $8,489,952, is by a wide margin the largest producer of base and precious metals. Elsewhere in the State, the Idarado mine in the Sneffels-Red Mountain district and the Camp Bird mine in the Telluride district are the largest producers in the San Juan Region. The Sunnyside mine in the Silverton district was reopened in 1962 and had substantial output. The Rico district (No. 15) is moderately active.

Despite the current trend, the future of metal mining in Colorado should be thought of in terms of moderate optimism. The recent increase in the price of silver has rejuvenated a few properties, and small flurries of this nature will be repeated as prices become favorable. Large concentrations of minerals in numerous districts await development of new techniques of discovery and development to make them economically important. In the Central City district the ores continue at depth with no apparent diminution of grade or size (Sims, Drake, and Tooker, 1963, p. 55). Exploration possibilities in the Summitville district (No. 31) are outlined by Steven and Ratté (1960b p. 65–66). In the Leadville and Tenmile (No. 39) districts the replacement ore bodies are accompanied by dolomitization of the limestone host rock; studies of intensity of dolomitization in the outlying areas of these districts could be a useful guide for finding new concealed ore bodies.

Geochemical prospecting for base-metal deposits has proved its usefulness. One of the more recent techniques involves soil testing for arsenic as a guide to gold lodes (Bayley and Janes, 1961). Another new development is a field test for tellurium (Lakin and Thompson, 1963), which could be used in districts such as Cripple Creek to outline areas of telluride minerals in advance of more intensive drilling and sampling.

Future mining in Colorado will be characterized by large scale operations which will require considerable investment for consolidating and rehabilitating properties and developing new flotation and smelting techniques for low-cost recovery of all possible byproducts. The colorful prospector and his burro have been largely superseded by teams of exploration specialists followed by large-scale mining operations using the giant earth-moving machinery of modern mining.

CRIPPLE CREEK DISTRICT

(By M. H. Bergendahl, U.S. Geological Survey, Denver, Colo.)

Cripple Creek is the leading gold producer of Colorado and the second largest gold district in the United States. It is entirely a precious metal district with gold values far exceeding those of silver. In Colorado, Cripple Creek is the only major precious-metal mining district outside of the Colorado mineral belt. It is at the site of a large volcanic center in the central part of an area of Precambrian granite.

The total production from Cripple Creek from 1891 through 1962 amount to 19,771,359 ounces of gold and 2,196,555 ounces of silver. The total value of the production through 1962 is $426,043,118, of which about $424,190,000 represents the gold and roughly $1,850,000 the silver. Mining at Cripple Creek ceased at the end of 1961, and the only production from the district in 1962 was from clean-up operations at the Carleton mill.

The following brief description of the geology and ore deposits has been abstracted from reports by Lindgren and Ransome (1906), Loughlin and Koschmann (1935), and Koschmann (1949).

The ore deposits of the Cripple Creek district are localized within or at the margin of an irregular mass of fragmental rocks generally known as "breccia" and composed of a mixture of stratified sedimentary rocks and volcanic breccia of Miocene age. These rocks occupy a steep-walled structural basin or caldera about 4 miles long and 2 miles wide in Precambrian rocks, principally granite. The basin subsided along steep faults as the "breccia" accumulated, and some faults or shear zones extended from the basin margin into the adjoining Precambrian rocks. Some of the faults were later filled with dikes. A small pipe of basaltic breccia, known as the "Cresson blowout" cuts the fragmental rocks in the south central part of the caldera.

Many of the fissures that were filled with dikes and veins coincide in trend with older fissures that controlled the development of the volcano. The prominent veins are along pre-volcanic shear zones in granite, and in later extensions and branches of these fissures in breccia. Individual veins are rather short and the vein zones are rather narrow. At depth the veins converge toward the roots of the caldera. Some ore shoots are shallow, but others extend to depths of as much as 3,000 feet with no indication of impoverishment.

In addition to veins, important deposits are found in collapse breccias and in large irregular bodies in shattered ground.

The ore minerals at Cripple Creek are gold, silver, and copper-tellurides.

PLACER GOLD

(By H. C. Prommel, Denver, Colo., and P. M. Hopkins, Golden, Colo.)

The recovery of gold from placer deposits in Colorado started in 1858 and has been continuous since then, yielding about $41,000,000 through 1962. Since 1868, when accurate record-keeping began, the largest production for 1 year was $1,063,195 in 1941; the lowest was $12,005 in 1944 (Prommel, 1945). The yearly production of placer gold and significant periods of operation are shown on figure 15.

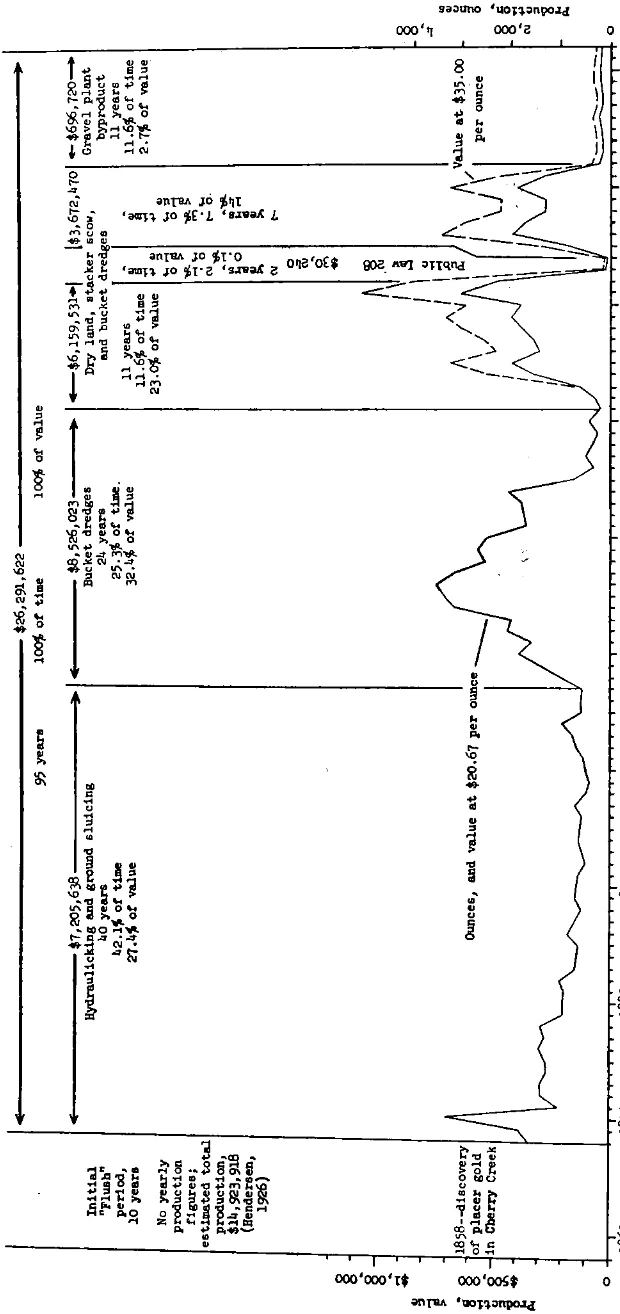

FIGURE 15.—Placer-gold production in Colorado, by significant periods of operation and years, 1858–1962.

Placer gold production is recorded for 37 of the 68 counties in Colorado (table 13). The number of producing counties for each significant period of placer operation in the State is shown below:

Year	*Number of producing counties*
1858–67	6
1868–1907	17
1908–31	22
1932–42	37
1943–44	8
1945–52	12
1953–62	12

TABLE 13.—*Placer-gold production in Colorado, by counties*

County	Period	Fine ounces	Value
Summit	1859–1962	739, 490	$15, 647, 608
Park	1859–1962	342, 284	9, 420, 409
Lake	1859–1962	358, 583	7, 783, 800
Clear Creek	1859–1962	139, 940	2, 918, 503
Chaffee	1859–1962	78, 723	1, 677, 763
Gilpin	1859–1962	48, 154	1, 501, 320
Adams	1922–1962	20, 195	690, 779
Jefferson	1858–1962	16, 558	553, 084
Routt and Moffat	1866–1962	20, 452	456, 913
San Miguel	1875–1962	9, 724	208, 068
Boulder	1859–1962	2, 593	87, 888
Montrose	1886–1962	2, 891	77, 127
Costilla	1875–1962	1, 496	32, 334
Gunnison	1861–1962	1, 046	25, 192
Douglas	1858–1962	722	20, 550
Larimer and Jackson	1895–1962	828	17, 794
Arapahoe	1885–1962	648	16, 764
San Juan	1873–1962	379	13, 161
Teller	1891–1962	381	12, 352
Denver	1929–1962	275	8, 484
Eagle	1880–1962	247	7, 882
Rio Grande	1870–1962	347	7, 213
Mesa	1885–1962	226	5, 066
Fremont	1881–1962	135	4, 501
Ouray	1878–1962	131	4, 299
Elbert	1926–1962	132	3, 983
Grand	1896–1962	100	2, 532
La Plata and Montezuma	1878–1962	51	1, 687
Delta	1894–1962	41	1, 384
Dolores	1879–1962	19	663
Pitkin	1880–1962	9	220
Huerfano	1875–1962	5	132
Garfield	1885–1962	2	40
Miscellaneous	1888–1962	242	5, 000
Total		1, 787, 049	41, 214, 495

Source: U.S. Department of Interior Bureau of Mines.

Yearly records are not available for the "flush" period, from 1858 to 1867, and it is difficult to separate accurately the lode and placer production. Henderson (1926), however, assigned the following total placer production values to six counties:

Lake County	$5, 272, 000
Summit County	5, 150, 000
Clear Creek County	2, 100, 000
Park County	1, 780, 000
Chaffee County	380, 000
Gilpin County	241, 918
Total	14, 923, 918

For the period 1868 to 1944, nine counties—Summit, Park, Lake, Chaffee, Gilpin, Clear Creek, Routt, Moffat, and Jefferson—produced

97.12 percent of the total placer gold and 28 counties produced the remainder. During the 1945–52 period, much of the production came from a bucket-dredge operation in Park County, some was a byproduct of sand- and gravel-washing operations in Denver and four adjoining counties, and a little came from hand-sluicing operations in several other counties. Small sluicing operations and byproduct gold from sand and gravel account for all the 1953–62 production.

The 1962 Annual Report of the State Bureau of Mines lists 33 placer operations operated by 88 men; 25 of these operations employing 63 men were in the sand- and gravel-washing plants located in Adams, Arapahoe, Clear Creek, and Jefferson Counties, while the remaining 8 operations carried on by 25 men were in Gilpin, Park, La Plata, Moffat, Routt, San Juan, Summit, and Teller Counties.

The fluctuations in Colorado placer-gold production shown on figure 15 are related to the history and nature of operations of each of the several significant periods of placer mining.

During the flush period, 1858 to 1867, mining was confined largely to the weathered outcrops of oxidized veins and to the steep-grade gulches below them; some of the ground was fabulously rich, but only relatively small areas were worked, mainly by hand digging and ground sluicing.

During the next 40 years, 1868 to 1907, some improvements were made in equipment, and hydraulic mining methods were introduced to work gulch deposits and steep-grade stream gravels, but nevertheless there was a gradual decline in output.

In the 1908–37 period, large bucket dredges were developed to exploit wide, low-gradient stream valleys that were not amenable to hydraulic mining or ground sluicing. Such dredges required initial capital investments of $100,000 to $500,000, careful engineering, and large yardages proved by sampling. During this period of 24 years, Summit County alone produced almost as much gold as 19 counties had produced in the preceding 40 years. This high level of production declined in the late 1920's due to several factors—lack of exploratory and development work, partial depletion of workable ground, litigation in Summit County, and the stock market crash in 1929.

A sudden and spectacular rise in Colorado's placer-gold production began in 1931 and by 1941 reached a peak that was highest in dollar value and third highest in quantity (ounces) since 1868. This rise can be credited to three major causes: (1) the increase in the value of gold from $20.67 to $35.00 per ounce, (2) improvements in machinery and equipment making it possible to work placers of any type and reasonable size profitably, and (3) decrease in amount of capital investment required to get medium-sized placer properties to the producing stage. During this period dry-land and stacker-scow dredges fed by draglines were introduced to work medium-sized placers while new as well as reconstructed large bucket dredges also entered the field in Park and Summit Counties.

Wartime conditions and Public Law 208, which restricted gold mining, practically dealt a "death blow" to placer mining in Colorado during the 1942–44 period.

In the post-war period of 1945 to 1952, total placer production in Colorado quickly returned to a moderately high level, mainly due to the output from the large bucket dredge near Fairplay in Park

County. This dredge resumed operation in 1945 and treated 17,000 to 20,000 cubic yards per day. However, gravel values of only 12 cents worth of gold per cubic yard, plus increasing costs for labor, supplies, and equipment, caused it to shut down in 1952. Smaller operations were started in other counties during this period, but none continued long. Some placer gold was also recovered as a byproduct of sand- and gravel-washing operations in the Denver area.

Since 1952, placer-gold production in Colorado has been small, and all has come as a byproduct of sand and gravel production or from small scattered operations.

Gold mining, whether lode or placer, has a unique economic problem. Its product has a fixed value that does not rise with increased industrial activity and costs, as do the values of other commodities. So during periods of rising costs, as in recent years, profits decrease and may disappear. Colorado does not lack gold placers, but it does lack known and proved deposits that can be operated profitably on a large scale under present conditions.

According to a qualified expert, a dredge with a capacity of 10,000 or more cubic yards per day, probably could operate at a profit in 1963 on gravel containing 20 to 25 cents in gold per cubic yard, if other local conditions are favorable (C. M. Romanowitz, Alameda, Calif., oral communication). Obviously, smaller capacity stacker-scow or dry-land dredges, which have higher operating costs than large bucket dredges, would require somewhat higher grade material as well as substantial quantities of gravel.

Gold-bearing gravels of 20 to 25 cents per cubic yard value have been worked in Colorado in the past, and large amounts of gravel of this grade might still be present in untested places. Even higher grade placer deposits probably occur in places, but they are probably too small to support any operation except a small one.

During the 1939–42 period, gravels worked at individual operations in the State ranged from about 12 cents to more than 90 cents gold per cubic yard. The larger operations, however, were all on low-grade gravels. Based on an average of about 91 percent of the total yardages worked in the State from 1939 to 1942, the calculated average values recovered from the placer gravels worked during these years are shown below:

Year	Yardage used in calculations	Percentage of total yardage worked in the State	Calculated average values in cents per cubic yard
1939	2,430,964	87.0	24.86
1940	2,340,000	89.7	22.80
1941	5,322,300	93.8	18.74
1942	2,430,964	92.0	24.95
Total	13,012,670	[1] 91.4	[1] 22.01

[1] Average.

Figure 16 shows the location of 31 large areas containing proven and potential placer deposits; many smaller areas are not shown. These larger areas are listed by counties and streams in table 14. Brief descriptions and histories of some of these areas are given below.

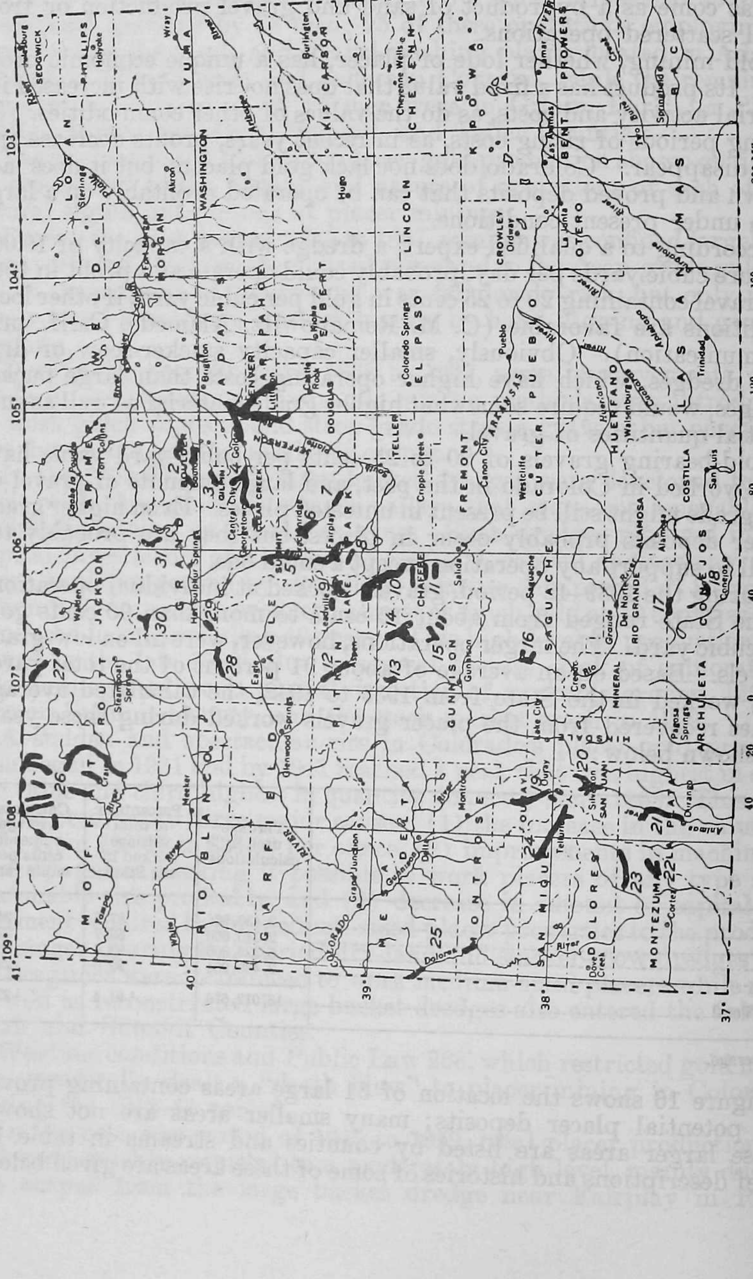

FIGURE 16.—Areas of proven potential gold-placer deposits in Colorado. Numbers refer to localities listed in table 14.

TABLE 14.—*Areas of proven or potential gold-placer deposits in Colorado*

[Numbers identify areas on fig. 16]

1. Denver, Jefferson, Adams, Arapahoe, and Douglas Counties: Denver and vicinity; South Platte River, Clear Creek, Cherry Creek, Plum Creek, and tributaries.
2. Boulder County: Boulder and vicinity; North Boulder Creek and Left Hand Creek and tributaries.
3. Gilpin County: Rollinsville and vicinity; South Boulder Creek and tributaries.
4. Gilpin and Clear Creek Counties: Central City, Idaho Springs, and Georgetown and vicinity; North and South Forks of Clear Creek and tributaries.
5. Summit County: Breckenridge and vicinity; Blue River and tributaries.
6. Park County: Como and vicinity; Upper Tarryall Creek and tributaries.
7. Park County: Middle Tarryall Creek.
8. Park County: Fairplay and Alma and vicinity; South Platte River and tributaries.
9. Lake County: Leadville and vicinity; American Gulch and other tributaries of Arkansas River.
10. Chaffee County: Buena Vista-Twin Lakes area; Arkansas River and tributaries.
11. Chaffee County: Chalk Creek, Cottonwood Creek, and other tributaries of Arkansas River.
12. Pitkin County: Aspen and vicinity: Roaring Fork River and tributaries.
13. Gunnison County: Crested Butte and vicinity: East River and tributaries.
14. Gunnison County: Taylor Park-Tincup area; Taylor River and tributaries.
15. Gunnison County: Ohio City and Pitkin and vicinity; Quartz Creek, Ohio Creek, and Timichi Creek and tributaries.
16. Saguache County: Cochetopa Creek and tributaries.
17. Conejos County: Alamosa River.
18. Conejos County: La Jara River.
19. Ouray County: Ouray and vicinity; Uncompahgre River and tributaries.
20. San Juan County: Silverton and vicinity; Animas River and tributaries.
21. La Plata County: Durango and vicinity; Animas River and tributaries.
22. Montezuma County: Mancos and vicinity; East and West Forks of Mancos River.
23. Montezuma and Dolores Counties: Rico and vicinity; Dolores River.
24. San Miguel County: Telluride and Placerville area: San Miguel River and tributaries.
25. Montrose and Mesa Counties: Gateway and vicinity; Dolores River.
26. Moffat County: Craig-Baggs area; Yampa River, Little Snake River, and tributaries draining the Iron Springs Divide area.
27. Routt County: Hahn's Peak area; Little Snake River and Elk River and tributaries.
28. Eagle County: Burns and vicinity; Colorado River.
29. Grand County: Radium and vicinity; Colorado River.
30. Grand County: Muddy Pass area; Muddy Creek and tributaries.
31. Grand County: Willow Creek Pass area; Willow Creek and tributaries.

Gilpin County, South Boulder Creek (area 3, fig. 16): During the 1860's Chinese placer miners worked the gravels along South Boulder Creek at what was then known as "Deadwood Diggings." Gamble Gulch, extending from the old town of Gilpin to where it enters South Boulder Creek, was hand-sluiced throughout its length during the 1860's and 1870's. About 30 years later, an English company attempted hydraulic mining on South Boulder Creek near Pactolus, a short distance above Pinecliffe. The company used hydraulic giants and a hydraulic elevator, but the gradient of the valley was insufficient to keep the sluice boxes from clogging, and the work was abandoned after about 3 acres had been worked. Forty years later a local company obtained leases on the ground, dug a 2,000-foot ditch to drain the old placer lake and found good values, but for lack of sufficient capital, surrendered the ground to other operators. After further test drilling, a 1,000-cubic-yard stacker scow was installed, and the placer was worked for 2½ placer seasons in 1937–1939. A total of 1,003,578 cubic yards of gravel, averaging 26.33 cents per cubic yard for a gross return of $264,850.17, was mined from about 75 acres. Average values per cubic yard were 38.37 cents in 1937, 25.6 cents in 1938, and 19.57 cents per cubic yard in 1939. The area can still be considered "potential" for small-scale placer operations.

San Juan and La Plata Counties, Animas River (areas 20 and 21): The Animas River and its tributaries drain some of the most highly mineralized parts of the San Juan Mountains in southwestern Colorado. Some placer mining was done on it in the 1860's at the place now called Baker's Bridge, some 16 miles upstream from Durango. No production was reported from 1868 to 1931, but a small production was made at times during the 1932–42 period. In 1937 the senior author investigated the Baker Bridge area by mapping, digging 29 test pits, and sampling. Seven separate stream gravel benches, ranging in elevation from 16 feet to 204 feet above the present water level of the river, were mapped, and five ancient stream channels were traced through hummocky outcrops of glaciated granite. A potential reserve of 16,150,000 cubic yards of gravel, of approximate 50-foot average depth and 30 cents or more average value per cubic yard, was established; values ranged from a few cents to $3.97 per cubic yard.

Since then the ground has been divided into suburban homesites and is probably lost for future gold mining.

Moffat County, Yampa and Little Snake Rivers and tributaries draining the Iron Springs Divide area (area 26): Moffat County has been a steady producer of placer gold from small operations since 1892 and ranks seventh among the 37 placer-gold producing counties in Colorado. The gold is obtained from fine-grained gravel bench deposits along gulches originating near the top of the Iron Springs Divide between the Yampa and Little Snake Rivers north of Craig, Colo. The divide is the remnant of an outwash plain or fine-grained alluvial fan of gold-bearing gravels and sand that at one time must have covered approximately 900 square miles. The bench deposits formed by gradual erosion of this large alluvial fan and redeposition on stream terraces at various elevations along the tributary gulches from near the top of the divide down to Lay Creek and the Yampa and Little Snake Rivers, about 1,000 feet lower in altitude.

During 1900 to 1904, a 20-mile ditch from Willow Creek originating in the Elk Mountains to the east provided water for the largest operation, a small steam-powered open-connected bucket dredge with 1-cubic-foot buckets. The dredge operating on one of the lower benches, produced about $115,000 in placer gold during several years, before its destruction by fire.

During 1937 and 1938, a dry-land dredge operated by the Eldorado Placer Mines Company produced a total of $56,000 in placer gold from gravels along Timberlake Creek, a tributary to Four Mile Creek emptying into the Little Snake River just below Baggs. The remainder of Moffat County's placer-gold production, about $150,000, has come from small-scale operations along many of the dry gulches, with water brought in by ditches. After the runoff season in the spring, prospectors placer mine along the bars of the Yampa River below Craig. Gold is evidently carried into the Yampa by Fortification Creek and its tributaries heading in the Iron Springs Divide country. Gold in the gravels of the Little Snake River and its tributaries above Baggs evidently comes from the Precambrian metamorphic and instrusive rocks of the Continental Divide to the east.

Although both the Yampa and the Little Snake Rivers are known to carry placer gold, no churn drill placer test holes have as yet been put down to bedrock anywhere along their valleys. Potential resources in the 70 miles or more of meander-covered stream valleys in the Yampa and Little Snake Rivers and some of the latter's tributaries above Baggs could be enormous.

In addition to gold, some of these placers contain monazite and rare-earth minerals of possible value. For additional information regarding these minerals in the gravels of this area, the reader is referred to pages 132 and 135.

Other areas: In Colorado, many drainage channels from mineralized areas remain untested to bedrock for placer gold, although small-scale placer mining on the upper gravel benches was carried on along their courses during the past. While major placer operations have been carried on in areas 1, 3, 4, 5, 6, 8, 9, and 10 (fig. 16) the potential of these areas is not exhausted. Of special interest for exploratory work and testing are areas numbered 12, 14, 18, 19, 22, 23, 24, 25, 27, 28, 29, and 31. Furthermore, although the Geological Survey and Bureau of Mines of the Federal Government have mapped and tested some of these areas, no thorough and systematic studies have been made of the placer possibilities of the entire State.

General outlook: Colorado contains many known gold-placer deposits that are not yet exhausted, and many others, including some that are very extensive, that have not yet been thoroughly tested. To test the many remaining promising areas, and to bring them into production will require careful geologic and engineering evaluation, and adequate risk capital. The longer testing is delayed, the greater the loss of gold-placer reserves. Urbanization, such as on the Animas River, steadily decreases placer ground. Great water storage and diversion projects remove more ground, as it is generally the gravel-filled valleys that are flooded. Nevertheless, if some of the potentially productive areas discussed above prove out, Colorado could produce 1.75 million ounces of placer gold again in the future, just as it did in the past.

FERROUS METALS

IRON

(By W. M. Brown and R. G. Reeves, U.S. Geological Survey, Washington, D.C.)

The availability of large quantities of usable iron ore along with an adequate fuel supply are necessary for the industrial progress of a nation. The United States annually consumes about twenty times more steel than the combined consumption of copper, lead, zinc, and aluminum (Carr and Dutton, 1959, p. 62). U.S. iron ore deposits have traditionally supplied the needs of the U.S. iron and steel industry until recent years, when considerable amounts of imported iron ore have supplemented domestic supplies. The location of major iron ore and coal deposits and other raw materials, transportation facilities, and market factors have brought about an eastern U.S. oriented steel industry; however, the growth of West Coast industry and trade have focused new attention on the iron ore deposits of the Western States.

With the discovery of usable iron ore deposits at the Orient and Calumet mines in the 1880's, the Colorado Fuel and Iron Corporation (C.F. & I.) began supplying some of Colorado's iron and steel needs from its Pueblo works. Other raw materials for the steel industry were readily available in nearby areas: coking coal from the Trinidad coalfields in Las Animas County, limestone from the Leadville Formation in the nearby mountains, and the overall mineral wealth of Colorado supplying other necessary ingredients. As a rail center, Pueblo was able to supply the frontier market as well as to meet local needs.

Total production of iron-rich ores in Colorado from 1872 to 1963 is nearly 6.1 million long tons. These ores have been used for several purposes, according to Harrer and Tesch (1959, p. 3–4). About 2,100,000 tons of hematite, limonite, and magnetite ores were mined for iron- and steel-making from 1872 to 1931, when production ceased due to the depletion of known sources of ores competitive with similar ores from other States. In addition to this type of ore, about 3 million tons of iron-silver-manganese ore was mined and used as smelter flux in the treatment of ores of other metals; nearly 1 million tons of manganiferous iron ore was produced for making ferromanganese and spiegeleisen; and smaller amounts of other types of iron ore have been used as heavy concrete aggregate and road metal, for making pigments, and as conditioners for iron-deficient soils.

The small size and remote location of most of the known Colorado iron-ore deposits have limited their past exploitation, and the present abundance of readily accessible high-grade iron ore and easily concentratable low-grade ores in the United States and elsewhere in the world suggests that this will not change in the foreseeable future. The surface geology of Colorado is well known, and it is unlikely that any near-surface large, high-grade or low-grade, easily-concentratable iron ore deposits will be found.

Iron is the second most abundant metallic element in the earth's crust; however, it is not present in most rocks in sufficient quantity to be profitably extracted. Although iron is either the principal or an important constituent of about 250 minerals, only a very few can be considered as ore minerals; these are the oxides magnetite (Fe_3O4, 72 percent iron) and hematite (Fe_2O_3, 70 percent iron), the hydrous oxides goethite, lepidocrocite, and turgite, commonly referred to as limonite ($nFe_2O_3.nH_2O$, approximately 60 percent iron), and the carbonate siderite ($FeCO_3$, 48 percent iron). Pyrite (FeS, 47 percent iron) is a byproduct source of iron in some places. Hematite and magnetite ores are the main sources of iron used in the United States; in western Europe, siderite ore as well is widely used.

Iron-ore deposits and occurrences in Colorado are varied in character and can be grouped only crudely into the four types shown on figure 17. These types are based partly on the dominant iron minerals present and partly on the habit of the deposits.

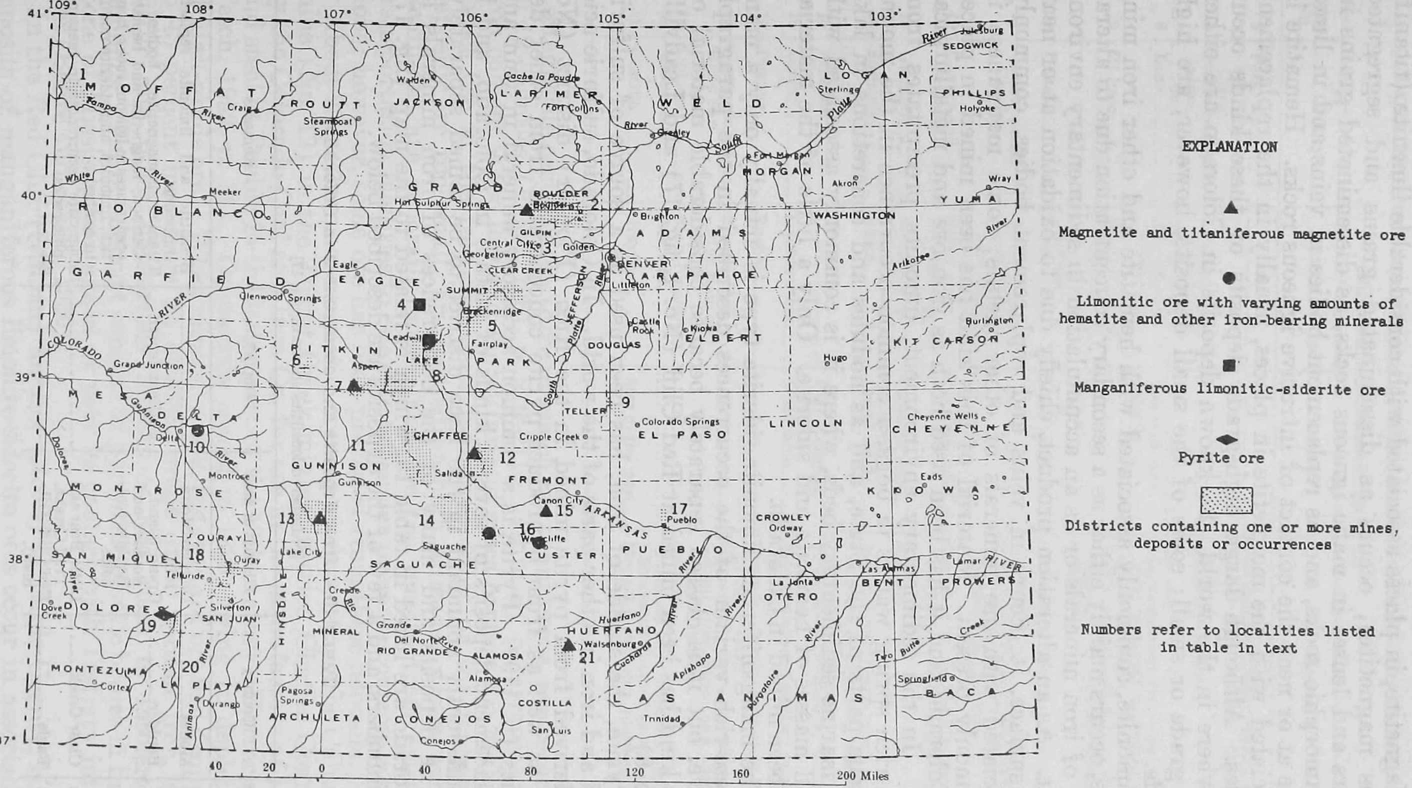

FIGURE 17.—Iron ore in Colorado. Numbered localities identified in table 15.

Magnetite, in places associated with considerable ilmenite (titaniferous magnetite), occurs as disseminated grains and segregated layers and lenses in mafic igneous rocks, as disseminated grains in metamorphic rocks, and as replacement bodies in veins and in limestone at or near the contact of intrusive igneous rocks. Hematite is associated with the magnetite in places, usually in the replacement bodies. Although large high-grade deposits of these kinds occur elsewhere in the world, the known deposits in Colorado are either low grade or small; some of the small deposits, however, are high grade.

Limonite, commonly associated with hematite and other iron minerals, occurs mainly either as a secondary concentration due to alteration of iron minerals or as an accumulation in sedimentary environment. As an alteration product, chiefly due to oxidation at or near the surface, it occurs in veins and replacement bodies, commonly associated with ore minerals of other metals; some manganese is commonly present. Material of this kind has been mined in places in Colorado, and it has been used both as iron ore and metallurgical flux. In the sedimentary environment, limonite precipitates from iron-rich spring waters in bogs, a common occurrence in the mountainous parts of the State, and as nodules and concretions in lake and marine sedimentary beds, where it is commonly associated with small masses of hematite and siderite. Only a little of the material has been mined in Colorado.

The manganiferous limonite-siderite type is actually only a manganese-rich variant of the occurrences described in the paragraph above, but it is classed separately because considerable material of this kind has been mined at Red Cliff (No. 4, fig. 17) and Leadville (No. 8).

Pyrite, the sulfide of iron, has been used as a source of sulfuric acid and iron in other parts of the world. In Colorado, sulfuric acid is derived from pyrite mined in the Rico (Pioneer) district (No. 19) as well as from byproduct pyrite concentrates from other deposits (p. 179). Pyrite is a common accessory mineral in vein and replacement deposits of several kinds of metals in Colorado, and it is sufficiently abundant in the Rico district to be mined separately.

The deposits and many of the occurrences of iron minerals in Colorado are listed in table 15, which is related to the map (fig. 17) by numbers, and a few of the deposits are described below.

TABLE 15.—*Iron deposits and occurrences in Colorado*

[Numbered localities shown on fig. 17]

Map No.	County	District or area	Deposit	Remarks
1	Moffat	Douglas Mountain.		Hematite and limonite replacing limestone.
2	Boulder	Grand Island, Boulder, and Boulder coalfield.	Caribou deposit	Titaniferous-magnetite bodies at Caribou; magnetite and hematite occurrences in igneous rocks; hematite, limonite, and siderite nodules in coalbeds.
3	Clear Creek	Little Bear and Trail Creeks.		Magnetite occurrences in metamorphic rocks.
4	Eagle	Red Cliff (Gilman).		See text.

TABLE 15.—*Iron deposits and occurrences in Colorado*—Continued

[Numbered localities shown on fig. 17]

Map No.	County	District or area	Deposit	Remarks
5	Park, Summit, and Clear Creek.			Scattered magnetite bodies in igneous rocks and limonite deposits in bogs.
6	Pitkin and Gunnison.	Avalanche and Rock Creeks.		Magnetite bodies.
7	do	Taylor Peak		See text.
8	Lake	Leadville and other areas.	Leadville deposits.	Iron-manganese-silver ore at Leadville; scattered magnetite occurrences elsewhere.
9	El Paso	Fountain Creek, Talca Gulch, and Manitou Springs.		Small hematite-goethite and ochre deposits in solution cavities in limestone.
10	Delta	Delta		Limonite in sedimentary rocks; small production.
11	Gunnison and Chaffee.	Garfield, Monarch, Tincup, Tomichi, and Gold Brick.		Varied types of occurrences but mostly magnetite bodies with some hematite and limonite.
12	Chaffee and Fremont.	Turret and Badger Creeks.	Calumet mine	See text for Calumet mine; small magnetite and hematite deposits elsewhere.
13	Gunnison	White Earth (Powderhorn).	Cebello Creek deposit.	See text.
14	Saguache	Blake	Orient mine	See text for Orient mine; limonite deposits in bogs and hematite replacing limestone.
15	Fremont		Iron Mountain deposit.	Titaniferous magnetite, small production.
16	Custer	Hardscrabble	Wahl mine	Manganiferous limonite; small production.
17	Pueblo	Pueblo		Limonite-siderite concretions in sedimentary rocks.
18	Ouray, San Juan, and San Miguel.	Eureka, Red Mountain and Ophir.		Numerous limonite deposits in bogs; small magnetite and hematite deposits in veins.
19	Dolores	Rico (Pioneer)		See text.
20	Montezuma	La Plata		Magnetite and hematite replacing limestone; limonite in bogs.
21	Costilla	Grayback	Star of the west	Magnetite replacing limestone; small production.

Magnetite occurrences, three of which are titaniferous, are recorded in 12 counties (Eckel, 1961, p. 210–211). In many occurrences, the iron content is too low and the sulfur and silica content too high for direct use in the iron and steel industry. Most of the magnetite deposits are too small, are located at high altitudes where winter conditions are generally severe, and are too remote from existing transportation facilities to be exploited under present economic conditions; however, some ore has been produced from these deposits.

About 250,000 tons of magnetite ore was produced from the Calumet mine (No. 12) in the Turret Creek mining district, Chaffee County, by the Colorado Coal and Iron Co. for use in the manufacture of iron and steel at Pueblo in the latter part of the 19th century (Harrer and Tesch, 1959, p. 14). Operations ceased in 1899, owing to depletion of high-grade ore. When mining ceased, the grade of ore had dropped to 43 percent iron from an original grade of 60 percent iron, and sulfur and other deleterious impurities had risen to intolerable amounts. The ore deposit consists of pyrometasomatic bodies in limestone of Mississippian age at or near its contact with Tertiary intrusive (Behre and others, 1936).

In the Red Cliff (Gilman) district (No. 4) of Eagle County, large deposits of manganiferous limonite-siderite ores occur in association with zinc ore deposits in Leadville Limestone. Owned by the New Jersey Zinc Co., about 200,000 tons of ore averaging 38 percent iron content has been mined for use as flux in nonferrous smelters. Reserves are estimated at from three-quarters to one million tons (Harrer and Tesch, 1959, p. 28).

Hematite is widespread throughout Colorado with known occurrences in 23 counties. The brown-red earthy variety is commonly associated with limonitic materials, and the black, massive variety with magnetite and other ores in veins or pyrometasomatic deposits. Six of the occurrences, though small, are significant (Eckel, 1961, p. 180–181). These are located in Chaffee (No. 12), Costilla (No. 21), Gunnison (No. 13), Lake (No. 8), La Plata-Montezuma (No. 20), and Saguache (No 14) Counties.

Extensive deposits of pyrite occur in many Colorado mining districts with other sulfide ores. In the Rico (Pioneer) mining district (No. 19) of Dolores County, the Rico Argentine Mining Co. has a flourishing sulphuric acid industry supplied by the extensive massive pyrite deposits. Substantial amounts of red hematite byproduct are obtained, which is a potential future source of iron.

Thin low-grade beds and concretions of siderite are widely scattered in Colorado, but are little used as a source of iron ore.

On the northwest slope of Taylor Peak in Pitkin County and on the southeast and east slopes in Gunnison County, several pyrometasomatic magnetite deposits occur at 12,000- to 13,000-foot altitudes (No. 7). Averaging 64 percent iron content, these deposits are located in the Leadville Limestone, in shale and limestone of the Weber Sandstone of Pennsylvanian and Permian age, and in Tertiary diorite intrusive bodies. The present inaccessibility of these deposits has prevented their utilization to date. Estimated resources are 3.5 million tons, with an approximate iron content of 64 percent (Carr and Dutton, 1959, p. 97).

The Cebolla Creek titaniferous magnetite and limonite deposits (No. 13) occur in an igneous body, mainly pyroxenite, in the White Earth mining district in Gunnison County. Only a small production of this low-grade iron ore has been recorded, and the resources have not been fully appraised (Singewald, 1912; Rose and Shannon, 1960).

The Orient mine in the Blake mining district (No. 14) of Saguache County was a CF&I producer of limonite ore from 1880 to 1931. Various grades of ore averaging 43 percent iron occur as probable oxidation products of pyrometasomatic magnetite-hematite deposits in the lower part of the Leadville Limestone and have been developed over a vertical range of 1,000 feet (Stone, 1934). Ore reserves of 5 million tons of about 43 percent iron (Carr and Dutton, 1959, p. 97), are inferred to exist in underground and open pits and on the dumps.

MANGANESE

(By M. D. Crittenden, Jr., U.S. Geological Survey, Menlo Park, Calif.)

The United States yearly consumes about 2 million long tons of high-grade manganese ore (more than 35 percent Mn). About 95 percent of the supply is used as ferromanganese in the production of steel, and for this purpose there is no known substitute; the remainder is used in chemicals and batteries. Because the United States has no deposits of high-grade ore capable of supplying domestic requirements, it has depended largely on imports, mainly from India, Africa, and South America. During normal times, foreign supplies have been readily available, but during national emergencies, as during both World Wars and the Korean conflict, these supplies have been curtailed or seriously threatened. Domestic production during these emergency periods and during the stockpiling program in the 1950's was encouraged by high prices and other means.

The production of high-grade manganese ore in Colorado totals 31,759 long tons (table 16), most of which was produced during and shortly after World War I, during World War II, and in the late 1950's. This total production of high-grade ore, however, is less than 2 percent of the present annual consumption. On the other hand, Colorado, has produced nearly 1 million tons of low-grade manganese ores, containing 10–25 percent Mn and 25–40 percent Fe. This material was used in the manufacture of spiegeleisen, a low-grade managanese alloy formerly used abundantly in steel making.

TABLE 16.—*Production of manganese ore in Colorado* [1]

[In long tons]

Year	High-grade ore (+35 percent Mn)	Low-grade ore (10–35 percent Mn)	Year	High-grade ore (+35 percent Mn)	Low-grade ore (10–35 percent Mn)
1891–1909		403, 654	1935		2, 625
1915	150	15, 946	1936		10, 568
1916	110	90, 850	1937		11, 577
1917	60	104, 315	1938		655
1918	4, 821	99, 137	1939		6, 710
1919	11, 166	11, 071	1940	200	2, 949
1920	3, 643	11, 056	1941	157	
1921	490	924	1942	458	39
1923	2, 278	18, 348	1943	631	
1924	5, 338	27, 058	1945		42
1925	743	7, 352	1947		33
1926		2, 925	1952		68
1927	84	26, 828	1957	156	
1928		18, 599	1958	187	
1929		17, 770	1959	1, 087	
1930		19, 730			
1931		3, 685	Total	31, 759	914, 514

[1] Compiled from U.S. Bureau of Mines Minerals Yearbook. Excludes fluxing ores from which no manganese was recovered.

Manganese is a constituent of many minerals, but generally only the manganese oxides are rich enough in manganese to be ore minerals. The common manganese oxides are pyrolusite (MnO_2), minerals of the psilomelane group (KMn_8O_{16}, or $BaMn_9O_{18} \cdot 2H_2O$, and others), and wad (an amorphous mixture of manganese and iron oxides with diverse amounts of water).

The distribution and geologic types of manganese deposits in Colorado are shown on figure 18; only a few of these deposits have been productive.

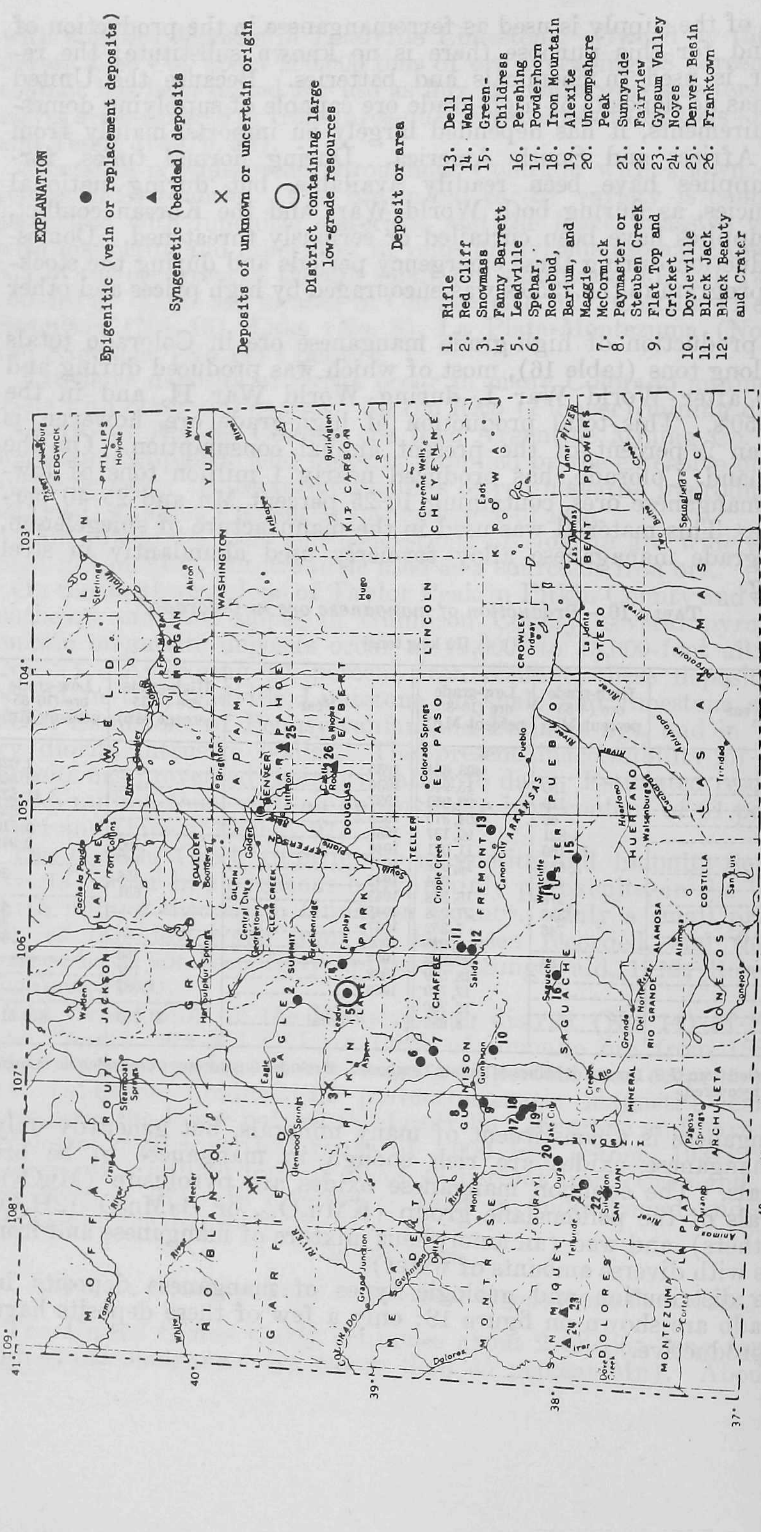

FIGURE 18.—Manganese in Colorado.

Epigenetic veins or replacement bodies are the most common type of manganese deposits in Colorado. Many are associated with deposits of precious and base metals, and in some of these iron minerals are abundant or dominant. In the primary, or unoxidized deposits, manganese mainly occurs in the gangue minerals, commonly as rhodochrosite (manganese carbonate), rhodonite (manganese silicate), and manganiferous siderite (iron carbonate); in place the iron oxide minerals magnetite and hematite are manganiferous. Some of the unoxidized deposits may yield low-grade manganese ore, but in most the manganese content is too low to be of value. On oxidation at and near the surface, however, the manganese-bearing minerals alter to oxides of manganese. The size and grade of these oxidized deposits depend on the form and grade of the original deposit and on the processes of alteration. In places masses of high-grade manganese ore occurs, but most of them are small and spotty, and commonly they have been mined for their precious- or base-metal content, or even their iron content, which yielded more value than would have the manganese. A variant of this type of deposit is commonly found in volcanic rocks or in neighboring beds of sedimentary rocks, where manganese oxides form veinlets, nodules, or small replacement masses; whether the managanese was introduced originally by warm volcanic waters or by oxidizing solutions percolating through the rocks is not clear. Although many of these occurrences have been prospected in Colorado, few have yielded any ore.

The Leadville district (No. 5, fig. 19), Lake County, contains the largest deposits of the epigenetic type with other metals. Between 1891 and 1925 it yielded about 810,000 tons of manganese ore, some high grade but mostly low grade (Emmons and others, 1927, p. 131). During this period it also yielded nearly 3 million tons of iron-manganese-silver ore that was used as flux in nonferrous smelters, where the manganese was lost. According to Hedges (1940) the Leadville district has about 2 million tons of inferred reserves of unoxidized manganoan siderite containing 10 to 15 percent Mn and 20 percent Fe, and an additional 2 million tons of oxidized material of comparable or slightly higher manganese content.

Material of similar grade and character occurs in the Red Cliff district (No. 2), Eagle County. About 200,000 tons has been mined for metallurgical flux; reserves are estimated to be about 1,000,000 tons (Muilenburg, 1919).

Considerable rhodonite occurs with base-metal deposits in the Sunnyside mine (No. 21), San Juan County. Although this silicate is too refractory to be used as a source of managanese, it has been used in welding-rod coatings, and this deposit offers a potential source of material for this purpose.

Syngenetic or bedded deposits of manganese occur in a few places in Colorado; they are all apparently small, but by selective mining a little high-grade ore has been obtained. The deposits in San Miguel County (Nos. 23 and 24) consist of nodules of manganese oxides in a thin limestone bed in the Jurassic Summerville Formation and of manganese minerals staining and impregnating beds of sandstone in other formations. The occurrence in the Summerville is similar to deposits that have yielded some ore in southeastern Utah (Baker and others, 1952). The deposits in Arapahoe and Douglas Counties (Nos. 25 and 26) are in the Dawson and Denver Formations.

The manganese deposits of Colorado will probably yield small quantities of high-grade ore at times when the price for this material is high, but no significant production can be expected. A quantatitve appraisal of resources cannot be made, but they must be classed as insignificant. A few million tons of low-grade manganese-bearing material is available in the Leadville and Red Cliff districts, and small quantities of similar material are available elsewhere, but these probably will not be utilized as sources of manganese except under conditions of extreme emergency.

MOLYBDENUM

(By R. U. King, U.S. Geological Survey, Denver, Colo.)

Molybdenum is a metal that is of prime importance to our modern ferrous metals industry. It is a silvery white metal, a little softer than steel, and has a melting point of 4730° F., which is higher than all other metals except tungsten, rhenium, osmium, and tantalum. It is ductile, and resistant to acids and oxidation at ordinary temperatures. Its importance is due to the beneficial properties of hardness, toughness, and resistance to wear and corrosion that are imparted to iron and steel when alloyed with molybdenum.

About 80 percent of the molybdenum consumed in the United States is used in the manufacture of high-temperature alloy steels, stainless steels, and castings; the rest goes into special alloys, refractories, chemicals, pigments, catalysts, lubricants, and agricultural products. New uses for molybdenum are being developed in the nuclear power field, and in missile and aero-space industries, and these give promise of an ever-increasing demand for this versatile metal.

Molybdenum is widely distributed in rocks of the earth's crust, averaging about 2.5 (0.00025 percent) parts per million. It is present in trace amounts in igneous, metamorphic, and sedimentary rocks; in soils; in ground water; oceans; hot springs; and in plant and animal tissues. It is never found in its pure or native state, but only in combinations with non-metallic elements such as sulfur and oxygen, and other metallic elements such as iron, calcium, tungsten, and lead. Its most common naturally occurring form, and the only one of current commercial importance, is in the mineral molybdenite (molybdenum disulfide, MoS_2). Other molybdenum minerals include wulfenite (lead molybdate), ferrimolybdite (hydrous ferric molybdate), powellite (calcium molybdate, commonly with tungsten), jordisite (amorphous molybdenum sulfide), and ilsemannite (molybdenum oxy-sulfate). Several rarer minerals of doubtful economic significance are known in which molybdenum is combined with one or more of the following elements: bismuth, copper, magnesium, vanadium, cobalt, and uranium.

Marketable forms of molybdenum are either molybdenite concentrates (95 percent MoS_2) or molybdenum oxide (MoO_3), which is made by roasting molybdenite concentrates.

Although the element molybdenum was identified in the latter part of the 18th century, it was not until the early part of the present century that its potential value to the metals industries was recognized and wide applications for its use were developed. Intensive search for the metal followed, which resulted in the discovery of high-grade deposits of wulfenite in Arizona and molybdenite in New Mexico, and of the large but lower grade deposit of molybdenite at Climax, Colo.

Commercial production of molybdenum in the United States began in 1898, but was relatively small and intermittent until 1914. Since 1914 production has increased yearly, with few exceptions to a current annual rate of about 65 million pounds. During the first quarter of the present century the United States contributed only a small portion of the world's molybdenum supplies, but since about 1925 between 65 and 90 percent of the world's molybdenum has been produced in the United States; 57 percent of the world's total production of molybdenum has come from Colorado. Significant production of molybdenum in Colorado began during World War I, and since that time Colorado has consistently supplied more than half of the United States production.

Molybdenite deposits are widespread in Colorado, being reported in at least 28 counties in the western half of the State. Molybdenite has been mined from only seven deposits, however, and only the deposits at Climax in Lake County and at Urad in Clear Creek County have yielded significant amounts of molybdenum. Since 1924 the entire production of molybdenum in Colorado has come from the Climax mine.

Five genetic types of molybdenum deposits may be described, based on similarities of geologic and physical features: (1) porphyry or disseminated, (2) contact metamorphic deposits, (3) simple quartz veins, (4) pegmatites and aplites, and (5) bedded deposits in sedimentary rocks. All five types occur in Colorado.

Forty-five deposits and occurrences of molybdenum are shown on figure 19. The deposits at Climax (No. 19, fig. 19) and Urad (No. 14) are the only deposits of major production. The deposits at Gold Hill (No. 28), the California mine (No. 30), Lamphere Lake (No. 29), the Redskin mine (No. 20), at the Bighorn Shaft (No. 7), and Mountain Lion-Keystone mine (No. 5) have yielded small amounts of molybdenum ore. Most of the other deposits contain scarcely more than trace amounts of molybdenum or small quantities of specimen material. Molybdenum is reported at a number of additional localities (Worcester, 1919), but the locations of some are indefinite, and the presence of molybdenum has not been confirmed at others.

The productive deposits, those of possible economic interest, and a few representatives of the deposits in which molybdenum is merely an occurrence, are described below by the five geologic types.

Molybdenum occurs in "porphyry" or disseminated deposits of molybdenite alone or in association with copper sulfides. The ore minerals are dispersed through relatively large volumes of altered and fractured rocks commonly in or near intrusive bodies of granitic or porphyritic rocks. These deposits, although large, have low metal content and are amenable only to large-scale, low-cost mining methods. This type of deposit is by far the most productive of

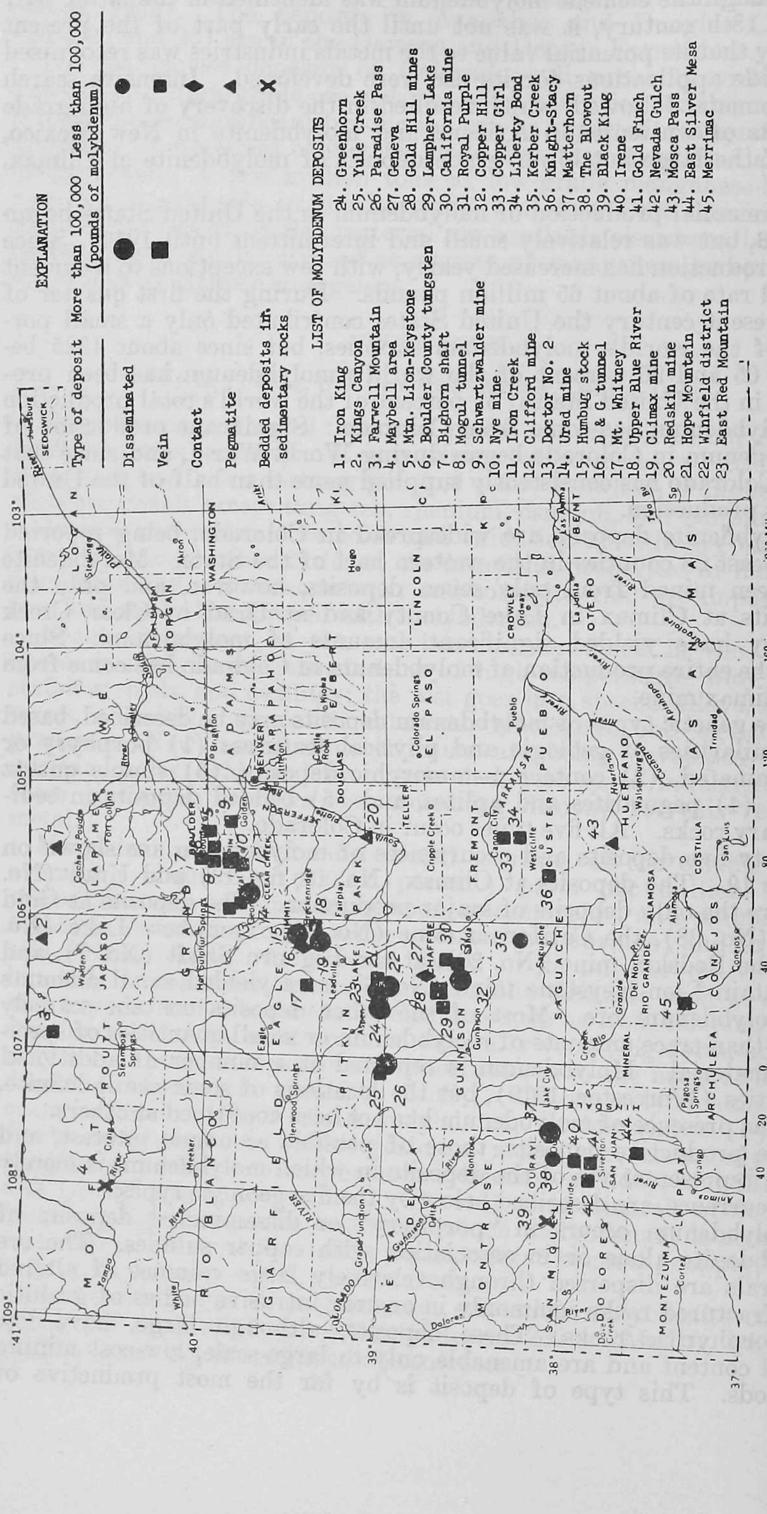

FIGURE 19. Molybdenum in Colorado.

molybdenum in the United States and offers the greatest resource potential. The deposit at Climax, Colo., where molybdenum is the principal product, and the porphyry copper deposit at Bingham, Utah, where molybdenum is a byproduct, are examples of this type.

The Climax mine (No. 19) exploits the largest known molybdenum deposit in the United States if not in the world. The mine, operated by the Climax Molybdenum Company Division, American Metal Climax, Inc., has, according to their annual report for 1963, ". . . reserves of 445 million tons of molybdenum ore which contain over two billion pounds of molybdenum sufficient to sustain the present rate of production until approximately the end of this century." The Climax deposit consists of a complex dome-shaped mass of fractured, silicified, and mineralized Precambrian granite, gneiss, and schist generally overlying a stock of quartz monzonite porphyry of Cretaceous or Tertiary age. Molybdenite associated with pyrite is dispersed in small amounts throughout the fractured mass forming a low-grade ore body several thousand feet in smallest dimension. Several commodities are recovered as byproducts from the ore. Pyrite concentrates are recovered in moderate amounts and are used in making sulfuric acid (p. 179). Tungsten occurs in the ore in amounts ranging from only a trace to a few hundredths of one percent, but because of the large tonnage of ore mined, Climax has been one of the leading producers of tungsten concentrates in the United States in recent years (p. 109). Tin occurs only in trace amounts but is recovered as a minor byproduct (p. 222). A small tonnage of monazite has been recovered in the past (p. 134), as has a small amount of topaz (p. 219). Detailed descriptions of the geology of the Climax deposit, including a historical account of its discovery and development, are given by Butler and Vanderwilt (1931), Vanderwilt and King (1955), and Wallace and others (1960).

The Urad mine (No. 14) in the Dailey district, Clear Creek County, is in the State's second largest molybdenum deposit. The deposit was discovered in 1914, and during World War I yielded several hundred thousand pounds of molybdenum from higher grade veins. The property was inactive until the beginning of World War II, when the Molybdenum Corporation of America began extensive development. During the mid-1940's several hundred thousand pounds of molybdenum were produced from the deposit, which is localized in a zone of fractured and altered granite around the southern margin of the Red Mountain granite porphyry stock (Carpenter, 1960, p. 321). Molybdenite associated with quartz and pyrite occurs chiefly in a few strong fissures or shear zones but also in veinlets and seams and as disseminations in altered and fractured granite between the fissures (Lovering and Goddard, 1950, p. 283), yielding a massive deposit of many millions of tons of low-grade molybdenite ore. In 1963 the American Metal Climax, Inc., became owner of the property and is currently preparing to bring the mine into production.

Molybdenite occurs in a disseminated deposit and in several vein deposits in the Winfield district (No. 22), Chaffee County. On the north slope of Winfield Peak molybdenite occurs in quartz-pyrite veins and veinlets and is weakly disseminated in altered and fractured quartz monzonite porphyry. In one of the vein deposits (Banker mine) molybdenite is associated with bismuthinite (Worcester, 1919, p. 41).

At the Greenhorn property (No. 24) near the head of Lincoln Creek in Pitkin County, and on Red Mountain on the Continental Divide, molybdenite is disseminated in fractured rhyolite porphyry and granitic rocks (Horton, 1916, p. 71; Worcester, 1919, p. 77). A mineralized area several hundred feet by a few thousand feet is indicated by discoloration of the country rocks from oxidation of pyrite. The molybdenum content in parts of veins is as much as 1 percent but the average content in the large disseminated body is only several hundredths of 1 percent.

Several other disseminated molybdenite deposits are known in the State, including the Humbug Stock (No. 15), East Red Mountain (No. 23), Paradise Pass (No. 26), Copper Hill (No. 32), and Matterhorn (No. 37). The total molybdenum content of these deposits is probably very large, but average grades are so low as to preclude profitable mining.

In the molybdenum-bearing contact metamorphic deposits, molybdenite is commonly associated with scheelite, bismuthinite, or copper sulfides in zones of silicated limestone or tactite bodies near contacts with granitic rocks. The deposits at the D and G Tunnel (No. 16) and at the Geneva claim (No. 27) are of this type. They are too small to warrant exploitation.

Numerous veins containing molybdenite occur throughout the Colorado mineral belt. Molybdenite commonly occurs alone or with pyrite in a quartz gangue, but also is associated in places with other metallic sulfides; tungsten, bismuth, and uranium minerals; and beryl.

At the Nye mine (No. 10) near Apex, Gilpin County, molybdenite occurs in quartz-pryrite veins and silicified shear zones in quartz monzonite porphyry. Some molybdenite also occurs in the altered and fractured wall rocks adjacent to the veins. In places in the major veins the molybdenite content may be several percent, but in the mineralized wall rocks the molybdenum content is only a few tenths of 1 percent. This deposit, currently being explored by the owners, is a potential economic source of molybdenum.

The Gold Hill mines (No. 28) are a group of mines that have exploited a series of molybdenum-tungsten-quartz veins in the Quartz Creek district, Gunnison County. Molybdenite is associated with huebnerite, chalcopyrite, scheelite, and pyrite in quartz veins cutting quartz monzonite gneiss. In some of the veins the molybdenite content is several percent, but because of the limited size of the individual deposits, they cannot be mined for molybdenum alone; however, a potential resource of molybdenum is present and might be economically recoverable as a co-product with tungsten under suitable conditions.

In the Mountain Lion-Keystone mine (No. 5) in the Magnolia district, Boulder County, high-grade pockets of molybdenite occur in quartz veins and pegmatite (Lovering and Goddard, 1950).

Molybdenite in small amounts accompanies the tungsten ores in some of the veins of the Boulder County tungsten district (No. 6) (Lovering and Tweto, 1953). The molybdenite occurs in seams and veinlets and rarely is disseminated in pegmatite and in the schistose wall rocks.

Molybdenite occurs in quartz-pyrite veins cutting mica schist at the Bighorn Shaft (No. 7) and in the nearby Boulder County mine, in the

Grand Island mining district (Lindgren, 1907). A small quantity of molybdenum ore averaging 0.5 percent molybdenite was mined through the Bighorn shaft in 1918, but the deposit has not been further exploited (U.S. Geol. Survey Mineral Resources U.S., 1918, p. 798).

Molybdenite occurs in quartz veins in a breccia zone in Precambrian metamorphic rocks near Lamphere Lake (No. 29), Gunnison County. The molybdenite is coarsely crystalline, and amounts to 2 or 3 percent of the vein material at places, but the average grade is less than 0.5 percent (Worcester, 1919, p. 64).

At the California mine (No. 30), Chaffee County, coarse molybdenite is associated with beryl in a quartz vein cutting quartz monzonite (Adams, 1953, p. 118).

On Nevada Gulch (No. 42) east of Ophir, San Miguel County, coarse molybdenite occurs in a quartz-pyrite breccia zone in quartz monzonite porphyry and in adjacent metamorphosed sedimentary and volcanic rocks (Worcester, 1919, p. 85). Some of the mineralized breccia contains as much as 1.5 percent molybdenum but the deposit is too small to warrant exploitation.

Some pegmatites in Colorado contain small quantities of coarsely crystalline molybdenite, but the desposits are not of commercial interest.

Small amounts of molybdenite are associated with beryllium and uranium minerals in greissen pipes at the Redskin mine (No. 20) near Tarryall, Park County. Small shipments of molybdenum ore were made from material recovered from high-grade pockets of molybdenite prior to 1920 (Worcester, 1919, p. 73), but the deposit has not been exploited for molybdenum since that time.

Bedded deposits in sandstone contain molybdenum in small amounts, commonly associated with uranium or vanadium. The molybdenum content generally amounts to no more than a few hundredths of a percent in the Plateau deposits in southwestern Colorado, but may be as much as several tenths of a percent in pockets in some of the uranium deposits in Tertiary sedimentary rocks in the Maybell area in the northwestern part of the State. The small quantity of molybdenum in this type of deposit is more likely to be detrimental than a possible source of byproduct molybdenum.

According to company reports, more than 100 million tons of ore have been mined from the Climax deposit to date, and reserves of over 445 million tons of molybdenite ore containing between 0.25 and 0.50 percent MoS_2 are known in the Climax molybdenum mine. At the current rates of production of 10 to 12 million tons of ore per year, these reserves would last another 30 to 40 years. The ore deposit at Climax has not yet been completely delineated, and the possibility therefore exists that additional ore may be discovered that will, in part at least, replace reserves currently being mined.

The outlook for molybdenum in Colorado for the foreseeable future is indeed bright.

The probable tonnage of molybdenum-bearing rock in the several disseminated type deposits in Colorado is large, and where average metal content is not less than about 0.1 percent molybdenum a significant potential resource of molybdenum exists. Other deposits of this type are known in the State, which have been explored at least to a small degree, and whose metal contents are indicated to be less than 0.1 percent, and are therefore not likely to be profitably minable, at least in the foreseeable future. Known resources of molybdenum are limited to the Climax and Urad deposits and perhaps a few other deposits of this type.

Although quantitative data are not available on which to base tonnage and grade estimates, the other types of molybdenum occurrences in Colorado, including simple veins, contact deposits, pegmatites, and bedded deposits, are not considered likely to constitute potential economic sources of molybdenum.

TUNGSTEN

(By S. W. Hobbs, U.S. Geological Survey, Denver, Colo.)

Tungsten is a metal of high strategic value whose importance depends mainly on the unusual physical and mechanical properties of the element, its alloys, and certain special compounds. In its pure form, tungsten is a white metal whose melting point of 3,410° C. is higher than that of any other metal. It has unusually high density, low vapor pressure, and favorable electrical and thermionic properties. Tungsten alloys and carbides are notable for their extreme hardness and wear resistance and particularly for retaining hardness at elevated temperatures. Industrial uses of tungsten devolve about these special properties.

Pure or substantially pure tungsten metal is important in electric lighting, electronics, and electrical contact applications. However, the greatest use of the metal is in alloy tool steel and in tungsten carbide used for cutting edges, dies, drill bits, wear-resistant machine parts, and other applications where extreme hardness is desirable. Over 70 percent of the consumption has recently been going into tool steel and tungsten carbide. Domestic consumption averaged 4,245 tons of tungsten metal in the period 1952–1961; consumption in 1962 was approximately 6,850 tons.

The United States has in general imported tungsten in amounts that exceed domestic production. Although the U.S. tungsten mining industry has operated continuously (except for 1921 and 1922) for over 50 years, the rate of production has ranged widely due to various economic factors and particularly the Government stockpiling program. Only a few domestic producers have been able to compete consistently on the open market with foreign producers (Holliday, 1960, p. 914). However, a large domestic productive capacity was demonstrated twice in the last two decades under conditions of special need or incentive: in 1943–45, to fill heavy demand of the war effort, and between 1950–56 under the influence of the price incentive of the Government stockpiling program. In 1955, production reached an all-time peak that was nearly four times the average annual production of the immediate post war period 1946–1950. Subsequent to the end of Government stockpile purchases in December 1956, the price dropped drastically and consequently production from many mines was stopped or radically reduced. In 1956, nearly 600 operations reported some production; in 1958, only two producers were active (U.S. Bureau of Mines Minerals Yearbook, 1956, v. 1, p. 1227 and 1958, v. 1, p. 1091). These facts illustrate dramatically the tungsten resource situation of the United States: there is a substantial supply of tungsten available at the present time if the need warrants paying the price to extract it.

Under normal conditions, however, not many domestic deposits are competitive in the world market.

Tungsten minerals are widely distributed in various rock types of the earth's crust, but for the most part seem to be genetically associated with igneous rocks of granitic composition. About 11 minerals contain tungsten as an essential component, but of these the only commercially important ones are those of the wolframite group—ferberite, $FeWO_4$, wolframite, (Fe, Mn) WO_4, and huebnerite, $MnWO_4$—and scheelite, $CaWO_4$. Although the wolframite group is economically the more important in the world as a whole, and also in Colorado, scheelite has accounted for nearly three-fourths of the United States total output.

In the United States, tungsten occurs principally in quartz veins that contain minerals of the wolframite group or scheelite or both, and in contact metamorphic deposits containing scheelite. It occurs also in hydrothermal replacement bodies in igneous, sedimentary, or metamorphic rocks, in places localized along shear zones and in stockworks, and in pegmatites and residual placer deposits. Many occurrences of tungsten-bearing manganese oxides of hydrothermal origin are known, and one at Golcanda, Nevada, was worked commercially. In many domestic deposits, tungsten is the only mineral recovered, although in a few localities it is associated either as the major commodity or as a byproduct with other marketable minerals such as molybdenite, gold. stibnite, and beryllium; in a few places silver, copper, lead or zinc are co-products with tungsten in ores.

Colorado has an impressive record in tungsten production relative to other states. Tungsten minerals were first recognized in the Ward and Nederland districts, Boulder County, in 1899 and 1900 respectively, and the first shipments of tungsten concentrates from this County were made early in the century. Although production was small in these early years, the increased recognition of the special properties of tungsten alloys and carbides together with the special demands during World War I and II greatly stimulated production from the Boulder County district and encouraged the search for other deposits. Lovering and Tweto (1953, p. 78–81) give a detailed history of the development of the Boulder County district which supplied almost the entire production of tungsten from Colorado up to about 1948. Since 1945 production from Boulder County has steadily diminished, and with the start of the recovery of tungsten as a byproduct from the molybdenum ore at Climax in 1948 this great mine has become the principal source of production in the State and one of the main producers in the Nation. Minor production has been made from mines in Chaffee, Gunnison, Park, San Juan, San Miguel, and Saguache Counties. Total production of tungsten from Colorado properties during the period 1900 to 1962 is 35,724 short tons of 60 percent concentrates whose valuation is nearly $48,000,000. Figure 5 shows the production trends of various mineral products in Colorado and illustrates the rapid growth of the ferro-alloy metals, tungsten, vanadium and molybdenum. Although tungsten is not shown separately and is the lesser of the three in value, its production trend reflects the increased demand during the two World Wars and a striking increase from 1950. Figure 6 shows the dollar value of tungsten and its percent of total commodity production for the period 1858 to 1962.

Tungsten deposits of Colorado are of three major modes of occurrence: (1) scheelite in Precambrian gneisses, where many small occurrences are known, chiefly in the limey rocks such a calcsilicate gneiss, amphibolite, skarn and impure marbles; (2) tungsten of the wolframite series minerals, with or without accessory scheelite, in veins or other types of ore deposits of Late Cretaceous or Tertiary age; and (3) tungsten in an unknown form in manganese deposits of Tertiary age, chiefly in the San Juan Mountains area. The principal tungsten deposits of Colorado are components of the Colorado mineral belt and appear for the most part to be related to a series of intrusive rocks of Tertiary age that are localized by older structural features along the belt.

Figure 20 shows the location and relative rank of 43 deposits in Colorado, and table 17 gives data concerning these deposits. All the productive deposits are shown as well as many small or unproductive deposits that illustrate a mode of occurrence that may have bearing on future discoveries; no attempt is made, however, to show every occurrence of tungsten minerals in the State. Most of the data for figure 20 and table 17 were derived from U.S. Geological Survey Mineral Investigation Map MR–25 (Lemmon and Tweto, 1962). The Colorado deposits are ranked in categories that correspond to those used by Lemmon and Tweto. The rank is based on production plus estimated reserves and indicate tungsten contents of: (1) greater than 10,000 short tons of tungsten metal, (2) 500 to 10,000 tons, (3) 10 to 500 tons, and (4) less than 10 tons. There are no deposits of No. 2 rank among the known Colorado occurrences. The references cited on table 17 are not intended to be complete but to list only the more important or more recent ones.

Colorado has long held its place among the leading tungsten producing states of the Union—for many years ranking first or second year after year, and for the last few decades, third, fourth, or fifth. It is the third ranking State in total production. The State contains both the oldest major producing district in the United States—Boulder County (No. 7, fig. 20)—and one of the newest major sources of tungsten concentrates—the Climax molybdenum mine (No. 13). These two districts have accounted for well over 95 percent of Colorado production. In spite of the fact that tungsten minerals are widely scattered in the mountainous parts of the State, and some 43 of these localities are plotted on figure 20, there are surprisingly few deposits that have yielded only small production and none that falls in rank No. 2 as used on figure 20 and table 17.

The famous tungsten deposits of Boulder County occur as ferberite-bearing chalcedonic quartz veins that cut Precambrian granite and metamorphic rocks. The veins appear to be related to latite porphyry dikes of Tertiary age and were deposited in fissures and brecciated zones that trend northeast or east-northeast. The relatively simple mineralogy includes fine-grained quartz, local concentrations of ferberite, a small amount of pyrite, and very minor amounts of other minerals.

The tungsten ore occurs in irregular shoots that are relatively small and are separated by barren stretches along the vein fissure that may or may not carry quartz. Color banding that parallels the walls of some veins results from different amounts of finely disseminated im-

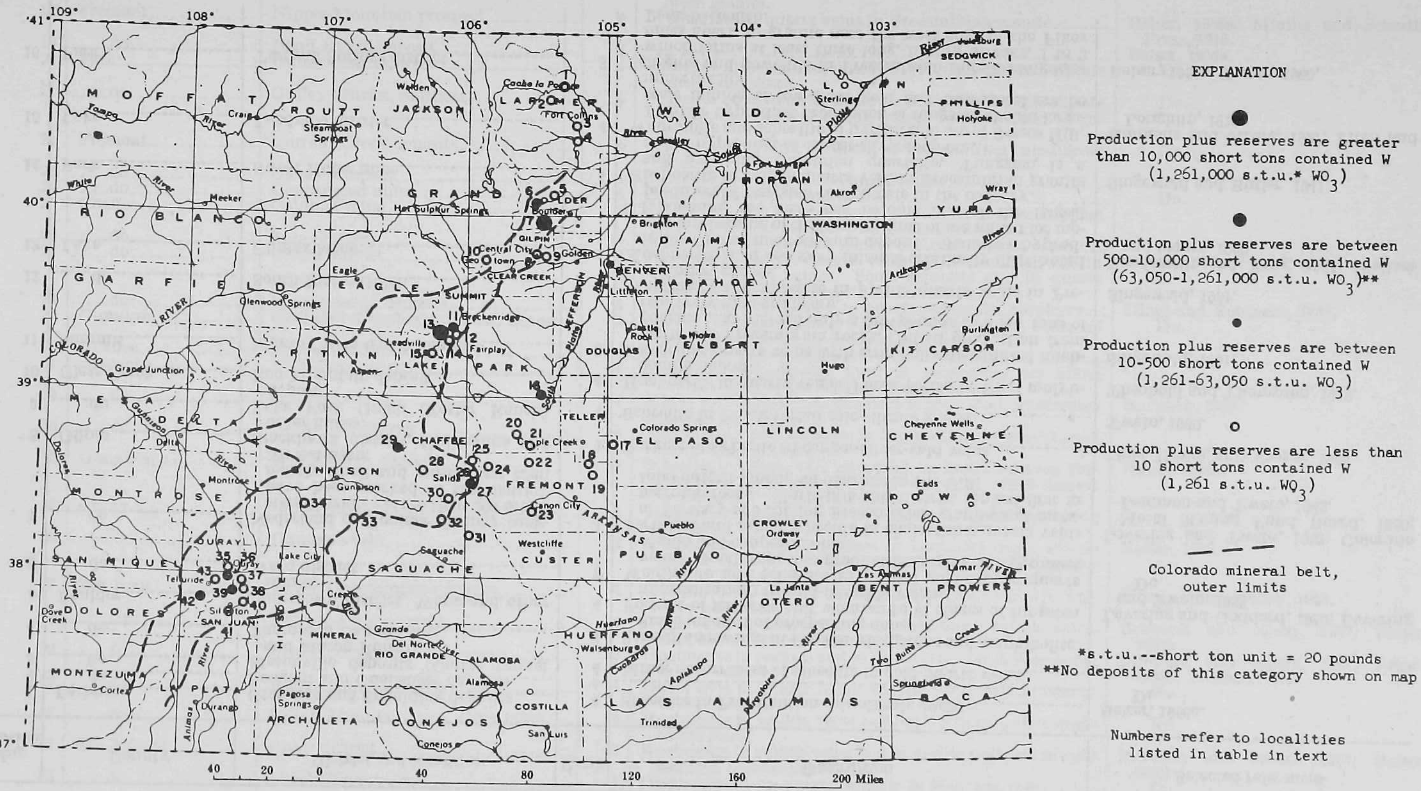

FIGURE 20.—Tungsten in Colorado. Numbers refer to localities listed in table 17.

TABLE 17.—*Tungsten mines and prospects in Colorado*

Map location	County	District and localities	Rank	Description	Selected references
1	Larimer	Greenock and Spaulding deposits	4	Scheelite in Precambrian calc-silicate gneiss	Belser, 1956a.
2	do	Lookout and Challenger deposits	4	do	Do.
3	do	Masonville deposits (Carter tunnel and Mason Ranch).	4	Minor occurrences of scheelite in gold-quartz veins	
4	do	Thompson Canyon area	4	Scheelite showings in Precambrian gneiss and amphibolite. Small amount of prospecting done.	
5	Boulder	Jamestown district, Wano and other mines.	4	Pockets of ferberite and wolframite (2 stages of tungsten mineralization) in gold-telluride veins.	Lovering and Goddard, 1950; Lovering and Tweto, 1953.
6	do	Ward district	3	Wolframite and scheelite in pyritic gold-copper quartz veins. Small tungsten production largely as byproduct of gold and copper mining.	Do.
7	do	Nederland or Boulder County tungsten district. More than 200 mines have been worked in the district, mostly small and mostly less than 200 feet deep.	1	Ferberite and minor scheelite in chalcedonic quartz veins of Tertiary age cutting Precambrian granite and metamorphic rocks. Until 1945 this district ranked first in total output among all districts in the U.S.	Lovering and Tweto, 1953; Colorado Metal Mining Fund Board, 1960; Lemmon and Tweto, 1962.
8	Gilpin	Blackhawk district, Chihuahua and other mines.	4	Pockets of ferberite in copper-silver-gold veins	Sims, Drake, and Tooker, 1963.
9	do	Lake Fork Gulch (Foster Ranch) deposit.	4	Scheelite in Precambrian calc-silicate gneiss	Tweto, 1960.
10	Clear Creek	Red Mountain deposit	4	Huebnerite in quartz veins(?) near border of Urad molybdenum deposit.	Theobold and Thompson, 1959.
11	Summit	Monte Cristo Gulch deposits	3	Lenticular quartz veins with erratically distributed huebnerite, in Precambrian rocks. Small production from pockets that yielded only a few pounds to a few tons of relatively high-grade ore.	Singewald, 1951.
12	do	South Platte Gulch	4	Wolframite and scheelite in pyritic quartz veins in Precambrian gneiss.	Singewald, 1951.
13	Lake	Climax Mine	1	Huebnerite is an accessory mineral erratically distributed in the Climax molybdenum deposit. Strictly a byproduct, but because of the large volume of ore mined for molybdenum, the mine has become one of the largest producers of tungsten concentrate in the country.	Vanderwilt and King, 1955; Wallace and others, 1960.
14	Park	Sweet Home mine	4	Huebnerite in sulfide-quartz vein in Precambrian granite and overlying Cambrian quartzite. Tungsten is a minor byproduct of copper-silver-lead ore.	Singewald and Butler, 1941.
15	Lake	Leadville district	4	Wolframite and scheelite in pyritic gold ore of Breece Hill. Possible byproduct production of tungsten should large-scale mining of low-grade gold and base-metal ore be undertaken.	Emmons and others, 1927; Fitch and Loughlin, 1916.
16	Park	Tarryall Springs district	3	Scheelite and powellite in Precambrian calcsilicate gneiss which forms at least three long, narrow streaks, 1 to 2 miles apart, in granite near the west edge of the Pikes Peak batholith.	Belser, 1956a; Tweto, 1960.

17	Teller	Heavystone prospect	4	Minor wolframite in quartz vein in shear zone in Precambrian granite.	
18	Fremont	Nipple Mountain prospect	4	Wolframite in quartz veins in Precambrian granite	Belser, 1956a; Mining and Scientific Press, 1916.
19	do	Bond Ranch deposit	4	do	Belser, 1956a.
20	Park	Guffey district, west	4	Scheelite at several localities in Precambrian calc-silicate gneiss and skarn.	Do.
21	do	Guffey district, southeast	4	Scheelite at several localities in Precambrian calc-silicate gneiss, and copper-bearing quartz veins or lenses in the gneiss.	Do.
22	Fremont	Current Creek deposits	4	Scheelite at several localities in Precambrian calc-silicate gneiss.	Do.
23	do	Oliver prospect	4	Scheelite in Precambrian amphibolite	Do.
24	do	Copperhead mine	4	Scheelite in copper-quartz ore	Do.
25	Chaffee	Calumet mine	4	Scheelite in iron ore; magnetite and tactite in Mississippian limestone near contact with granodiorite stock.	
26	do	Sage prospect	4	Scheelite in psilomelane matrix of strong breccia zone	Do.
27	do	Cleora district	3	Scheelite in copper-quartz veins of Precambrian age in several copper mines. Some scheelite also in quartz fragments in thick breccia on flat thrust fault.	Belser, 1956a; Tweto, 1960.
28	do	Mount Aetna deposits	4	Huebnerite-quartz veins in quartz monzonite porphyry	Dings and Robinson, 1957.
29	Gunnison	Gold Hill (Cumberland Pass) deposits	3	Several huebnerite-molybdenite-quartz veins, some of which are pyritic, in Precambrian granite.	Do.
30	Chaffee	Poncha Pass area	4	Scheelite in quartz veins in Precambrian schist	
31	Saguache	Villa Grave deposit	4	Tungsten in unknown form in manganese ore filling breccia along faults cutting volcanic rocks.	
32	do	Bonanza district	4	Minor wolframite in copper sulfide ore. Best occurrences in Rawley tunnel.	Burbank, 1932.
33	do	Cochetopa district	4	Scheelite in small amounts in Precambrian pegmatite and metamorphic rocks.	
34	Gunnison	White Earth district	4	Scheelite in quartz and clay veins on faults between Precambrian rocks and Tertiary volcanics. Best known in Kazar and Lilly Belle mines.	Belser, 1956a.
35	Ouray	Ouray district	4	Tungsten in unknown form in manganiferous hot spring deposits.	
36	do	Dunmore vein	3	Huebnerite in siliceous pipes in Dunmore mine, and in quartz at other localities in Dunmore vein. Country rock is Tertiary volcanics.	Kelley, 1946.
37	San Juan	Upper Uncompahgre district	4	Huebnerite in pockets in base-metal sulfide veins in Tertiary volcanic rocks.	Belser, 1956b; Kelley, 1946.
38	do	Animas Forks deposit	4	Huebnerite in quartz bands in base-metal sulfide veins. Best shown in Tom Moore mine.	Burbank and others, 1947; Belser, 1956b.
39	do	Cement Creek-Gladstone area	3	Huebnerite in pockets and in bands of quartz in base-metal sulfide veins.	Burbank and others, 1947; Belser, 1956b; Prosser, 1910.
40	do	Ruby mine	4	Huebnerite in quartz bands in base-metal sulfide vein in volcanic rocks.	Do.
41	do	Sultan Mountain area, Dora mine	3	Huebnerite in sulfide veins cutting Tertiary quartz monzonite stock.	Do.
42	San Miguel	Ophir district	3	Huebnerite in sulfide veins and in quartz stringers in vein walls; in quartz monzonite.	Burbank and others, 1947; Belser, 1956b.
43	do	Marshall creek area	4	Huebnerite in base-metal sulfides in Montana vein	Do.

purities in the chalcedony as well as ore-grade stringers of chalcedony and ferberite. In much of the ore, ferberite forms the matrix of a breccia of chalcedony or country rock, but solid seams of high-grade ferberite ore free from breccia fragments are known. The widths of the ferberite-bearing veins range widely, but the average of most of the veins mined is 6 to 12 inches.

Tungsten minerals are characteristically spotty in their distribution and the Boulder County deposits are no exception. High-grade ore may give way abruptly along strike or dip to barren quartz gangue, and conversely, barren veins may open abruptly into commercial ore. Veins only a few inches wide may contain rich ore shoots of less than 1,000 tons that contain 5–20 percent WO_3, or 5,000–20,000 units WO_3. Average ore shoots yield 2,000–3,000 units WO_3.

At the Climax molybdenum mine in Lake County, huebnerite occurs as a minor constituent disseminated in greater or lesser amounts through portions of the molybdenum ore body from which it has been recovered as a byproduct since 1948. Large blocks of ore contain 0.02 to 0.04 percent WO_3, but some as little as 0.001 percent and some as much as 0.1 percent. The Climax ore body with its very low grade, disseminated mode of occurrence of tungsten and very large tonnage is thus in marked contrast to the small, highgrade, unpredictable ore shoots of Boulder County.

The geology of the Climax area is given in the section on molybdenum, page 105 of this report.

The tungsten resource position of Colorado devolves primarily around the two major producing districts described above. Boulder County production and potential has gradually declined since the period of peak output in 1917, but continued small production will probably be possible in years to come, dependent entirely upon a favorable economic climate. Reserves in Boulder County in the past have seldom equalled a year's output and future production will require the discovery of new ore shoots—a costly and uncertain undertaking. There are no geological reasons, however, to rule out the existence of as yet undiscovered blind ore shoots, which certainly will be found when and if the incentive is great enough. Thus, Boulder County is still a potential source of tungsten, but probably at a level far below its eminent past position.

The gradual decline in production of Boulder County tungsten has been compensated for since 1948 by the development of highly successful methods for recovering huebnerite as a byproduct of the molybdenum ore at Climax. Large reserves of molybdenum ore that carry minor amounts of huebnerite, and improved recovery technique together with increased milling capacity, assure major production of tungsten for many years. Not only is Climax a leading source of current production, but it is also one of the country's leading tungsten resources for the future.

The collective resources of the numerous minor deposits in Colorado are small. Tungsten minerals of the wolframite series occur in minor deposits in the Hoosier Pass area (Nos. 11, 12 ,14) of Summit and Park Counties, in pockets in some of the base metal veins of the San Juan Mountains area (Nos. 35–43), in quartz-molybdenite veins at Gold Hill (No. 29) in Gunnison County, and in traces at a few other localities. These wolframite deposits, like those of Boulder County and Climax, are located along the Colorado mineral belt and, like deposits of other metals in the belt, apparently are related in origin to the Tertiary intrusive rocks that characterize the belt. The scheelite that has been found at numerous places in lime-silicate gneiss of the Precambrian metamorphic series has yielded little ore in the past and reserves are negligible. Deposits of this type, although wide-spread, appear to be of Precambrian age and to differ in origin from the wolframite deposit in the mineral belt. Tweto (1960) has summarized information on deposits of this kind.

The long-range resource potential of tungsten in Colorado is difficult to evaluate. Certainly the Colorado mineral belt and the Precambrian terrains are to be considered tungsten provinces in the sense that the incidence of tungsten minerals within them is well above average and the potential for new economic discoveries is higher. Tungsten, however, is notably erratic in its mode of occurence, and any long range predictions of tungsten production must take cognizance of the fact that most tungsten ore shoots are small, frequently widely spaced, and, even if high-grade, not always amenable to profitable exploitation. Nevertheless, the potential exists for future major discoveries and continued effort toward a geological understanding of the Colorado tungsten province together with continued prospecting, exploration, and technological innovation for handling lower grade ores will undoubtedly add to the already impressive record of Colorado as a major source of domestic tungsten.

VANADIUM

(By R. P. Fischer, U.S. Geological Survey, Denver, Colo.)

About 2,000 short tons of vanadium have been consumed annually in the United States in recent years. Three-quarters of this has gone into special engineering, structural, and tool steels, where it is used as an alloy to control grain size, impart toughness, and inhibit fatigue. The other principal domestic uses have been in nonferrous alloys and chemicals (Busch, 1960, 1961).

From 1907 to 1962, about 54,000 short tons of vanadium in vanadium pentoxide and other concentrates have come from vanadium mills in Colorado. This represents nearly 95 percent of total production of vanadium from domestic ores and about half of the total recorded world production. Of the total yield from Colorado mills, about 47,000 short tons of vanadium was recovered from ores mined in Colorado; the rest came from ores mined in Utah, Arizona, and New Mexico, and shipped to Colorado mills. The vanadium recovered from ores mined in Colorado has a value of about $190 million.

This vanadium has come from deposits of vanadium- and uranium-bearing sandstone. Other domestic sources consist of byproduct vanadium recovered from phosphate rock mined in Idaho and vanadium obtained from vanadate minerals mined from the oxidized zones of base- and precious-metal deposits in Arizona, Nevada, and New Mexico.

The principal foreign sources of vanadium have been a deposit of vanadium-bearing asphaltite in Peru, vanadate minerals from the oxidized zones of base-metal deposits in Africa, and vanadium-bearing iron deposits in Europe and Africa. These iron deposits and similar ones in many parts of the world contain very large resources of vanadium. Probably this type of deposit will become increasingly important as a source of vanadium in the future.

In addition to the productive vanadium-bearing sandstone deposits in Colorado, vanadium occurs in more than trace amounts in gold-telluride deposits and some iron deposits in the State. These three geologic types of deposits are described below and their distribution is shown on figure 21. Trace amounts of vanadium occur in many types of rocks; these occurrences are not described.

Most of the productive vanadium deposits in sandstone are in the Morrison Formation, and the Entrada and Navajo(?) Sandstones in western Colorado. These deposits yield ore ranging from 1 to 5 percent V_2O_5 and averaging about 1.5 percent. Ore from the Morrison Formation also averages about 0.25 percent U_3O_8 but that from the Entrada and Navajo(?) Sandstones averages only about 0.07 percent. (See table 1 for age and stratigraphic position of these formations.)

Deposits in the Morrison Formation in Colorado (chiefly Nos. 1–9, fig. 21) have yielded about 35,000 tons of vanadium; a little more than 80 percent of this has been recovered as a byproduct. From 1911 to 1923 these deposits were worked primarily for radium, a daughter product of uranium; some vanadium and a little uranium were recovered as byproducts. From 1936 through World War II these deposits were mined chiefly for vanadium, with a byproduct yield of uranium. Since 1948 these deposits have been mined for uranium, but they have yielded large supplies of byproduct vanadium. Mining was intensive during the 1950's and early 1960's. Ore production declined a little in 1963 as the mining companies began cutbacks to adjust their level of operations to the requirements of the stretch-out program of the U.S. Atomic Energy Commission.

The deposits in the Entrada and Navajo(?) Sandstones have been mined for vanadium, yielding about 12,000 tons; a little byproduct uranium has been recovered from these ores. The ore bodies at Placerville (No. 13), San Miguel County, were worked from 1909 to 1920 and again during the 1940's; the deposit on Rifle Creek (No. 15), Garfield County, was productive from 1925 to 1932 and in the 1940's and early 1950's; and the ore bodies in the Barlow Creek-Graysill Creek area (No. 12) in Dolores and San Juan Counties were mined in the 1940's and 1950's.

All of the deposits in the Morrison, Entrada, and Navajo(?) are similar in mineralogy and shape. The primary ore minerals are silicates and oxides of vanadium and uranium. The vanadium minerals mainly impregnate the sandstone, coloring the rock gray; in the Morrison Formation the uranium minerals chiefly replace fossil wood. A variety of secondary minerals, mostly uranium vanadates, form in the zone of oxidation (Weeks and Thompson, 1954). Accessory minerals consist of a sparse amount of common sulfides of iron, copper, and lead. Virtually no gangue minerals, other than those that constitute the host sandstone, are associated with these ore deposits.

The ore bodies form tabular layers that lie nearly parallel to the bedding of the host rock but do not follow the bedding in detail. These layers range from an inch to more than 20 feet in thickness, though mostly they are only a few feet thick; commonly they thicken or thin abruptly. They are irregularly shaped in plan, though they

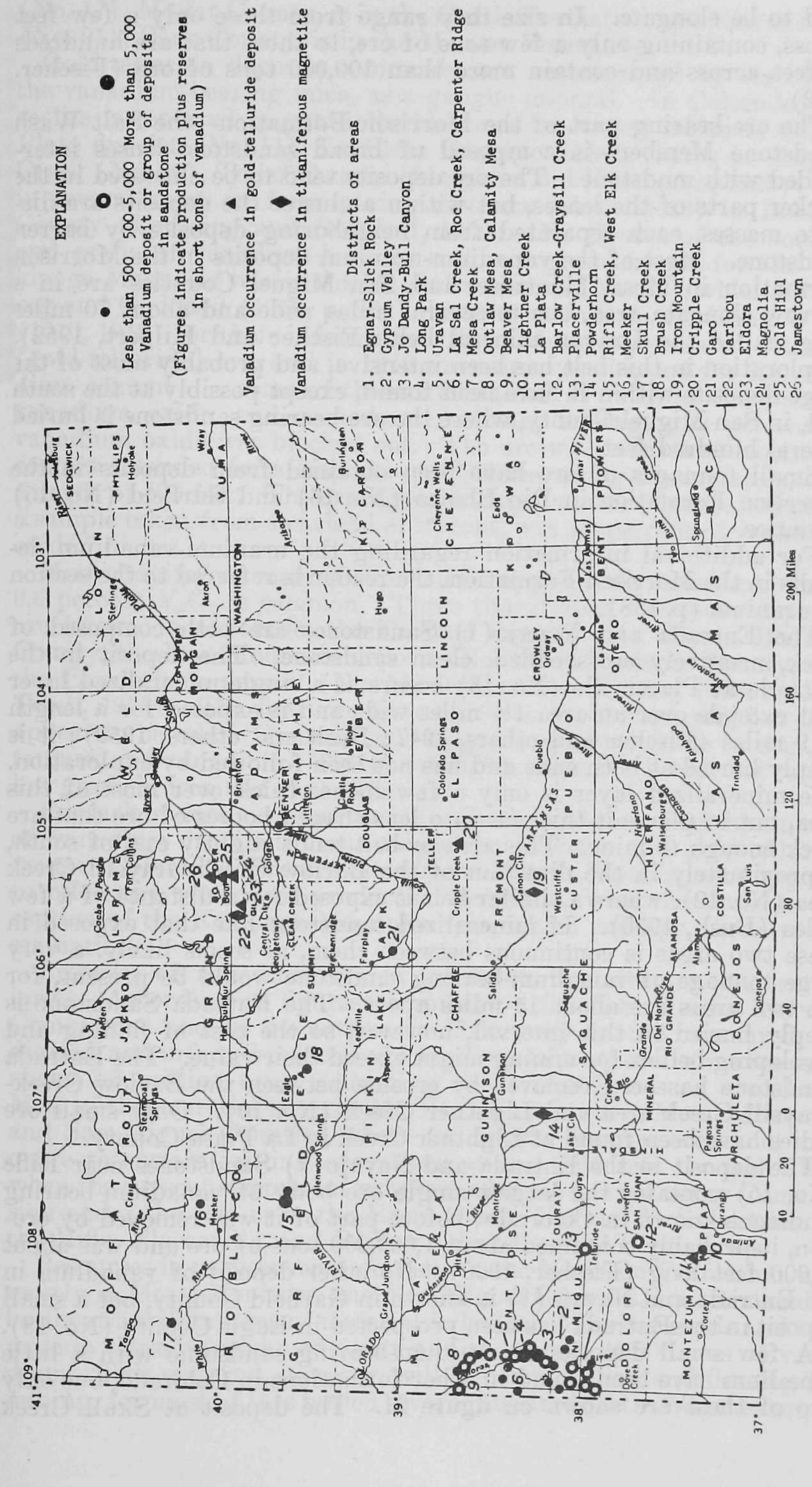

FIGURE 21.—Vanadium in Colorado.

tend to be elongate. In size they range from those only a few feet across, containing only a few tons of ore, to those that are hundreds of feet across and contain more than 100,000 tons of ore (Fischer, 1942).

The ore-bearing part of the Morrison Formation—the Salt Wash Sandstone Member—is composed of broad sandstone lenses interbedded with mudstone. The ore deposits tend to be clustered in the thicker parts of the lenses, but within a cluster the deposits are discrete masses, each separated from neighboring deposits by barren sandstone. Most of the vanadium-uranium deposits in the Morrison Formation in Mesa, Montrose, and San Miguel Counties are in a narrow elongate area, one to several miles wide and about 70 miles long, called the Uravan mineral belt (Fischer and Hilpert, 1952). Exploration in this belt has been intensive, and probably most of the large deposits within it have been found, except possibly at the south end, in San Miguel County, where the ore-bearing sandstone is buried several hundred feet.

Small tonnages of ore have been obtained from deposits in the Morrison Formation in Rio Blanco (No. 16) and Garfield (No. 15) Counties.

For additional information regarding the uranium-vanadium deposits in the Morrison Formation, the reader is referred to the section on uranium (p. 138).

The Entrada and Navajo(?) Sandstones are both composed of thick, massively crossbedded, clean sandstone. The deposit in the Entrada at Placerville (No. 13) occurs as a single mineralized layer that extends over an area 1½ miles wide and is exposed for a length of 9 miles (Fischer and others, 1947; Bush and others, 1959); it is deeply buried at both ends and has not been followed by exploration. The mineralized layer is only a few inches thick over most of this area, but in places it thickens into lens-shaped bodies of ore that are thick enough to mine. This area or belt tends slightly east of south, approximately in the direction of the Barlow Creek-Graysill Creek area (No. 12), where a similar belt is exposed for a distance of a few miles (Bush, 1956). If mineralized sandstone like that exposed in these two areas is continuous between them, as seems likely, a very large tonnage of vanadium-bearing sandstone would be present, for the two areas are about 15 miles apart. The Entrada Sandstone is deeply buried in this interval, however, so the cost of finding and developing bodies for mining might exceed their value. The Entrada Sandstone has been removed by erosion between the Barlow Creek-Graysill Creek area and Lightner Creek (No. 10). Only small ore bodies have been found at Lightner Creek in La Plata County.

The deposit in the Entrada and Navajo(?) Sandstones near Rifle (No. 15) contains the largest single ore body of vanadium-bearing sandstone known in Colorado; before part of it was removed by erosion, it probably contained about 1,000,000 tons of ore and was about 10,000 feet long (Fischer, 1960). No other deposit of vanadium in the Entrada and Navajo(?) is known in Garfield County, but a small deposit in the Entrada has been prospected in Eagle County (No. 18).

A few small deposits of uranium-bearing sandstone with a little vanadium have been found in other formations in Colorado, but only two of these are shown on figure 21. The deposit at Skull Creek

(No. 17), Moffat County, is in the Curtis Formation and that at Garo (No. 21), Park County, is in the Maroon Formation.

Gold-telluride deposits commonly are accompanied by roscoelite, the vanadium-bearing mica, as a gangue mineral. In Colorado, roscoelite is reported in gold-telluride veins in several mines in the La Plata district (No. 11), La Plata County (Eckel, 1949); at Cripple Creek (No. 20), Teller County (Loughlin and Koschman, 1935); and in several veins in four mining districts (Nos. 23–26) in Boulder County (Lovering and Goddard, 1950). No figures of the amount and grade of vanadium-bearing rock are given except for the Kekionga-Magnolia vein in the Magnolia district (No. 24), which Lovering and Goddard (1950, p. 234) describe as follows, crediting Wood (1910, 1912) for their information: "Vanadium is associated with the [gold-telluride] ore, and in 1910 some ore was shipped for its vanadium content . . . some of the ore contained as much as 6.28 percent vanadium oxide, and a moderate tonnage averaging 2 percent of vanadium oxide was blocked out. The ore with a marked vanadium content extended for a distance of 1,500 feet along the surface and to a depth of 400 feet. The average of a large number of tests, including a sample taken from a carload of 20 tons, was 4.3 percent of vanadium oxide."

Most titaniferous magnetities contain appreciable vanadium; about 0.5 percent V_2O_5 is common. Three titaniferous magnetite deposits are known in Colorado, the Caribou deposit (No. 22) in Boulder County, the Iron Mountain deposit (No. 19) in Fremont County, and the Powderhorn deposit (No. 14) in Gunnison County (Harrer and Tesch, 1959). The first two have not been much explored, but they appear to be relatively small and only of moderate grade in iron, titanium, and vanadium. The Powderhorn deposit is larger but rather low grade in iron and vanadium.

For lack of data, no quantitative estimate can be made of the amount of vanadium in titaniferous magnetite deposits and gold-telluride veins in Colorado. From what is know of these deposits, none appears to offer any vanadium production potential, with the possible exception of the Kekionga-Magnolia vein, which perhaps merits re-examination.

Reserves of vanadium ore in sandstone deposits are moderately large. According to figures compiled by the U.S. Atomic Energy Commission and by the author, as of January 1, 1963, measured, indicated, and inferred reserves of vanadium-bearing sandstone ore total about 3.3 million tons, containing about 26,500 tons of vanadium. Most of this material is in the Morrison Formation in Mesa, Montrose, and San Miguel Counties, where the known reserves are about adequate to sustain milling operations at the 1964 rate through 1970, when the present stretch-out program of the Atomic Energy Commission ends; the rest is in the Entrada and Navajo(?) Sandstones in the Rifle, Placerville, and Barlow Creek-Graysill Creek areas.

Resources in undiscovered deposits in the Morrison Formation, also mostly in Mesa, Montrose, and San Miguel Counties, are estimated to be about 5 million tons of material in bodies of similar grade and tonnage to those being mined today and to contain 40,000 tons of vanadium. This material, however, will be costly to find and develop for mining, for most of it is buried several hundred feet. Whether or not it is found and mined will depend largely upon the demand and price for uranium in the future.

In the Entrada Sandstone in the Placerville and Barlow Creek-Graysill Creek areas and the intervening ground, resources in undiscovered bodies like those that have been mined in these areas probably exceed 10 million tons of rock and contain at least 80,000 tons of vanadium. Probably very little of this material can be found and mined at a profit under prevailing economic conditions.

No resources of vanadium-bearing sandstone in other parts of the State are estimated; for practical purposes they are judged to be negligible.

MISCELLANEOUS METALS

BERYLLIUM

(By W. R. Griffitts, U.S. Geological Survey, Denver, Colo.)

Beryllium is a light metal that has many varied uses as a pure or alloyed metal and in compounds. For many years more than half of the total supply has been added to copper to make a strong, hard, fatigue-resistant alloy. This alloy approaches steel in strength and hardness, but retains the electrical and thermal conductivity of copper, and lacks steel's tendency to spark during impact or abrasion and to rust. Beryllium-copper alloy is much used in springs that carry electricity or are subjected to vibration; it is also used in special tools. Alloys with nickel are also hard and strong, and they are used in dies for extruding aluminum and other materials. Alloys with aluminum and magnesium have been used to a small extent and may become increasingly important. Beryllium metal itself was used only for a few special laboratory instruments until the onset of the atomic energy and space programs. Beryllium and its oxide are excellent moderators and reflectors of neutrons in reactors and the metal has been used as a canning metal for fuel units of reactors. Although the high cost of the metal has caused other materials to be used for these purposes, several special purpose reactors have beryllium as an important component. Beryllium is used in modern airborne and marine inertial guidance mechanisms because of its lightness, rigidity, and dimensional stability. Larger amounts are used as connecting rings between stages of Minuteman missiles and in heat shields of space capsules, but the unfortunate brittleness of the metal has prevented large-scale use of it as a structural material in manned aircraft and rockets. This has not prevented the use of beryllium in brake discs and other parts of aircraft where brittleness is not important. A speculative use of the metal is as missile fuel or as a component of explosives.

Beryllium is consumed in much smaller amounts than many other metals. The consumption of ore by the United States increased from 1,013 tons in 1946 to an all-time high of only 9,692 tons in 1960.

Adequate and increasing supplies of beryllium ore have been maintained by importing the mineral beryl, which contains 10 to 14 percent BeO. This high-grade ore is obtained mainly from pegmatites in South Africa, Brazil, Argentina, India, and Australia. Only about 6 percent of the total supply of ore is from domestic deposits. All the productive pegmatitic beryllium deposits are small; no more than 15 in the United States have yielded as much as 100 tons of ore and the largest mine in the world has produced a total of less than 4,000 tons.

The low productivity of domestic pegmatites has caused attention to be given since 1950 to non-pegmatitic veins and other hydrothermal deposits. The first vein deposit in the United States to be mined for beryllium is at the Boomer mine in Park County, Colo. Other hydrothermal deposits have been found elsewhere in Colorado and in other Western States. A group of especially large deposits is now being developed in the Spor Mountain area, Utah (Staatz, 1963, Griffitts, 1964); when in production, the additional supply of beryllium may well stimulate a marked growth of the entire beryllium industry.

Pegmatite deposits constitute a readily recognized type that are described in the section on pegmatite minerals. Non-pegmatitic beryllium deposits, by contrast, are found in almost all genetic types of hydrothermal and vein deposits. Most of the economically interesting deposits known in Colorado are rather coarse-grained high temperature or hypothermal veins. On the other hand, the helvite-bearing veins in San Juan County are a lower-temperature type, and hot springs near Ouray are depositing beryllium-bearing tufa at even lower temperature. The last two types of deposits are only of academic interest. Most of the known deposits of beryl-bearing pegmatites and of beryllium-bearing veins in Colorado are shown on figure 22.

The non-pegmatitic beryllium deposits of Colorado are principally in veins at and near the Boomer mine, Badger Flats area (No. 8, fig. 22), Park County, in veins and crystal-lined cavities at Mt. Antero (No. 10), Chaffee County, and in veins and crystal-lined cavities in and near the St. Peters Dome-Mt. Rosa area (No. 7), El Paso County. The deposits of Park and El Paso Counties are of Precambrian age and are related to granite of the Pikes Peak batholith. Those in Chaffee County are of Tertiary age.

The Badger Flats area (No. 8) is near the southwest flank of the Pikes Peak granite batholith. Beryllium occurs principally in four parts of the area, but most of the beryllium produced there has come from the Boomer mine.

The Boomer mine was opened in the 1890's in a search for silver and is reported to have yielded a carload of lead-silver ore. The mine was subsequently abandoned and remained idle for many years, being prospected briefly for molybdenum during World War I and for uranium in the early 1950's. Beryl crystals were noted on the mine dump and in old workings, and beryllium mining began in 1956.

The Boomer mine is at the southern edge of a small intrusive mass of fine-grained granite. The veins at this mine cut both the granite and the metamorphic host rocks of the granite. The first beryl ore found was in veins in metamorphic rock and was in bodies or shoots several tens of feet in length and as much as 8 feet in width. In this ore, beryl was in matted crystals and granite-textured aggregates and was associated with quartz, fluorite, white mica, galena, and small amounts of copper minerals, arsenopyrite, and siderite. Some of the beryl crystals were altered to mixtures of bertrandite (a hydrated beryllium silicate) and sericite. Ore bodies subsequently found in the granite were not as clearly localized along fractures as were the veins in metamorphic rocks. They show a texture similar to that of granite and consist of beryl and bertrandite, which is dominant in

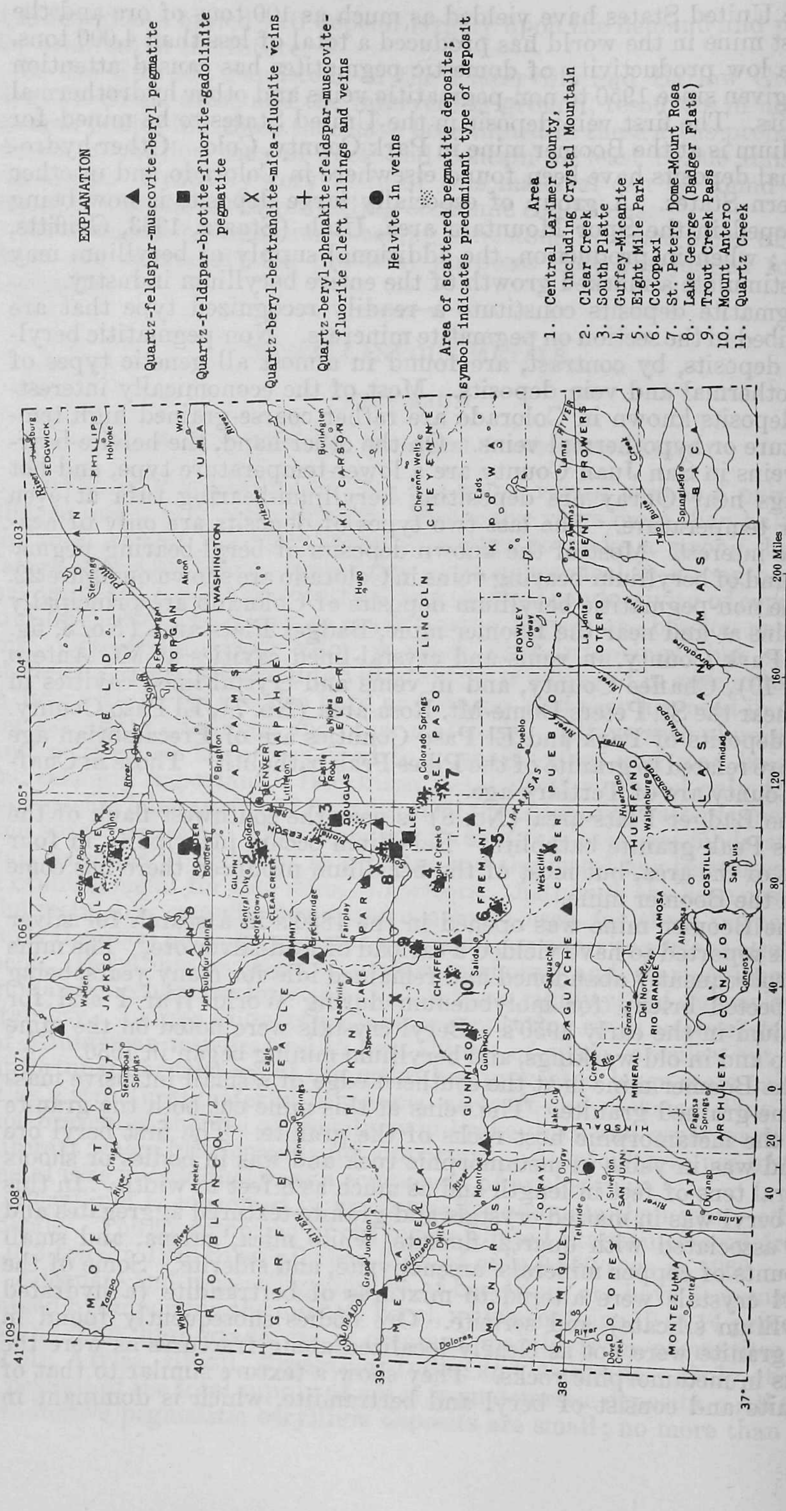

FIGURE 22.—Beryllium in Colorado.

places, accompanied by quartz, white mica, and fluorite. The granite and metamorphic rocks in the mine have been altered to greisen, a gray to white rock composed mainly of quartz and mica. Fine-grained topaz, accompanied by gray quartz, forms white bodies—locally spotted with tiny wolframite crystals—a foot or more across in the mica-rich greisen.

Longer veins are found in granitic gneiss about a mile east of the Boomer mine. They are largely quartz, with separate shoots of beryl, galena, and wolframite and accessory topaz, fluorite and cassiterite. Though longer, these veins have yielded less beryllium ore than the shorter and richer veins at the Boomer mine. Other deposits of beryllium minerals are known as in Redskin Gulch, about 2 miles northeast of the Boomer mine, and also near the town of Tarryall, about 3 miles north of the Boomer mine.

The Mt. Antero area (No. 10) has both quartz-rich and feldspathic veins that contain beryl and that cut granite, irregularly shaped bodies of granite containing beryl, and cavities in granite that are lined with crystals of beryl, bertrandite, and phenakite (beryllium silicate). Other minerals that occur with the beryl include siderite, fluorite, molybdenite, rutile, brannerite, topaz, apatite, and magnetite (Adams, 1953).

The veins in granite in the Mt. Rosa-St. Peter's Dome area (No. 7) have been known to mineral collectors for many decades, but the presence in them of beryl and fine-grained bertrandite was discovered only within the last decade. The bertrandite is in very fine-grained brick-red aggregates of quartz and hematite, which are with white vein quartz and many other minerals, including minerals of niobium, thorium, fluorine, and the rare earths.

Beryllium minerals have been found in pegmatites in many parts of Colorado but they have been mined principally in Larimer (No. 1), Jefferson (No. 2), Fremont (No. 5 and 6), and Gunnison (No. 11) Counties.

Two distinct types of pegmatite found in Colorado are described in the section on pegmatite minerals. The fluorite-bearing pegmatites in the Pikes Peak batholith (No. 3) contain very little beryl but do contain rare-earth minerals, including gadolinite, an yttrium-beryllium-iron silicate, which has been mined in several places. The fluorite-free pegmatites found in the other pegmatite districts commonly contain beryl but seldom contain gadolinite. Beryl forms clusters of crystals in the inner parts of pegmatite bodies, commonly along or near the margins of the quartz cores. Single clusters of crystals may yield a few pounds to, exceptionally, a few tons of beryl. These clusters may be separated from one another by thicknesses of barren pegmatite ranging from several yards to several hundred feet. Hence, mining of pegmatite beryl tends to be a process of removing only crystals that crop out, or of removing beryl crystals encountered while mining feldspar, mica, or lithium minerals. Few if any zones in Colorado pegmatites are rich enough in beryl to permit mining of barren rock between beryl concentrations. The small size of individual concentrations of beryllium minerals contrasts sharply with the larger size of the ore bodies in the Boomer mine and with the large size of some pegmatite bodies. Several pegmatites north of Clear Creek in Jefferson County (No. 2) contain chrysoberyl (beryl-

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lium aluminate) as well as beryl, but they are otherwise similar to the quartz-feldspar-muscovite-beryl pegmatites found elsewhere.

The presence of several thousand tons of ore may be inferred in veins in an area of a few acres near the Boomer mine. Similar amounts may exist in the veins of the Mt. Rosa-St. Peter's Dome area, but the latter deposits have not yet been demonstrated to be economically minable. Smaller amounts might be found in the Mt. Antero area.

It is difficult either to estimate accurately the beryl resources in Colorado pegmatites or to point out the location of the remaining deposits. Nevertheless, unexplored pegmatite bodies with exposed beryl concentrations undoubtedly remain in the pegmatite districts shown by triangular symbols on the map. These districts therefore may produce several tens of tons of beryl annually for 10 or more years.

NIOBIUM AND TANTALUM

(By R. L. Parker, U.S. Geological Survey, Denver, Colo.)

Niobium (columbium) and tantalum are two refractory metals that have become increasingly important in modern technology. They have certain physical properties which make them useful in electronic, nuclear, chemical, and high-temperature metallurgical applications. Both metals have important uses in the manufacture of vacuum tube elements, cryotrons, corrosive-resistant vessels and laboratory ware, high-temperature nonferrous alloys, and stainless steel of special properties. Niobium has special use as a container for nuclear fuel. Tantalum has special application in capacitors, rectifiers, and surgical implants and as a catalyst in the manufacture of butadiene rubber (Miller, 1959; Barton, 1962).

The United States is the world's largest consumer of niobium and tantalum, but it is a small producer (Barton, 1962). Except for the period 1956–59, domestic production of these metals constituted an exceedingly minor fraction of the domestic consumption (fig. 23).

In 1958 domestic production, which came principally from Idaho placers, reached an all time high of nearly 12 percent of the domestic consumption, but since 1959 domestic production has been negligible. In 1962 imports of niobium and tantalum concentrates were about 6,234,000 pounds.

Colorado, with a total production close to 20,000 lbs. of niobium-tantalum concentrates, ranks fourth among the states as a producer of these elements. Even so, Colorado has produced only a little more than one percent of the nation's total production, which in turn is an exceedingly small fraction of the nation's consumption (Barton, 1962).

Niobium and tantalum do not occur in nature as free metals but are found commonly together as constituents of minerals that are compounds of niobium, tantalum, and oxygen, with minor amounts of titanium, tungsten, iron, manganese, rare earths, uranium, thorium, sodium, calcium and others. The most important ore minerals are: columbite-tantalite, $(Fe,Mn)(Nb,Ta)_2O_6$; pyrochlore, $NaCaNb_2O_6F$; microlite, $(Na, Ca)_2Ta_2O_6(O, OH, F)$; euxenite, $(Y, Ca, Ce, U, Th)(Nb, Ta, Ti)_2O_6$; samarskite, $(Y, Er, Ce, U, Fe, Th)(Nb, Ta)_4O_6$; and fergusonite, $(Y, Er, Ce, Fe)(Nb, Ta, Ti)O_4$. Niobium and tantalum are also contained in various amounts in titanium minerals—sphene, rutile (ilmenorutile), and ilmenite (Palache and others, 1944).

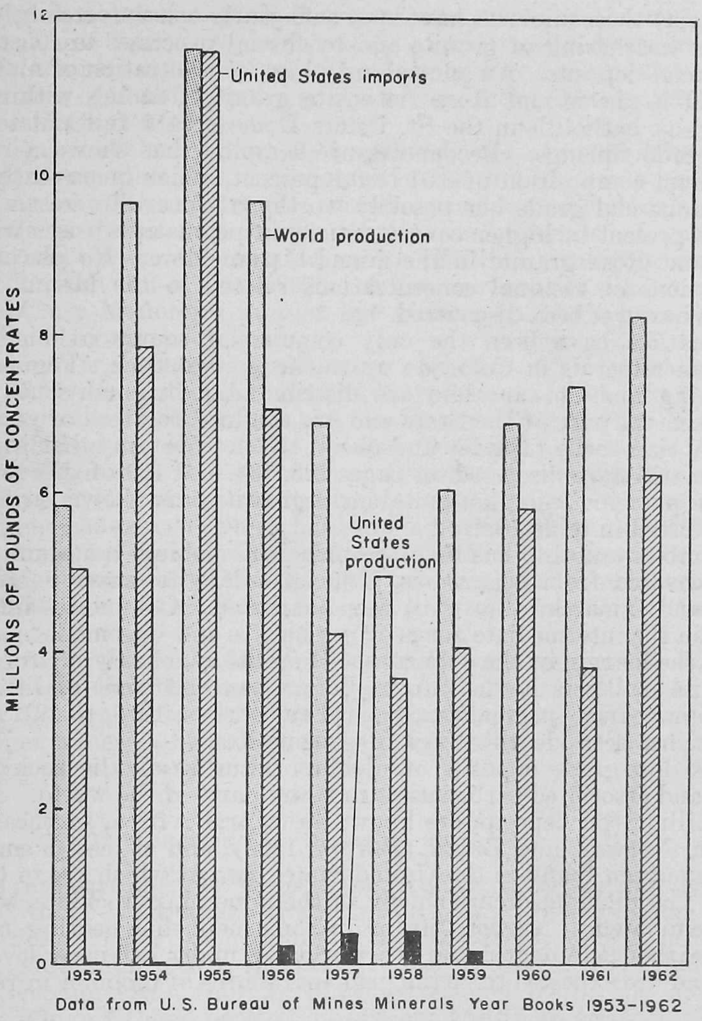

FIGURE 23.—World and United States production and United States imports of niobium and tantalum concentrates, 1953–62 (data from U.S. Bureau of Mines Minerals Yearbooks 1953–62).

Niobium is not an exceedingly rare element in the earth's crust; it is about as abundant as cobalt and more plentiful than lead. Tantalum is much rarer than niobium, but still more abundant than antimony, silver, or gold. Compared with many other valuable elements whose crustal abundance is less than niobium or tantalum and which tend to concentrate in discrete ore bodies, rich deposits of niobium and particularly tantalum are scarce. They are largely restricted to granitic rocks and pegmatites, alkalic rock complexes and carbonatites, and placers derived from these rocks.

Some granitic rocks contain disseminated niobium-tantalum minerals as primary rock constituents, and in some places (for example in Nigeria) these minerals have been sufficiently concentrated by deep residual weathering of granite and by fluvial processes to constitute commercial deposits. An anomalously high concentration of niobium is found in the Mount Rosa riebeckite granite that lies within the Pikes Peak batholith in the St. Peters Dome area a few miles west of Colorado Springs. Reconnaissance sampling has shown a range in niobium composition of 0.01 to 0.1 percent, which is currently below commercial grade but possibly worthy of future interest. Niobium is present in higher concentrations in pegmatitic lenses within the Mount Rosa granite in the mineral, pyrochlore. No placer accumulations or residual concentrations related to the Mount Rosa granite have yet been discovered.

Pegmatites have been the only commercial source of niobium-tantalum minerals in Colorado up to the present time. Pegmatites containing niobium-tantalum are distributed in a north-south belt in the central part of the State and are confined to areas of exposed Precambrian rocks (Hanley and ohers, 1950). Certain other aspects of pegmatites are discussed on pages 128, 134, and 169 of this report, and the principal niobium-tantalum pegmatites are shown on figure 24 and listed in table 18.

Columbite-tantalite has been the principal niobium-tantalum mineral recovered from pegmatites, although microlite, euxenite, fergusonite and samarskite have all been marketed. Columbite-tantalite occurs in the intermediate zones of pegmatites and in some it is localized at the margin of the core zone. Microlite commonly occurs with lepidolite in layers in the intermediate zones, and cores of lithium-beryllium-bearing pegmatites (Staatz and Trites, 1955, p. 42). Pyrochlore has been identified in a few pegmatites.

Large low-grade deposits of niobium occur in alkalic rock complexes and associated carbonatites in many parts of the world. Some multimillion ton deposits are known in central Africa, southeastern Canada, Norway, and Brazil (Barton, 1962), and at least 5 smaller ones have been found in the United States, two of which are in Colorado. The niobium occurs chiefly in the mineral, pyrochlore, which is disseminated in carbonatite or in some nepheline-bearing rocks. Many carbonatite deposits in the world are under extensve development and are expected to be the principal source of niobium in future years.

In Colorado alkalic rock complexes containing niobium occur at Powderhorn, Gunnison County (No. 37, fig. 24) and near Westcliffe in Custer and Fremont Counties (No. 42, fig. 25). The Powderhorn complex (Olson and Wallace, 1956), consists of a central carbonatite core that has a basal area of 1½ square miles. The carbonatite is surrounded by several square miles of alkalic rocks, principally pyroxenite, nepheline- and melilite-bearing rocks, and fenites (syenitic rocks formed as a replacement of the enclosing granite) that grade outward into granite. The niobium mineral, pyrochlore, is dispersed in the carbonatite as well as concentrated in certain zones in the carbonatite and constitutes a large potential source of niobium.

Two genetically related alkalic complexes have been discovered in the northern Wet Mountains, Fremont and Custer Counties (Parker and Hildebrand 1963). The largest complex, centered about McClure Mountain, about 13 miles north of Westcliffe, occupies an area of about 20 square miles and is composed of gabbro-pyroxenite, biotite hornblende syenite, nepheline syenite, and nepheline-bearing mafic rocks. These rock types are roughly concentrically distributed. A smaller complex composed mostly of pyroxenite and gabbro underlies an area of about 2 square miles at Gem Park about 5 miles southwest of McClure Mountain.

Carbonatite dikes and small irregular bodies are abundant in the Gem Park complex, and a few occur in the granitic rocks bordering the complex. The carbonatites contain pyrochlore and other niobium minerals as well as rare earth and titanium minerals. Locally the gabbro and pyroxenite contain lueshite ($NaNbO_3$) and thorium minerals (Parker and others, 1962). A few carbonatite dikes occur in the McClure Mountain complex but niobium minerals have not yet been found in them.

Colorado is a potential producer of niobium. The pyrochlore deposit at Powderhorn is one of the largest known concentrations of niobium in the United States. According to Grogan (1960), exploration of the E. I. DuPont de Nemours & Co., "has indicated an ore reserve of considerably more than 100,000 tons of Nb_2O_5 in rock averaging at least 0.25 percent Nb_2O_5. An impressive amount of ore averaging 0.35 percent Nb_2O_5 has been indicated in areas large enough to be mined by open cutting, and ore of still higher grade occurs in significant amounts." Resources of niobium in the northern Wet Mountains are unknown but are presently under study by the U.S. Geological Survey.

Pegmatites in Colorado, because of their relatively small size and the sporadic distribution of niobium and other minerals within them, do not constitute a large resource of niobium. Historically, niobium-tantalum minerals have been largely byproducts in the mining of feldspar, mica, or beryl.

RARE EARTHS

(By J. W. Adams, U.S. Geological Survey, Denver, Colo.)

The rare-earth metals comprise the 15 elements having atomic numbers 57 to 71—lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). One of these, promethium, is not known to occur in nature. Yttrium (Y), with atomic number 39, is also classed with the rare earths because of its chemical similarities and geochemical affinities.

The first seven elements listed above (La through Eu) are included in the cerium group of rare earths, so-called because cerium is their most abundant member. The remaining eight elements (Gd through Lu) together with yttrium are called the yttrium group. The two groups are also referred to respectively as the "light" and "heavy" rare earths.

The properties of the members of the two groups of rare earths are sufficiently distinct to cause one group to predominate over the other in most minerals, even though all or nearly all are ordinarily present (Olson and Adams, 1962). The rare earths have many industrial applications such as in the steel industry, non-ferrous alloys, glass manufacture and glass polishing, sparking alloys, and carbon electrodes for arc lights and projection lamps. Rare-earth requirements are, however, relatively small compared to many other metals, domestic consumption in 1958 being only about 1,600 short tons of rare-earth oxides (Baroch, 1960, p. 687). The rare-earth industry is developed almost entirely around the cerium group elements, primarily cerium, lanthanum, praseodymium, and neodymium. Although considerable research is being directed to finding uses for yttrium and the heavy rare-earth elements the current demand for these is small.

The rare earths are found in a large number of minerals, but only a few of these are found in sufficient concentration to be used as ores. The most widely used source mineral is monazite, a rare-earth phosphate, but important deposits of bastnaesite, a rare-earth fluorcarbonate, are currently being mined at Mountain Pass, Calif. Both monazite and bastnaesite contain dominently cerium group elements. Minerals in which the yttrium group predominate include xenotime, an yttrium phosphate, and euxenite, a multiple oxide of yttrium, niobium, and titanium.

Commercial monazite commonly contains 55 to 60 percent combined rare-earth oxides and between 3 to 10 percent thorium oxide (Kelly, 1962b, p. 5), so that monazite is used not only for its rare-earth content, but as the principal ore mineral of thorium (see Thorium chapter) as well. This results in a complex interdependence between the production of thorium and the rare earths.

The marketing of ores of the rare earths is difficult as there is no established market comparable to those of the more widely used metals, and prices of their ores are generally determined by negotiation between buyer and seller. Detailed information on the economic factors of rare earths is given by Kelly (1962b).

Rare-earth-bearing minerals have been found at a large number of localities in Colorado (fig. 24) representing several different geologic environments, including pegmatites, vein deposits, carbonatites, igneous and metamorphic rocks, and ancient and modern placers.

Pegmatites are a type of igneous rock generally considered to represent the crystallization product of residual magmatic fluids and as such may contain concentrations of a number of rare elements whose properties inhibited their entry into the minerals of earlier formed rocks. The rare earths are among these elements and appear in pegmatites in a number of mineral species in which they are the major constituent as well as being a vicarious constituent of several others.

In Colorado pegmatites, the most common rare-earth-bearing minerals are probably allanite, a complex silicate of calcium, iron, aluminum, and the cerium group rare earths, monazite and euxenite. Rare-earth-bearing fluorite also is abundant in some pegmatites. In addition to these, many other species have been reported (Haynes, 1960; Eckel, 1961) some of which have been sufficiently abundant in individual deposits to be of economic interest.

In zoned pegmatites, those in which distinctly different mineralogical units are present, rare-earth minerals may be concentrated in certain zones and be rare or absent in others. They also may be present in fracture-controlled bodies or irregular replacement units unrelated to the zonal pattern. In unzoned pegmatites, any rare-earth minerals that may be present will be distributed erratically throughout the body. Concentrations of rare-earth minerals in pegmatites are therefore largely restricted to the zoned type, where large single crystals occur in sufficient abundance to encourage their recovery when the deposit is being mined for other commodities such as feldspar, quartz, beryl, or mica. This has been common practice in Colorado and else-

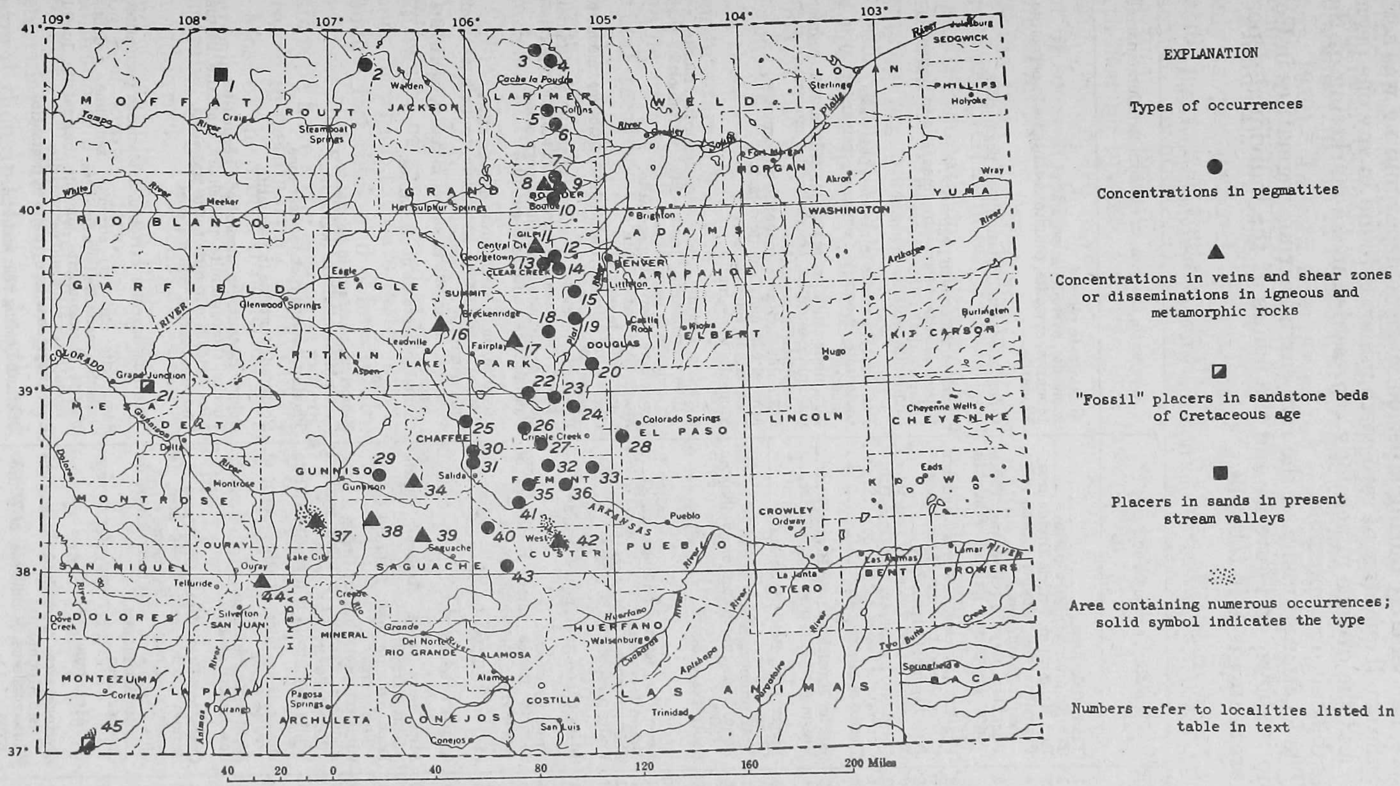

FIGURE 24.—Rare-earth, thorium, and niobium-tantalum localities.

where, particularly during a period when feldspar mining was active, but the small quantity of rare-earth minerals found in any one pegmatite and the diverse mineralogy represented make marketing of these ores difficult or impossible.

The location of many of the rare-earth-bearing pegmatites in Colorado is shown on figure 24 and the names of the individual deposits or areas are given in table 18.

TABLE 18.—*Rare-earth, thorium, and niobium-tantalum occurrences* [1]

Map No.	Locality, as shown on fig. 24	Rare earth, thorium, or niobium-tantalum minerals
1	Timberlake area	Monazite in placers.
2	Temple prospect, Mica Basin	Monazite, cyrtolite in pegmatite.
3	Red Head claim, Prairie Divide area	Monazite, cyrtolite, columbite-tantalite in pegmatite.
4	Pegmatite near Copper Queen mine, Prairie Divide area.	Monazite.
5	Buckhorn, Crystal Silica, and Tantalum prospects, Crystal Mountain area.	Columbite-tantalite, tantalite in pegmatites.
6	Hide-above prospect, Storm Mountain	Thorium minerals in pegmatite.
7	Cerite prospects, north of Jamestown	Cerite, allanite, bastnaesite, monazite in pegmatite.
8	Blue Jay mine, Jamestown	Uranothorite in fluorite deposit.
9	New Girl prospects, east of Jamestown	Columbite-tantalite in pegmatite.
10	Beryl No. 1 prospect, near Gold Hill	Do.
11	Central City area	Xenotime, monazite in metamorphic rocks.
12	Roscoe area, Clear Creek	Gadolinite, monazite, xenotime, samarskite(?) in pegmatite.
13	Beaver Brook area near Bergen Park	Columbite-tantalite, monazite, gadolinite in pegmatite.
14	Burroughs mine, near Bergen Park	Columbite-tantalite, euxenite(?), monazite, allanite, xenotime in pegmatite.
15	Bigger mine, Bald Mountain	Columbite-tantalite, monazite in pegmatite.
16	Climax mine	Monazite in molybdenite deposit.
17	K-W prospect, near Tarryall	Monazite in vein deposit.
18	Lone Lode, northwest of Wellington Lake.	Monazite in pegmatite.
19	South Platte district	Cyrtolite, allanite, gadolinite, monazite, thorite, xenotime, fergusonite, bastnaesite, yttrofluorite, yttrian synchisite in pegmatites.
20	Lone Pine, Rampart Range	Pyrochlore, thorite in pegmatite.
21	Grand Mesa area	Monazite in fossil placer.
22	Shore prospect, Wilkerson Pass	Euxenite(?) in pegmatite.
23	Teller prospect, Lake George	Gadolinite, yttrofluorite, allanite, xenotime, monazite in pegmatite.
24	Black Cloud mine, near Florissant	Fluocerite, monazite, allanite, samarskite, yttrotantalite, thorite, xenotime, fergusonite, gadolinite in pegmatite.
25	Trout Creek area	Euxenite, allanite, monazite in pegmatites.
26	Meyers Ranch mine, northwest of Guffey.	Columbite-tantalite in pegmatite.
27	Guffey area	Euxenite, monazite, allanite in pegmatites.
28	St. Peters Dome area	Thorite, bastnaesite, pyrochlore, columbite-tantalite, niobian rutile in pegmatites.
29	Quartz Creek district	Microlite, columbite-tantalite, monazite, samarskite in pegmatites.
30	Mica-Beryl mine, Railroad Gulch, Turret area.	Columbite-tantalite in pegmatites.
31	Rock King prospect, Railroad Gulch, Turret area.	Do.
32	Olhio prospect, Currant Creek	Xenotime, monazite in pegmatite.
33	Phantom Canyon, 2 miles west of Eightmile Creek.	Columbite-tantalite in pegmatite.
34	White Pine area, 1 mile south of White Pine.	Thorium-bearing rock in shear zone.
35	Devils Hole mine, 5 miles north of Texas Creek.	Columbite-tantalite in pegmatite.
36	Eight Mile Park area	Columbite-tantalite, monazite in pegmatites.
37	Powderhorn area	Thorite, thorogummite, pyrochlore, monazite, bastnaesite, synchisite in carbonatite and veins.
38	Cochetopa Creek-Razor Creek area	Thorium-bearing vein material.
39	Barium Lode, Jacks Creek area, 14 miles northwest of Saguache.	Do.
40	Villa Grove area, west flank Sangre de Cristo Mountains.	Xenotime, euxenite, cyrtolite, monazite in pegmatites.
41	Cotopaxi area	Samarskite and (or) euxenite, xenotime, gadolinite, allanite, monazite in pegmatites.
42	Wet Mountains area	Thorite, thorogummite, ancylite, bastnaesite, lueshite, monazite in veins and carbonatite.
43	Crestone area, west flank Sangre de Cristo Mountains.	Euxenite, monazite, cyrtolite in pegmatite.
44	Whitecross area, ¾ mile east of Whitecross.	Thorium-bearing vein material.
45	San Juan Basin, south of Cortez	Monazite in fossil placers.

[1] Data largely from Olson and Adams (1962), and Parker (1963).

The known occurrences of rare earths in vein deposits in Colorado are largely in the alkalic rock areas near Powderhorn (No. 37, fig. 25) in Gunnison County (Olson and Wallace, 1956) and in the Wet Mountains (No. 42) in Custer and Fremont Counties (Christman and others, 1959). In both these areas the rare earths occur in thorite-bearing veins, mineralized shear zones, and carbonatite bodies. Rare-earth minerals are obscure in these deposits and their presence commonly is best detected by analytical methods. Rare-earth-bearing apatite, however, is abundant in the Powderhorn area, and bastnaesite, synchisite, xenotime (?), and cerite (?) have also been noted (Olson and Wallace, 1956, p. 702). In the Wet Mountains deposits, rare-earth-bearing apatite, ancylite, and bastnaesite (Parker and Hildebrand, 1963, p. 10) have been found, but much of the rare-earth content of some deposits may be contained in thorite and in yet unrecognized minerals.

Aside from their occurrence in pegmatites and carbonatites, rare earths are present in other igneous rocks, notably granites and rocks of alkalic composition. Although local concentrations of recognizable rare-earth minerals do occur in such rocks, most commonly the elements are present in the form of very small dispersed crystals of such accessory minerals as monazite, xenotime, allanite, or rare-earth-bearing apatite or sphene. Allanite is relatively abundant in some granites such as in parts of the Pikes Peak and Boulder Creek batholiths. Some of the allanite in the Pikes Peak Granite has been altered to bastnaesite (Adams and Young, 1961).

In these rocks, however, the quantities of the individual rare-earth elements rarely will exceed a few hundred parts per million, and their recovery would be feasible only if other valuable minerals warranted mining and milling of the rock. An example of this is the experimental recovery of monazite from the molybdenite ore at Climax (No. 16), Lake County (p. 105). Although monazite forms only 0.005 percent of the rock (Arkansas-White-Red River Basins Inter-Agency Committee, 1955, p. 110) a substantial quantity could be produced if the demand for the mineral becomes greater.

Concentrations of rare-earth minerals in metamorphic rocks have been found in Gilpin County in the Central City district (No. 11) (Young and Sims, 1961) where both xenotime and monazite occur as aggregates of sand-sized crystals in migmatized biotite gneiss. The zones in which the rare-earth minerals are found are a maximum of about 5 feet thick and a few hundred feet long and contain about 1 to 5 percent by volume combined xenotime and monazite. Deposits of this type have some economic potential. Similar occurrences may be present in metamorphic terrain in many other areas in the State.

Most of the world production of rare earths has come from placer deposits in which monazite and other heavy minerals have been concentrated in sands formed by the weathering of igneous and metamorphic rocks. Beaches along the coasts of Brazil, India, and Florida, and stream placers in Idaho and in the southeastern states are among the best known deposits of this type. Some sedimentary rocks in Colorado and other western states contain placer deposits that were formed along ancient shores of retreating seas. These placers are lenticular bodies that vary greatly in size, but may be as much as several thousand feet in length and several hundred feet in width.

They are weakly radioactive and contain monazite, ilmenite, zircon, and other heavy minerals derived from older rocks; these minerals, together with quartz and feldspar, are cemented with hematite and carbonate minerals to make a dark-colored dense rock that may form prominent outcrops. Several deposits of this type are found in sandstone of Late Cretaceous age in the San Juan Basin (No. 45) in Montezuma County (Chenoweth, 1957) and one occurrence is known on the flank of Grand Mesa (No. 21) in Mesa County (Murphy and Houston, 1955). Fourteen fossil placers in Montezuma County were examined by Dow and Batty (1961) who estimate that they contain a total of 253,500 tons of rock containing 0.89 percent TiO_2, 0.08 percent ZrO_2, and 0.03 percent equivalent ThO_2. Much of the radioactivity represented by the equivalent ThO_2 is due to monazite, but some is undoubtedly contributed by minor amounts of thorium and uranium in other minerals.

Rare-earth minerals can probably be found in the sands of streams draining any crystalline rock areas in Colorado. Monazite has been reported in several placers (pp. 93 and 135), the most significant of which appears to be those near Timberlake (No. 1) in Moffat County. Small-scale operations for gold in the placer area have produced over one-quarter million dollars (Prommel, 1942), but no recovery of the monazite appears to have been made.

Geologic studies of the rare-earth deposits of Colorado have been insufficient to outline the extent of reserves and resources of these elements. There has been no important production of rare-earth elements from any Colorado deposits, although small lots of high-grade ores recovered from pegmatites are purchased from time to time by manufacturing chemists, and within the past decade some experimental production of yttrium from Colorado ores has been attempted (Haynes, 1960, p. 382).

Currently-used sources of rare earths, such as imported monazite and California bastnaesite, appear to be ample to fill present domestic requirements for these metals, notably those of the cerium group with which the industry is chiefly concerned. Some change in the pattern of raw material requirements may develop, however, through the intensive research being made to find new uses for yttrium and other individual members of the rare-earth group. This may result in commercial interest in deposits in which one or more rare-earth elements are abundant, and in the search for such deposits the wide variety of rare-earth minerals found in Colorado and their occurrence in several different environments offer considerabl promise. Some production of rare-earth elements might result also as a byproduct in future utilization of the thorium deposits in the Powderhorn and Wet Mountains areas.

THORIUM

(By M. H. Staatz, U.S. Geological Survey, Denver, Colo.)

Thorium is a silver-gray metal that, like uranium, is the parent of a series of radioactive decay products ending in a stable isotope of lead. Thorium differs markedly from uranium in that its minerals tend to be dispersed rather than concentrated in significant deposits, and that its minerals are relatively stable during weathering.

Although thorium has several industrial uses, over 90 percent of that consumed in the United States is used in thorium-magnesium alloys and gas mantles. Minor amounts are used in refractories, polishing compounds, chemicals, drugs, and electronic products.

Present thorium requirements are relatively small compared to many other metals, and in 1961 only 121 tons of ThO_2 were consumed in the United States (Baker and Tucker, 1962, p. 1210). The source of most of the ThO_2 consumed in the United States has been imported monazite.

Domestic monazite has come chiefly from placer deposits in North Carolina, Florida, and Idaho. Minor amounts of thorite ore have also been produced intermittently in Idaho and Colorado.

Colorado has marketed small amounts of thorium-bearing ore from a number of sources (Kelly, 1962b, p. 2–3). In 1950, 26 tons of monazite were produced as one of the byproducts of the Climax molybdenum mine. Prior to 1956 a few hundred pounds of thorium-bearing multiple oxide minerals had been mined from several pegmatites; this ore was used, however, mainly for its rare earth content. In 1956 about 16 tons of multiple oxide minerals were produced from pegmatites, and in 1957, 132 tons of thorium-bearing ores were obtained from pegmatites. In 1958, 1,008 tons of thorite ore were mined, mainly from veins in the Wet Mountains, and in 1959 about 8½ tons of thorite ore were mined from the Powderhorn district. No thorium ore was produced from 1960 through 1963.

The marketing of ores of thorium and the rare earths is difficult as there is no established market comparable to those of the more widely used metals, and prices of their ores are generally determined by negotiation between buyer and seller. Detailed information on the economic factors of thorium and rare earths is given by Kelly (1962b).

A major potential use of thorium is in atomic reactors. Thorium metal, however, cannot be used directly in nuclear reaction, but it can be converted to a fissionable uranium isotope by neutron capture. The use of thorium for nuclear energy is only in the experimental stage, and it is in competition with relatively cheap, abundant uranium (Kelly, 1962b, p. 25). In 1961 the U. S. Atomic Energy Commission had built or committed for construction five different types of reactors to study the use of thorium as a nuclear fuel (Baker and Tucker, 1962, p. 1211). If thorium reactors become competitive with those using uranium, then thorium requirements will increase appreciably.

Thorium is found in a large number of minerals, generally associated with the rare-earth elements. Most thorium minerals, however, are not sufficiently rich in thorium to be a commercial source of this metal. The most important source mineral for thorium in the world is monazite, a phosphate of the cerium group rare earths. The thorium content of this mineral is variable, but commercial monazite generally contains from 3 to 10 percent thoria (ThO_2) and 55 to 60 percent combined rare-earth oxides. Monazite is found in pegmatites, granites, syenites, carbonatites, veins, metamorphic rocks, and both modern and fossil placers. Other potential sources of thorium are thorite and thorogummite, and multiple oxide minerals such as euxenite, samarskite, and fergusonite. Thorite and thorogummite are found in veins and pegmatites. The multiple oxide minerals occur in pegmatites and in placers derived from pegmatites. The thorite and thorogummite vein deposits are the most important potential source of thorium in Colorado.

Thorium is found in veins in nine areas in the State. Most of the veins occur, however, in the Powderhorn area (No. 37, fig. 24), Gunnison County, and Wet Mountains area (No. 42), Custer and Fremont Counties. Both areas have an alkalic igneous rock complex, and in both the veins have the following similarities: They are steeply dipping, and commonly contain quartz, feldspar, carbonate minerals, and barite. The thorium minerals are thorite and thorogummite, and all veins are heavily impregnated with iron oxides.

The Powderhorn area has over 200 thorium-bearing veins (Hedlund and Olson, 1961, p. B-283). They range in length from a few feet to 3,500 feet and in width from a fraction of an inch to 10 feet; most are less than 1 foot thick. Chip samples of the veins contain from 0 to 4.9 percent ThO_2 (Olson and Wallace, 1956, p. 718–720).

The Wet Mountains area has at least 400 thorium-bearing veins (Christman and others, 1959, p. 519). Most are less than 5 feet wide and between 100 and 1,000 feet long. The largest, however, is 50 feet wide and 5,000 feet long. More than 100 samples of the veins from different localities ranged from 0.02 to 12.5 percent ThO_2 (Singewald and Brock, 1956, p. 585).

Thorium has been reported in one or several veins in other areas (fig. 24) but little is known of the thorium occurrences in these areas. The fluorite ore of the Blue Jay mine at Jamestown (No. 8), Boulder County, has small amounts of uranothorite (Phair and Shimamoto, 1952). The K–W prospects (No. 17), Park County, are on a small vein that contains monazite. The Jacks Creek (No. 39) (Brown and Malan, 1954, p. 12) and the Cochetopa Creek-Rasor Creek (No. 38) (Burbank and Pierson, 1953, p. 2) areas in Saguache County each have several veins that resemble those found in the Powderhorn and Wet Mountains districts. In the White Pine area (No. 34), Gunnison County, altered rock along a fault zone was found to contain thorium (Olson and Adams, 1962), and from the dump of an old mine in the Whitecross area (No. 44), Hinsdale County, a sample containing thorium was collected (Pierson and others, 1958, p. 407).

Monazite and the rare-earth mineral xenotime form 1 to 5 percent of a zone in metamorphic rocks at three localities near Central City (No. 11), Gilpin County. These zones are 1 to 5 feet thick and have a maximum length of a few hundred feet (Young and Sims, 1961).

About 0.005 percent monazite is disseminated in the molybdenum-bearing igneous rock that is mined as molybdenum ore at Climax (No. 16), Lake County (Arkansas-White-Red River Basins, Interagency Committee, 1955, p. 110). Some monazite has been recovered as a minor byproduct from this ore, and this occurrence represents a potential source of a small amount of monazite if economic conditions are favorable.

Thorium-bearing pegmatites occur in 28 areas in the central mountainous part of Colorado (fig. 24 and table 18). Thorium occurs in pegmatites in these areas in one or more of the following minerals: monazite, euxenite, samarskite, fergusonite, allanite, and thorite. These thorium-bearing minerals are generally erratically scattered through a narrow zone near the central part of a pegmatite. Thorium minerals are generally too sparse to mine for these minerals alone, although some euxenite and samarskite has been recovered as a byproduct of feldspar or quartz mining. Small amounts of euxenite have been produced from the Yard and the Clora May pegmatites, Trout Creek area (No. 25), Chaffee County. Samarskite has been produced from a number of pegmatites in Jefferson County, including the Burroughs (No. 14) and Bigger (No. 15) mines. Of special interest are a number of pegmatites on Stove Mountain in the St. Peter's dome area (No. 28), El Paso County, where the pegmatites have been altered, as late thorite was introduced (W. M. Sharp, 1964, oral communication). About 40 tons of thorium ore have been produced from scattered fluorite-rich masses.

Placers, although they are generally the principal source of thorium minerals in other states, are undeveloped in Colorado. A number of fossil placers, however, occur in western Colorado. These placers are lens-shaped bodies ranging from a few tens of feet to several miles long and from a few tens of feet to several hundred feet wide (Chenoweth, 1957, p. 213, 216). They are ancient beach placers and occur in well-sorted sandstone beds of Late Cretaceous age. Heavy minerals make up 50 to 60 percent of the sandstone and consist of ilmenite, zircon, and garnet, with minor amounts of monazite, rutile, spinel, epidote, magnetite, and tourmaline. Fossil placers occur in Mesa County on Grand Mesa (No. 21) and in Montezuma County in the Colorado part of the San Juan Basin (No. 45), where they contain an estimated 253,500 tons of sandstone with an average grade of 0.89 percent TiO_2 and 0.03 percent equivalent ThO_2 (Dow and Batty, 1961, p. 45).

Monazite has been reported in the sands of several streams in Colorado. Day and Richards (1906, p. 1192–1193) report that two samples taken from sand near Timberlake (No. 1), Moffat County, contained 416 and 520 pounds of monazite per ton of black-sand concentrate, which, according to W. C. Overstreet (written communication, 1964), represent one of the highest grade samples known for black sands in western United States. Day and Richards (1906, p. 1190–1195) also report monazite in sands near Buena Vista, at Central City, in the San Lima Valley (San Luis Valley?) in southern Colorado, and Kithil (1915, p. 13) reports monazite in sands in Newlin Gulch and in the Platte River south of Denver; these localities are not shown on figure 24.

Thorium has been produced only sporadically in Colorado because of the small demand for this element and the present competition with more cheaply mined foreign ores. Increased demand for thorium depends on advances in technology as a result of current and projected research. Present uses do not favor an increased demand in the immediate future, but the possibility of thorium as a source of atomic power and as an alloy in some of the new special-use metals now being developed suggest an increase in demand in the not-too-distant future. A few tons of high-grade thorium-rare earth ores will continue to be produced from pegmatites from time to time as a byproduct of feldspar or quartz mining. Future thorium production in Colorado, however, probably will come largely from the thorite veins of the Wet Mountain and Powderhorn areas. These two areas could yield a moderate tonnage of thorium ore containing 0.5 percent ThO_2.

URANIUM

(By A. P. Butler, Jr., U.S. Geological Survey, Denver, Colo.)

Uranium is a metallic element that can be used as a source of atomic energy. Natural uranium is a mixture of three isotopes, U^{238}, U^{235}, and U^{234} which make up 99.28, 071, and 0.0058 percent, respectively, of the mixture. The U^{235} isotope fissions (splits) readily and the U^{238} isotope when properly exposed to neutrons can be converted to an isotope of plutonium, Pu^{239}, which too is fissionable. The fissioning of these heavy isotopes yields a very large amount of energy in relation to a unit weight. This energy can be released suddenly and explosively, which makes uranium of great significance for military uses, or slowly so that uranium also has a potentially important use as a source of sustained power. Since 1942, when a self-sustaining nuclear reaction was first demonstrated, the available uranium has been used mainly to satisfy military requirements. Some is used in nuclear reactors to furnish heat for generating electricity, and this use is increasing gradually. A small amount of uranium is also used in the ceramic, chemical, and electrical industries.

Uranium is widely distributed in the United States in rocks of many types and ages. Deposits in continental sedimentary rocks are the principal present sources of uranium. Most of the deposits are in sandstone but some are in limestone and coaly carbonaceous rocks. Veins and related fracture-controlled deposits are also a source of uranium but are less important than deposits in sandstone. Marine phosphorites and some marine black shales are of potential future importance. Some byproduct uranium has been recovered from phosphate rock mined in Florida (U.S. Atomic Energy Commission, 1962, p. 173). Summary descriptions of the different occurrences are given by Finch (1955), Schnabel (1955), Stocking and Page (1956), and Butler and others (1962).

The United States has been the principal consumer of uranium in the past 20 years. In the years 1958 through 1962 the United States acquired from 26,400 to 34,600 tons of U_3O_8 annually (Parker and Tucker, 1963, table 4), and in 1962 nearly 60 percent of the uranium acquired came from ore mined in this country. From 1947 to the end of 1962 about 108,000 tons of U_3O_8 had been produced from about 40,000,000 tons of ore mined in the United States. Colorado's contribution was about 8,400,000 tons of ore with value of about $176,000,000.[1] In recent years uranium has ranked second in value among the metals produced in the State, but it ranks seventh in cumulative value.

Most of the uranium ore mined in Colorado is processed into concentrates at mills in the State.

The development of uranium mining in Colorado reflects the varying relative importance of three metals: radium, vanadium, and uranium. Uranium ore was first discovered in the State in 1871 at the Wood mine in the Central City district, Gilpin County (Sims and others,

[1] The tonnage for the period from 1947 to June 30, 1955, was compiled by geologists, U.S. Geological Survey, from data made available by Grand Junction Office, U.S. Atomic Energy Commission, and the value was estimated from effective price schedules on basis of average grades in years 1952 to 1954, inclusive. The amount and value for period July 1, 1955, to Dec. 31, 1962, were totaled from annual volumes of the Minerals Yearbook, U.S. Bureau of Mines.

1963, p. 5). This district was the first source of uranium mined in the United States and, by 1900, veins in the district had yielded about 36 tons of U_3O_8 (Sims and others, 1963, table 1). Shortly thereafter the center of activity of uranium mining shifted to the area in Mesa, Montrose, and San Miguel Counties, now known as the Uravan mineral belt (Fischer and Hilpert, 1952), where uranium was first mined from deposits in sandstone in 1898 (Wright and Everhart, 1960, p. 330).

Shortly after 1910 deposits in sandstone of the Morrison Formation had become one of the principal world sources of radium. For about a dozen years they were mined intensively for radium and yielded some byproduct uranium and vanadium; but in 1923, mining practically ceased as pitchblende from the Belgian Congo became a source of radium (Fischer, 1942, p. 364). Intensive mining of the deposits was resumed in 1937 for vanadium rather than radium (Fischer, 1950, p. 2) and continued until 1944, when the end of urgent demand for vanadium again caused a decline in mining. Events near the end of World War II demonstrated the strategic significance of uranium, and beginning in 1948 the newly created U.S. Atomic Energy Commission established a series of graduated price schedules for uranium ore to encourage mining and search for it in the United States. This stimulus resulted in the discovery and development of many deposits and brought about a steady increase in uranium mining in Colorado until 1961.

The search for uranium proved so successful that the U.S. Atomic Energy Commission, the sole purchaser, announced (1960, p. 57) that purchases of uranium ore after April 1, 1962, would be limited to annual quotas allocated to individual properties. Also from that date until the end of 1966, instead of buying ore at the graduated prices previously in effect, the Commission would pay $8.00 per pound for U_3O_8 in concentrates produced mostly from reserves discovered before November 28, 1958. As a result of this change the production of uranium ore in Colorado and in the United States declined in 1962 for the first time since 1947. In 1962 the U.S. Atomic Energy Commission proposed to continue the purchase of uranium until 1970 from those suppliers who would agree to defer delivery of a part of their pre-1966 quotas until 1967 and 1968, but the price to be paid in 1969 and 1970 will not exceed $6.70 per pound of U_3O_8 (Parker and Tucker, 1963, p. 1274). Adjusting to these changes in procurement will result in some further decline in the annual rate of uranium production through 1967.

Uranium deposits in Colorado occur in rocks of varied ages and lithologic types. They include peneconcordant deposits in which the mineralized layers are approximately concordant with the bedding and deposits in crosscutting veins. They are described below. Readers interested in more information on these deposits are referred to a report by Wright and Everhart (1960).

Peneconcordant deposits are in continental sandstone and are the most important uranium deposits in Colorado. They have been the source of slightly more than 90 percent of the uranium ore mined in the State. The deposits consist of masses of rock impregnated with uranium minerals. The mineralized rock is partly in lenticular layers approximately concordant with the bedding and partly in adjoining elongate podlike masses commonly called "rolls" (Shawe and others, 1959). Where deposits are most numerous and best developed, they typically tend to be grouped in clusters. A cluster, individual deposits in the cluster, and any rolls present are generally elongated in a common direction (Fischer, 1956, p. 151). Deposits contain from less than a ton to several hundred thousand tons of ore, and their uranium content ranges from a trace to several percent, but the average content of ore mined is generally between 0.2 to 0.3 percent.

The mineralogy of the deposits ranges from fairly complex to fairly simple depending on the proportion and amounts of metallic elements and the state of oxidation of the deposits. Vanadiferous uranium deposits contain vanadium and uranium in ratios generally between 1:1 and 15:1, about as much iron as vanadium, and minor amounts of other metallic elements. In the oxidized, near-surface deposits, which were the source of ore mined during the early operations, carnotite and tyuyamunite, yellow uranyl vanadates, were the conspicuous uranium minerals, and the deposits were originally called "carnotite deposits." The accompanying vanadium minerals are greenish-gray and light-brown silicates and brightly colored vanadates. In unoxidized deposits the ore is dark colored and the uranium minerals are mainly uraninite and coffinite (hydrous uranium silicate), and the vanadium minerals mainly are montroseite and vanadium silicates. Pyrite is generally present, and galena, sphalerite, and molybdenite occur sparsely (Weeks and others, 1959, p. 69–73).

In the uranium deposits with little or no vanadium, the uranium-bearing minerals of the oxidized zone are a wide variety of uranium phosphates, silicates, carbonates, sulfates, and arsenates, of which autunite and uranophane are probably most common. In the unoxidized parts of deposits the uranium is in uraninite or coffinite, or both, and some pyrite is generally present.

The peneconcordant deposits are most numerous and largest in the Morrison Formation of Jurassic age in the Plateau province near the border of the State. Rocks of Tertiary age contain some large deposits in Moffat County, moderate-sized deposits in Fremont County, and a scattering of smaller deposits from Logan and El Paso Counties in the Plains province to the intermontane basins and parks of the Mountain province. Other mostly small deposits in rocks of late Paleozoic to Cretaceous age are widely scattered mainly on the flanks of ranges within the Mountain province. The distribution of the deposits is shown on figure 25.

Deposits in the Morrison Formation have been the source of about 85 percent of the ore mined. Tertiary rocks have been the source of most of the remainder. A small amount has come from deposits in other formations of Jurassic and Cretaceous age.

Nearly all the deposits in the Morrison Formation are in the Salt Wash Sandstone Member, which crops out widely in the western part of the State. This member was formed as an alluvial fan by a braided system of aggrading streams which flowed and diverged northeastward (Craig and others, 1955). In Colorado this member is mostly interbedded sandstone and mudstone. The principle

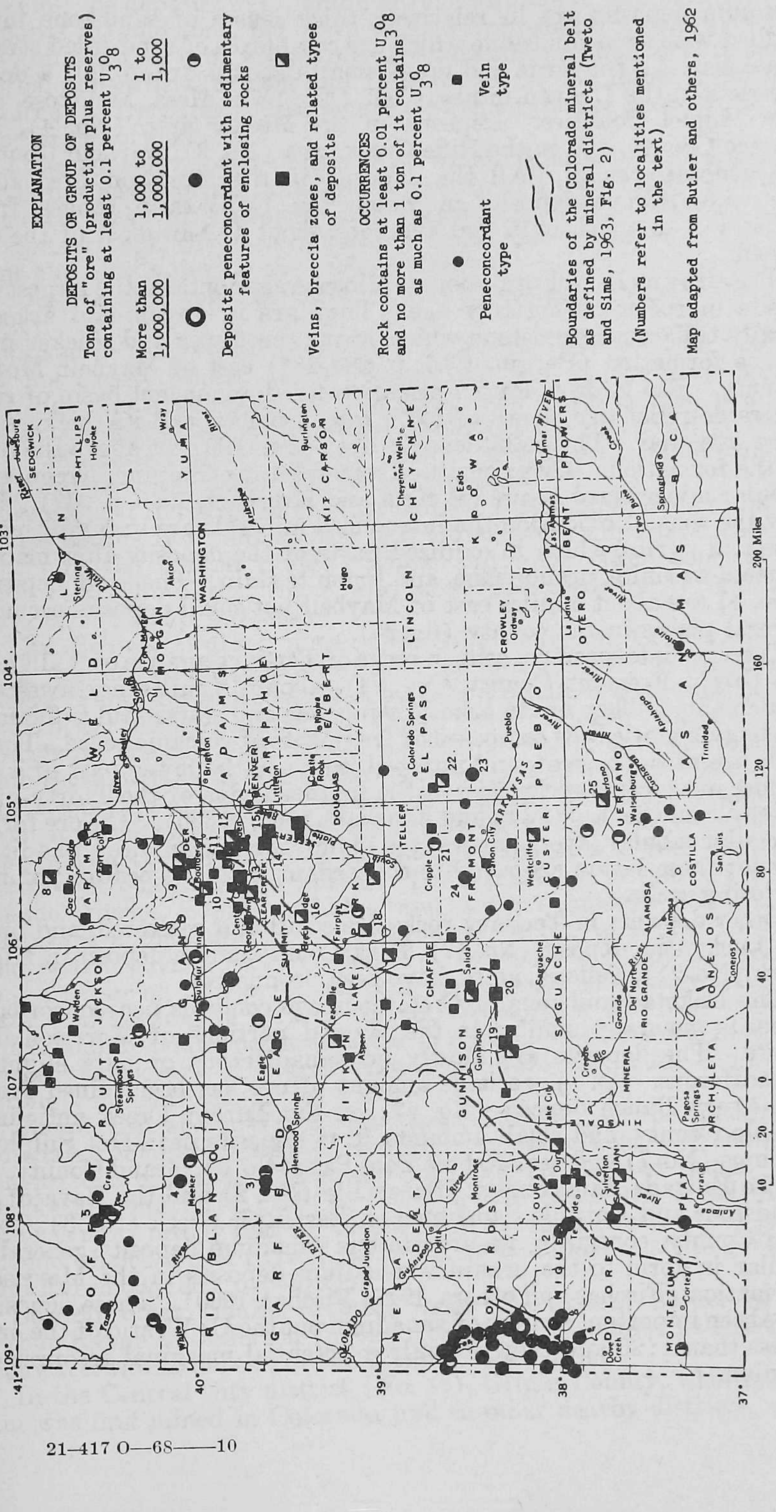

FIGURE 25.—Uranium in Colorado.

uranium deposits are in relatively thick lenses of sandstone interbedded with some mudstone which are complexes of sand-filled stream channels. All the large and many small deposits are in half a dozen districts in the Uravan mineral belt (No. 1) in Mesa, Montrose, and San Miguel Counties. Deposits in the Meeker area (No. 4), Rio Blanco County, and in the Rifle Creek area (No. 3), Garfield County, are generally small. All the deposits in the Morrison Formation are vanadiferous deposits in which the U:V ratio ranges from about 1:3 to about 1:15 and averages about 1:4 in most of the ore mined.

The Browns Park Formation of Miocene age contains the largest deposits in rocks of Tertiary age. They are in stream-laid arkosic, locally tuffaceous sandstone which forms the upper and thicker part of the formation (Bergin, 1957, p. 280–283) east of Maybell, Moffat County. The Browns Park Formation filled an ancient basin of considerable relief to a depth of 2,000 feet in places, and its thickness is very irregular. The main deposits are 500 to 600 feet above the base of the formation. They consist of somewhat overlapping, irregularly tabular mineralized layers (Wright and Everhart, 1960, p. 347). Below the zone of oxidation the introduced minerals are uraninite, coffinite and pyrite, which in oxidized parts of the deposits alter mainly to meta-autunite, uranophane, and limonite stain. The large deposits (No. 5) are about 5 miles east of Maybell but small deposits occur at several places in the county (fig. 25).

Intermediate-sized deposits in rocks of Tertiary age are on Tallahassee Creek, Fremont County (No. 24), about 18 miles northwest of Canon City. They are in arkosic sandstone and water-laid tuffaceous to conglomeratic beds composed of fragments of volcanic rocks. These beds are at the base of, and interbedded with, the lower part of a sequence of volcanic rocks close to the southern edge of the Thirty-nine Mile volcanic field (Wright and Everhart, 1960, p. 360). The ore forms irregular tabular layers mineralized mainly with uraninite and a little pyrite; these layers are roughly concordant with the bedding of the enclosing rocks.

Other deposits in Tertiary rocks are small and scattered, and only the Lucky Jim deposit (No. 17), Park County, and a deposit in High Park (No. 21), Teller County, have been productive.

The Dakota Sandstone of Cretaceous age contains peneconcordant deposits generally similar to the layered portions of Morrison deposits. The deposits are mostly nonvanadiferous or only slightly vanadiferous. An appreciable amount of ore has been mined from the Avery Ranch deposit (No. 23) on the Turkey Creek anticline, Pueblo County, and small amounts from deposits near Hot Sulphur Springs (No. 7) and near Rabbit Ears Pass (No. 6), Grand County.

The Entrada Sandstone at Placerville (No. 2) and the Navajo(?) Sandstone and Entrada Sandstone on East Rifle Creek (No. 3), Garfield County, contain large uraniferous vanadium deposits generally similar in form to the uranium-vanadium deposits in the Morrison Formation (Fischer and others, 1947; Fischer, 1960). These deposits have been important sources of vanadium but the U:V ratio of the ores is less than 1:20 and they are only a potential marginal resource of uranium.

Vein-type deposits in Colorado are subordinate in importance to the deposits in sandstone, but have yielded appreciable amounts of ore. Deposits of this type are mainly fracture fillings, but include stockworks, mineralized breccia and fracture zones, and mineralized rock adjacent to fractures. Most deposits of this type are probably of hydrothermal origin.

Although the veins are in rocks of widely different kinds and ages, including metamorphic and granitic rocks of Precambrian age, sedimentary rocks of Paleozoic and Mesozoic age, and volcanic rocks of Tertiary age, they are thought to have been emplaced in Teritary time and mostly during the period of mineralization that created most of the metalliferous deposits in the Colorado mineral belt (see p. 22).

Except in the Central City district, the vein-type uranium deposits are not closely related to the deposits of base and precious metals, although the distribution of the large- and medium-sized uranium deposits reflects the general trend of the Colorado mineral belt (fig. 25). Numerous other deposits shown on figure 25, all small, are widely distributed within the belt and outside it.

Deposits at the Schwartzwalder and the Pitch mines and on the Los Ochos claims rank among the half dozen most important vein deposits in the United States. These and some other deposits are described below; they have also been described by Wright and Everhart (1960, p. 347–364).

The Schwartzwalder mine (No. 11), Jefferson County, is the most productive vein deposit of uranium in the State. It is in a complexly branching southeastward extension of the Rogers breccia reef fault near the edge of the Front Range (Sheridan, 1956, p. 130). Several fault breccias and high-angle reverse faults cutting metamorphic rocks of the Idaho Springs Formation strike northwesterly and dip steeply to the southwest and northeast. The main faults and fault breccias and subsidiary less steeply dipping faults are mineralized where they cut brittle, competent lime-silicate rock and garnetiferous quartz-biotite gneiss. The metallic minerals are pitchblende, pyrite, copper sulfides, and some sphalerite and galena. They are accompanied by a gangue of quartz, ankerite, adularia, and sparse garnet. Ore bodies of a few feet to about 200 feet in length occur on four principal veins and several subsidiary veins and extend an aggregate vertical distance of at least 900 feet. Several thick podlike bodies occur adjacent to some of the veins where closely spaced subsidiary fractures branching from the main faults are strongly mineralized.

The deposit at the Wright lease mine (No. 14), on the outskirts of Idledale, Jefferson County, is also in a fault near the southeast end of one of the northwesterly trending breccia-reef faults. Ore shoots are mostly in parts of a single vein where the trend of the fault is more nearly north. The mineral assemblage consists of pitchblende, chalcopyrite, pyrite, marcasite, and abundant calcite (Wright and Everhart, 1960, p. 353).

Several other smaller deposits near the eastern border of the Front Range in Jefferson County are generally similar to either the Schwartzwalder deposit or the Wright lease deposit.

In the Central City district (No. 13), Gilpin County, where uranium was first mined in Colorado, and in other nearby districts, uranium occurs as pitchblende "in small lenses, pods, stringers, or rarely as larger ore shoots" in numerous fissure veins which have been of value mainly for gold or for lead and zinc (Sims and others, 1963, p. 41). Sixteen of these have yielded some uranium ore.

Elsewhere in the Front Range the Fairday A.M. mine (No. 9) on the northwest side of the Jamestown district, Boulder County, has been most productive, but uranium also has been mined at the Copper King mine (No. 8) in northern Larimer County and at the Gem Dandy and other nearby properties (No. 16) in the vicinity of Kenosha Pass, Park County. At the Fairday mine pitchblende accompanied by pyrite and quartz and a sparse molybdenum mineral occurs in veins in a conjugate fault system of north- and northeast-striking strike-slip faults mostly where the faults cut schist and gneiss of the Idaho Springs Formation (Wright and Everhart, 1960, p. 352).

The principal vein deposits outside the Front Range are in Saguache County. They include the Pitch mine (No. 20) and nearby deposits in the vicinity of Marshall Pass, and the Los Ochos deposit (No. 19) about 20 miles southeast of Gunnison.

In the Marshall Pass area the principal deposits are in or adjacent to a steeply dipping reverse fault along which metamorphic rocks on the east are in contact with sedimentary rocks of Ordovician to Pennsylvanian age on the west. The ore occurs mainly as veinlets of pyrite and pitchblende in fractured limestone, arkosic sandstone, and shale of the Belden Formation and subordinately as replacements of limestone adjacent to the fault. A little ore also occurs in the Harding Sandstone adjacent to the fault and in the Harding Sandstone, the Chaffee Formation, and colluvium at places 1½ miles distant from the fault (Wright and Everhart, 1960, p. 357–359).

The deposit on the Los Ochos claims consists of secondary uranium minerals, pitchblende, and marcasite in fractured and silicified sandstone and mudstone of the Morrison Formation and adjacent underlying schist and gneiss of Precambrian age where these rocks have been broken by an east-trending fault several miles long and by branching segments of the fault (Wright and Everhart, 1960, pp. 353–357). Although the crystalline rocks are mineralized, most of the workable part of the deposit, which is now largely mined out, was in the sedimentary rocks.

Some deposits in sedimentary rocks, mainly sandstone, are apparently localized by fractures and consist partly of mineralized rock adjacent to the fractures and partly of the uranium and accompanying minerals filling and coating the fractures. Although it is not certain that these deposits are more closely related to typical veins than to the peneconcordant deposits, they are shown as veins and related types on the map (fig. 25). None are known to contain more than a few thousand tons of ore. The productive deposits include one (No. 18) in sandstone of Permian age near Garo, Park County, where uranium is accompanied by some vanadium and copper (Wilmarth, 1959); the Mike Doyle deposit (No. 22) in the Morrison Formation in El Paso County southwest of Colorado Springs (King and others, 1953, p. 3); the Mann and Pallaoro lease deposits (No. 15) in the Dakota Sandstone southeast of Morrison, Jefferson County, where pitchblende and pyrite occur in fractures in sandstone in the footwall of a fault (Wright and Everhart, 1960, p. 363); the Stumbling Stud deposit (No. 25) in the Dakota Sandstone in the vicinity of Badito Cone, Huerfano County, where uranium minerals are partly associated with silicified fluorite-bearing fractures and partly disseminated in sandstone (Wright and Everhart, 1960, p. 362); and the deposit at the Old Leyden coal mine (No. 12) north of Golden, Jefferson County, where carnotite and uranium in unidentified form occur with silicified, veined, and brecciated coal and sandstone of the Laramie Formation (King and others, 1953, p. 3).

Uranium has also been mined from an unzoned uraninite-bearing pegmatite on the outskirts of Idaho Springs (Sims and others, 1963, p. 10).

In addition to the exploitable resources of uranium, a substantial amount of lower grade material is closely associated with ore in the peneconcordant deposits in sandstone, particularly in the Morrison Formation. In some deposits in the Salt Wash Sandstone Member, which the Geological Survey explored by drilling, rock containing between 0.02 and 0.1 percent U_3O_8 has a volume two or three times that of ore-grade rock (written communications: Boardman and others, 1956; Bell, 1950, 1953; Brasher, 1952; Fischer, 1952; and Stager, 1951), and an average U_3O_8 content of between 1/4 and 1/3 that of ore-grade material included in reserves. The amount of contained uranium in the lower grade material is about one-half the amount in resources of ore grade. Comparable proportions of lower grade material may be present in similar deposits in other formations. The vanadium ores in the Navajo(?) and Entrada Sandstones (p. 116) are also marginal resources of uranium.

At the end of 1962 the U.S. Atomic Energy Commission estimated that the reserves of uranium ore in Colorado were 3,300,000 tons with an average grade of 0.30 percent U_3O_8 [2]. About 90 percent of the reserves are in the Morrison Formation in Mesa, Montrose, and San Miguel Counties. If the rate of mining is generally adjusted to conform with the stretch-out proposal of the U.S. Atomic Energy Commission, known reserves in the Morrison Formation will probably be exhausted by the end of 1970. Reserves in most other areas in the State would be depleted in three to seven years after 1962, if mining continued at the 1962 rate.

The resource potential, however, is somewhat larger than known reserves alone would indicate. Although the Salt Wash Sandstone Member of the Morrison Formation in Mesa, Montrose, and San Miguel Counties has been intensively explored since 1948, about 5 million tons of undiscovered resources comparable in quality to ore that has been mined may be present in the Uravan mineral belt. Part of this probably is near known deposits and part in the less intensively explored southernmost Colorado portion of the belt.

Some undiscovered resources are probably present in peneconcordant deposits in other areas, especially in the Tertiary rocks in Moffat County and in Fremont County. Additional resources may also be found in vein deposits at places mainly near the margins of the Colorado mineral belt.

[2] John A. Patterson, address before the National Western Mining Conference, Denver, Colo., Feb. 8, 1963.

Most of the undiscovered resources are in concealed deposits. They will be difficult and costly to find and to develop. A substantial portion of them is likely to be found only under conditions as favorable for exploration as prevailed from 1950 to 1958.

Known marginal resources in peneconcordant deposits are fairly large and could be exploited if demand for uranium were great enough to bring about a substantial increase in price. In addition, concealed vanadium deposits thought to be present in the Entrada and Navajo(?) Sandstones (p. 120) probably contain an appreciable amount of uranium and are a potential resource of uranium whenever economic conditions may warrant the cost of finding and developing such hidden deposits.

SMELTER BYPRODUCTS—ANTIMONY, ARSENIC, BISMUTH, CADMIUM, SELENIUM, AND TELLURIUM

(By M. D. Dasch, U. S. Geological Survey, Washington, D.C.)

Antimony, arsenic, bismuth, cadmium, selenium, and tellurium occur in many mining districts of Colorado. Several of these commodities have been recovered as byproducts during the smelting and refining of metallic ores mined in the central and western part of the State. Of these six elements, cadmium is the only good conductor of heat and electricity, and therefore the only true metal. The other five elements are commonly referred to as semi-metals or metalloids, for they have properties that are intermediate between those of metals and nonmetals. Their characteristics, uses, and production are briefly discussed in the following paragraphs.

Smelters have not been in operation in Colorado since 1960. Figures concerning the previous production of smelter byproducts in the State are, for the most part, unavailable. Even if these past annual statistics were released, however, they would be somewhat misleading, for although much of the ore processed by Colorado smelters came from local mines, some of it originated in neighboring States such as Utah.

Antimony.—Antimony is an element that can occur in several different forms, a property referred to as allotropy. In the common form, it is a brittle, tin-white material with a metallic luster. The element is alloyed with certain metals in order to harden them and to inhibit corrosion. In 1962, the most recent year for which complete production statistics are available, the greatest use for antimony was as antimonial lead. Significant quantities of the element also were used in plastics, flame-proofing chemicals and compounds, pigments, and in ceramics and glass (Spencer and den Hartog, 1963a, table 7). Although antimony possesses no indispensable properties, it is technologically superior to other elements in many of its uses. Furthermore, it is relatively cheap and can be substituted for more expensive metals.

Antimony is found in two types of deposits: one type is simple both mineralogically and structurally, the other is complex. In the simple type the minerals consist predominantly of stibnite (antimony trisulfide), native antimony, and in places their oxidized equivalents. They occur in siliceous gangue and may be accompanied by small quantities of pyrite and other metallic sulfides. In the complex type of deposit, antimony is present in sulfosalts of copper, lead, and silver, or in sulfides of copper, lead, zinc, and silver. Stibnite less commonly is the principal antimony mineral in these complex ore bodies. Antimony ore mined in the United States has come primarily from the complex type of deposit. Most of the Colorado deposits are of the complex variety.

Silver-bearing ores shipped from some mining districts in the State are rich in a variety of antimony-bearing sulfosalts, including tetrahedrite, a copper-antimony sulfide, and three silver-antimony sulfides—pyrargyrite or "dark-ruby-silver," polybasite, and miargyrite. Stibnite is present in some districts.

Antimony generally is a byproduct, at times a coproduct, recovered from metallic ores, especially those of lead. Antimony ores range from low grades of 1 to 2 percent to high grades that approach the content of pure stibnite, 71.5 percent antimony. Antimony production through 1943, in San Juan County, Colo., was less than 500 tons (White, 1951, fig. 3). There is no other recorded production of this commodity in the State.

Arsenic.—Arsenic is a brittle, poisonous, allotropic element that is widespread in small quantities. In the common form, it has a near metallic luster and is tin-white or silver gray; exposure to air turns it black. Arsenic seldom occurs in the native state. More commonly it is found in one of three minerals: arsenopyrite (iron arsenide-sulfide), orpiment (arsenic trisulfide), or realgar (arsenic monosulfide). In places, arsenic is mineralogically associated with copper, lead, cobalt, nickel, iron, and silver, with or without sulfur. Ores mined in some Colorado districts are rich in a variety of arsenic-bearing sulfosalts that, in places, contain much silver; these include two copper arsenic sulfides, tennantite and enargite; and two silver arsenic sulfides, proustite or "light ruby-silver," and pearceite.

Arsenic is recovered as a byproduct during the processing of copper, lead, and less commonly, gold and silver ores. No domestic deposits are mined solely for arsenic content at the present time. Elemental arsenic has not been recovered as a byproduct in this country since 1950. Instead, the element has been produced and consumed as arsenic trioxide or arsenious oxide, commercially called white arsenic. It is used primarily in the manufacture of calcium and lead arsenate insecticides. Since 1944 there has been a marked decrease in its consumption, owing to public preference for less toxic, organic insecticides, such as DDT. The only extensive application of white arsenic, other than as a poison, is in glassmaking.

In 1920 the American Smelting and Refining Company produced 5,000 tons of white arsenic at the Globe plant near Denver. Arsenical baghouse flume and flue dust from lead smelters at Pueblo, Durango, and Leadville, and from other parts of the West, were treated. Arsenic was produced from this plant throughout the 1920's, when the commodity commanded a high price owing to serious crop damage in the South by the cotton boll weevil. In 1928 and 1929, Colorado ranked third in the Nation in white arsenic output. Production figures were not reported after 1929, although it appears that arsenious oxide was produced in the State during the 1940's (U.S. Geological Survey and U.S. Bureau of Mines, Mineral Resources of the U.S., Annual volumes).

Bismuth.—Bismuth is a brittle, reddish-silver element that has a metallic luster and is chemically similar to antimony and arsenic. Bismuth minerals are present in small quantities throughout the world. Native bismuth, bismuthinite (bismuth trisulfide), bismutite (bismuth carbonate), and a number of other bismuth-bearing minerals generally occur in stringers and pockets in hydrothermal veins. In some places, bismuth enters into the crystal lattice of certain ore minerals, such as galena (lead sulfide). Few deposits are concentrated enough to be mined solely for bismuth. Generally it is produced as a byproduct of lead ores, and to a lesser extent of copper, tungsten, and gold ores.

In 1962, 65 percent of the bismuth metal consumed in the United States was used in fusible and other types of alloys. Thirty-four percent was used in pharmaceuticals, and in other industrial and laboratory chemicals (Spencer and den Hartog, 1963b, p. 322). In the future, bismuth may become increasingly important in nuclear and electronic applications, and in thermoelectric elements and liquid reactors. Although other metals can be substituted for the element in some of its uses, bismuth has a relatively stable position in the present economy.

As early as 1885, a small amount of bismuth may have been mined in Colorado near Loveland. From 1900 to about 1912 Colorado produced most of the nation's bismuth. Ores from the Leadville district were responsible for much of the bismuth recovered during this 12-year period. Complete production figures are not available; the most productive year, however, appears to have been 1901 when 318 short tons of bismuth ore, worth about $25,488 before shipping and treatment, was shipped from Lake and Ouray Counties. In 1915 the American Smelting and Refining Company reported recovery of considerable bismuth from lead bullion received from the Leadville smelter. It appears that bismuth was produced in Colorado during the 1940's but no statistics are available.

Cadmium.—Cadmium is a soft, ductile, bluish-white metal. It is produced commercially from two sources. One is greenockite, a rather rare, yellow to orange cadmium sulfide that commonly occurs as a coating on zinc minerals, especially sphalerite. The other source consists of zinc minerals, such as sphalerite, where cadmium is in solid solution with the mineral.

Zinc ore may contain up to 1.4 percent cadmium. Ores mined in the western United States, however, generally carry no more than 0.25 percent of the metal. Cadmium-bearing ores are never mined for the metal itself. It is recovered solely as a smelter byproduct from zinc-bearing ores.

The uses of cadmium have remained relatively unchanged since 1907, when the metal was first produced in the United States. It is used primarily in electroplating, especially in transportation and communications equipment, and in fasteners. Significant quantities of the metal are consumed in the production of pigments and chemicals.

In 1910, the American Smelting and Refining Company began cadmium production at the Globe smelter in Denver. During that year a few hundred pounds of the metal was recovered; it probably originated in zinciferous ores of the Leadville district. Production of cadmium has been reported annually from the Globe plant since the early 1930's. Both primary metallic cadmium and cadmium compounds are produced. The cadmium has been recovered from flue dust, dross, and other byproduct material received from smelters in Colorado and from other states.

Selenium.—Selenium is a allotropic element that is widely distributed in small quantities in the earth's crust. It occurs as a brick-red amorphous powder, a brownish-black glassy mass, a gray metallic crystalline mass, or as red crystals. Selenium can act either as metal or nonmetal, electrical conductor or insulator, hydrogenator or dehydrogenator, colorant or decolorant. It is highly toxic; in places it accumulates in healthy plants in great enough quantities to be lethal to browsing animals.

Selenium rarely occurs in the native state. Most commonly it is in a combined form in sulfides and selenides, and is associated with copper, iron, uranium, and other metals. On the Colorado Plateau, selenium commonly occurs as clausthalite, a lead selenide. No known selenium-bearing ores can be profitably mined only for the element. Copper sulfide minerals are the most common source of selenium, although lesser quantities are recovered from lead-smelter flue dusts.

High-purity selenium is used chiefly in electronic applications; commerical-grade selenium is consumed by the chemical, rubber, metallurgical, ceramic, and glass industries. Although several selenium-bearing sedimentary formations crop out over wide areas of Colorado, they have not been processed for the element.

Tellurium.—Tellurium is a toxic, tin-white element that resembles antimony in appearance and is related to sulfur and selenium. It is neither widespread nor concentrated in large quantities. It rarely occurs in the native state, but is present in more than 40 minerals, none of which is processed solely for the element. Tellurium is recovered as a byproduct of copper and lead ores and is commonly associated with gold and silver. Tellurides, or tellurim-bearing minerals, are both varied and abundant in many Colorado mining districts. Eighteen species have been recognized in the State. The more common ones are: the silver-gold tellurides, sylvanite and petzite; the gold tellurides, krennerite and calaverite; the silver telluride, hessite; and the bismuth telluride, tetradymite.

Only small quantities of tellurium are required in its many applications. It is used in the ceramic, chemical, metallurgical, and rubber industries. Tellurium was satisfactorily substituted for selenium when that element was not available in sufficient quantities during the early 1950's. The future of tellurium is uncertain. It is potentially useful in thermoelectric devices, which convert heat from solar energy or radioactivity to electricity, and which may become increasingly important in space travel.

Even though tellurium-bearing minerals are unusually abundant and widespread in Colorado, they are present only in small quantities, and there is no published record of tellurium production in the State. The Cripple Creek district is the most famous telluride locality in the United States. Between 1891, when the camp was first opened, and 1914, 431 tons ($258, 756,600) of refined gold was produced, the ores of which were estimated to have contained 600 tons of tellurium. Reportedly, the tellurium was treated as a waste product and no effort was made to recover it (U.S. Geological Survey, Mineral Resources of the U.S., Annual volume, 1914). The tellurium of commerce is obtained entirely as a byproduct of refining copper and lead ores, in which the form of tellurium is unknown.

Reported occurrences of antimony, arsenic, bismuth, cadmium, selenium, and tellurium in the mines and mining districts of Colorado have been discussed by Vanderwilt and others (1947), Del Rio (1960a), and Eckel (1961). Bismuth occurrences in the State have been listed by Cooper (1962), antimony occurences have been listed by White (1962), and selenium occurrences in sedimentary sulfides have been summarized by Coleman and Delevaux (1957). Ore deposits containing these six elements are briefly summarized in the following paragraphs by county and by district or deposit; their locations are shown on figure 26. A resource statement concludes the discussion.

Many of these deposits or districts listed below are also described in this report in the sections dealing with the commodities produced. (See Contents.)

Boulder County, Gold Hill district (No. 7, fig. 26): Tellurides of gold and silver, predominantly sylvanite and petzite, are the most important ore minerals. A bismuth telluride, tetradymite, occurs in the Red Cloud mine. The silver-lead-copper ores, which are of secondary importance, are primarily composed of galena and the arsenic-bearing sulfide, tennantite.

Jamestown district (No. 6): Gold and silver tellurides, krennerite and petzite, occur in veins. Masses of nearly pure, somewhat oxidized, tellurium in the John Jay mine weigh up to 25 pounds.

Magnolia district (No. 8): This gold-silver district is noted for a great variety of telluride ore minerals, especially sylvanite, petzite, and hessite.

Nederland tungsten district (No. 9): Telluride minerals are relatively common in the eastern part of this district, in ores similar to those of the Gold Hill and Jamestown districts, and generally separate from the tungsten deposits. The antimony-bearing sulfosalts, miargyrite and polybasite, are sources of silver.

Ward district (No. 5): Gold-telluride ore is present in several mines, especially those in the eastern part of the district.

Chaffee County, Trout Creek Pass pegmatite area (No. 21): Bismutite occurs in several pegmatites of the area that have been mined for feldspar and rare-earth minerals; 800 pounds of bismutite was shipped from the Yard pegmatite.

Winfield (La Plata) district (No. 20): Native bismuth and bismuthinite occur in many mines and are rich in silver where molybdenum is not present.

Clear Creek County, Silver Plume-Georgetown district (No. 12): Antimony and arsenic minerals (polybasite, argentiferous tetrahedrite, and proustite) are important sources of silver in complex sulfide veins. Stibnite occurs in the Terrible mine.

Clear Creek and Gilpin Counties, Central City-Idaho Springs district (No. 11): Arsenic, bismuth, and tellurium minerals occur in complex veins that have yielded gold, silver, lead, copper, zinc, and uranium. Cadmium has been reported from two localities in Gilpin County near Central City. Greenockite coats sphalerite in the Jones mine and in the Running lode.

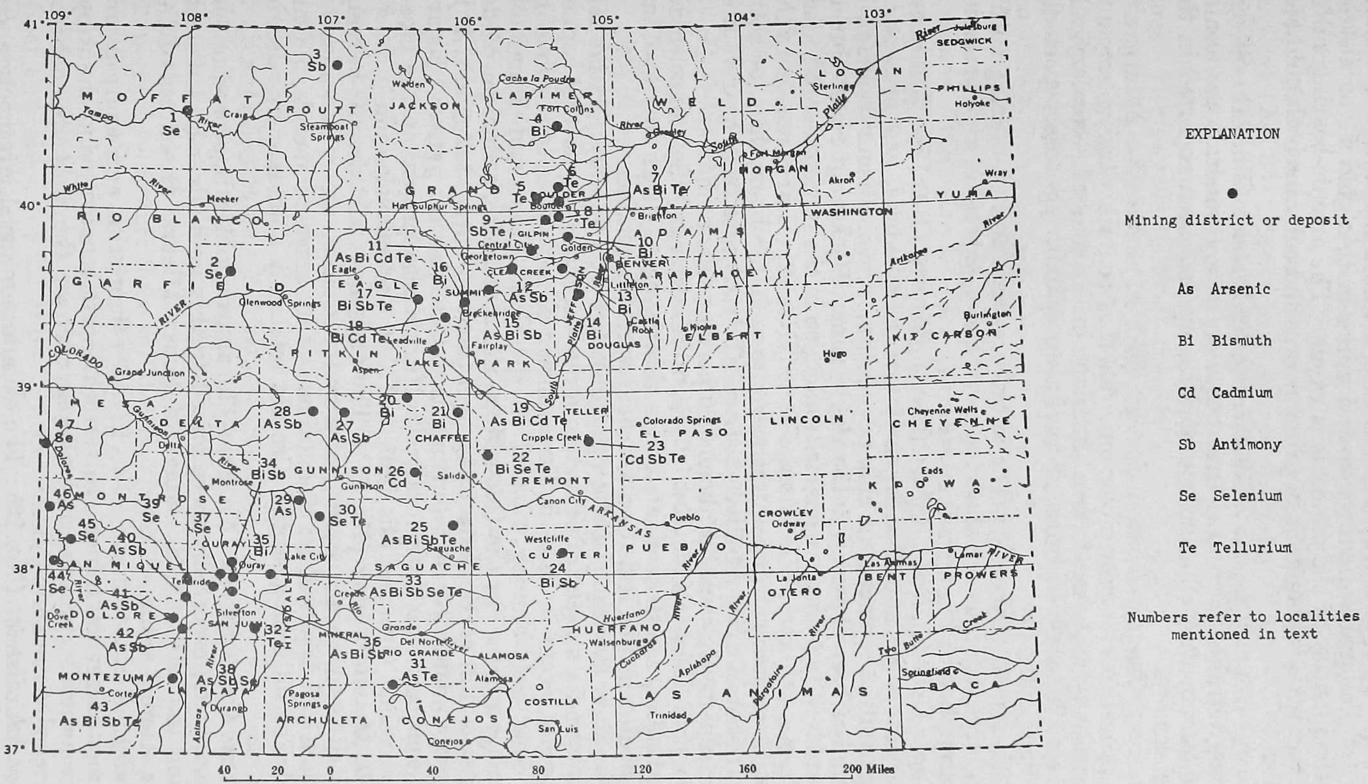

FIGURE 26.—Antimony, arsenic, bismuth, cadmium, selenium, and tellurium in Colorado.

Conejos and Rio Grande Counties, Platoro-Summitville district No. 31: Tellurides occur in several mines in this gold-silver district but the identity of the minerals is vague. The arsenic-bearing sulfosalt, enargite, is abundant in primary ores and contains both gold and silver.

Custer County, Rosita Hills-Silver Cliff district (No. 24): Silver-bearing tetrahedrite and several other antimony minerals are locally abundant in veins; bismuth mineralization has been reported in the Bassick mine.

Dolores County, Dunton district (No. 41): Massive pyrargyrite and proustite, the ruby-silver minerals that contain varying amounts of antimony and arsenic, are abundant in the zone of secondary sulfide enrichment. Clusters of radiating stibnite crystals reportedly line vugs in the ore.

Rico district (No. 42): The antimony- and arsenic-bearing sulfosalts, argentiferous tetrahedrite, polybasite, pearceite, and proustite are abundant in high-grade silver ores.

Eagle County, Red Cliff (Gilman) district (No. 17): Antimony minerals, polybasite and argentiferous tetrahedrite, are present in copper-silver replacement chimneys in limestone. Bismuth mineralization has been reported in the Eagle mine. Pockets of rich telluride ore are locally present in quartzite and also in the limestone ore bodies.

Fremont County, Whitehorn district (No. 22): Large masses of the bismuth-tellurium mineral, tetradymite or tellurobismuthite, or both, are present in this gold-silver district. Tetradymite from near Whitehorn reportedly contains about 0.20 percent selenium.

Garfield County, Rifle district (No. 2): Galena and the lead selenide, clausthalite, are disseminated in a thin layer adjacent to vanadium ore bodies in the Rifle and Garfield vanadium mines.

Gunnison County, Cebolla (Vulcan) district (No. 30): Native tellurium and a variety of tellurium minerals, including several copper tellurides, occur in veins in Precambrian schist. Petzite is probably the chief gold-bearing mineral in the Good Hope and Mammoth Chimney mines. In the Good Hope mine, tellurite, tellurium oxide, occurs as dull coatings up to 1/8 inch thick on native tellurium; it is very abundant where tellurium is interstitial to pyrite. Native selenium, associated with native sulfur, is also present in the Good Hope vein. One analysis indicated 0.40 percent selenium.

Elk Mountain area (No. 27): The antimony- and arsenic-bearing ruby-silver minerals, pyrargyrite and proustite, occur in mines on Teocalli and White Rock Mountains. Other arsenic minerals, including lollingite, iron arsenide, also are relatively abundant in veins in the area.

Goose Creek district (No. 29): The arsenic minerals, scorodite and arsenopyrite, reportedly were mined in this gold-silver-lead district during the 1920's (U.S. Bureau of Mines, Mineral Resources of the U.S., Annual volume, 1925).

Ruby (Irwin) district (No. 28): Arsenopyrite and enargite are common in several mines. Silver-bearing tetrahedrite and the ruby-silver minerals, prousite and pyrargyrite, are the most abundant of the rich silver ore minerals.

Tomichi district (No. 26): The cadmium mineral, greenockite, occurs as an accessory sulfide in some pyrite-quartz veins. It forms yellow coatings on sphalerite in the Bill Short mine; a specimen, practically free of visible greenockite, reportedly contained 0.24 percent cadmium.

Hinsdale County, Lake City mining area (Galena and Lake Fork districts) (No. 33): Pyrargyrite and proustite occur as disseminations in cracks in sulfide ores, as irregular masses along fissures, and as crystals in vugs. Massive silver-bearing tetrahedrite also is an important and abundant ore mineral. Bismuth minerals occur in several mines. High-grade telluride ore has been shipped from the Golden Fleece mine. Selenium (aguilarite) has also been reported from these workings.

Jefferson County, Bigger pegmatite mine (No. 14): The Bigger pegmatite contains rounded to thin-bladed masses of bismuthinite and bismutite in quartz.

Burroughs mine (No. 13): The Burroughs pegmatite has some bismuthinite, which is largely altered to bismutite.

Ralston Creek district (No. 10): Native bismuth is present in the Mena and Schwartzwalder uranium mines.

Lake County, Leadville district (No. 19): Bismuth, primarily in the form of bismuthinite, is present in small quantities as a common constituent of primary and secondary ores; bismuth ore has been mined in the district. Arsenopyrite is widespread and locally abundant in replacement deposits. The telluride, hessite, is a host for gold in several mines. Cadmium is present in the zinc-bearing lead ores.

La Plata and Montezuma Counties, La Plata district (No. 43): Native tellurium and a variety of gold- and silver-bearing telluride minerals, hessite, sylvanite, and coloradoite, occur in abundance. Proustite, miargyrite, and pyrargyrite are the principal ore minerals in the ruby-silver belt that crosses the northern part of the district. Tetrahedrite contains some arsenic and is one of the most widely distributed sulfides, especially abundant in telluride ores. A bismuth sulfosalt has been reported in moderate quantities.

Larimer County, Hyatt beryl mine (No. 4): Bismuthinite and bismutite are present in the Hyatt pegmatite and are associated with beryl, lithiophyllite, and several uranium minerals.

Mesa County, Corvusite mine (No. 47): The greatest concentration of a selenide yet to be found on the Colorado Plateau occurred as a band of clausthalite around a fossil log in this mine.

Moffat County, Maybell district (No. 1): Several uranium deposits in the Tertiary Browns Park Formation contain varying amounts of selenium. Samples from the Gertrude mine ranged from 0.01 to 0.11 percent and a sample from the Marge mine contained 0.98 percent selenium (Rosenbaum and others, 1958, p. 11).

Montrose County, Bull Canyon district (No. 45): Crystals of native selenium form fernlike aggregates in high-grade vanadium-uranium ore of the Peanut mine. Samples of marcasite-pyrite contain up to 0.65 percent selenium; these sulfides, however, are sparse in the ore.

La Sal district (No. 46): The copper-arsenic mineral, domeykite has been found in only one mine in Colorado. In the Cashin mine it occurs as slabs, several inches in diameter, that are associated with native copper and silver in a small part of the ore body. Luzonite, another arsenic mineral, is also present as veinlets and replacement masses.

Ouray County, Poughkeepsie Gulch district (No. 35): Sulfobismuthites of lead and silver form high-grade pockets in vein deposits.

Uncompahgre (Ouray) district (No. 34): Bismuth and antimony minerals reportedly are associated with complex sulfides in veins and replacement deposits.

Sneffels district (No. 37): Selenium values ranging from 0.09 to 1.5 percent have been reported in mattes from zinc-box precipitates of the Camp Bird mine, although the element has not been detected in the ore itself.

Ouray and San Juan Counties, Red Mountain district (No. 36): The antimony- and arsenic-bearing sulfosalts, tetrahedrite, polybasite, proustite, and enargite are widespread in precious- and base-metal deposits. Bismuth minerals, such as cosalite, have been reported from several mines.

Routt County, Hahns Peak district (No. 3): Stibnite reportedly is present in sufficient quantity to form an ore deposit of antimony. Gold-silver-lead-copper mineralization is concentrated in small veins.

Saguache County, Bonanza district (No. 25): Tennantite contains both arsenic and antimony in this district; it is widely distributed and an important source of silver in all veins. Bismuth (cosalite) is present in minor amounts. A variety of gold and silver tellurides is present in the northern part of the district, especially in the Empress Josephine and St. Louis mines.

San Juan County, Bear Creek district (No. 32): High-grade gold and silver telluride ores have been mined from quartz veins.

San Miguel County, Mount Wilson district (No. 40): Arsenopyrite, the most abundant metallic mineral in several mines, tetrahedrite, and small amounts of stibnite occur in quartz veins in association with other sulfides and precious and base metals.

Placerville district (No. 39): Selenium occurs in several mines as galena-clausthalite (a mineralogic sample contained 10.0 percent selenium) and as selenium-bearing pyrite (samples assayed up to 0.41 percent selenium); these metallic minerals are sparse.

Slick Rock district (No. 44): The selenium mineral, clausthalite, is present in sparse chalcocite nodules in the Cougar mine. Samples assayed up to 4.93 percent selenium; elemental selenium substitutes for sulfur in the chalcocite.

Telluride district (No. 38): The district supposedly received its name from an isolated specimen of sylvanite. Actually there is no authentic occurrence of telluride minerals in the gold and silver ore of the Telluride district, although both selenium and tellurium have been reported from smelted concentrates of the Liberty Bell mine. Arsenopyrite, silver-bearing tennantite and tetrahedrite, and the ruby-silver minerals are common in some mines.

Summit County, Breckenridge district (No. 16): Bismuthinite is present in many moderate-temperature deposits of base and precious metals and is associated with pyrite and quartz. In the early days, native bismuth was found in placers in the district.

Kokomo district (No. 18): Tetradymite, bismuth telluride, occurs in large quantities in the Gold Crest vein and is associated with quartz, pyrite, and gold. Cadmium reportedly is present in ores in this lead-zinc-silver district.

Montezuma district (No. 15): Tetrahedrite and the ruby-silver ore minerals, miargyrite, pyrargyrite, and proustite are abundant in many parts of the district. Bismuthinite is present in bismuth-silver veins; for many years the oxidized mineral, bismite, formed a noteworthy part of the ore in the Missouri mine in Hall Valley. Localized pockets of bismuth sulfides have yielded ore with high enough bismuth content to be considered a potential although minor source of the element.

Teller County, Cripple Creek district (No. 23): The most fabulous gold and silver telluride deposit in the United States is in the Cripple Creek district. Calaverite is the principal source of gold, and krennerite and sylvanite are important telluride ore minerals; native tellurium, however, apparently is absent. Antimony occurs in the district as stibnite and silver-bearing tetrahedrite. Stibnite is a common constituent of the rich gold ores and has been found in masses weighing up to 50 pounds at the C. K. and N. mine. A large amount of cadmium, probably greenockite, is present with sphalerite of the Last Dollar mine.

In Colorado, the production of antimony, arsenic, bismuth, cadmium, selenium, and tellurium is, for the most part, dependent upon the mining, smelting, and refining of ore mined for the major metals. Antimony and arsenic are present in silver, copper, and lead ores; bismuth is associated with lead ores; cadmium is present in zinc ores; selenium occurs in copper, lead, and uranium ores; and tellurium is common in gold and silver ores. Source minerals for the major metals mined in Colorado contain many of these minor elements. Eckel (1961, p. 5) has tabulated the approximate value of Colorado mineral production from 1858 through 1957 by groups of minerals; these data are summarized as follows:

The total value of gold produced from the principal sources in Colorado from 1858–1957 was about $906 million, of which about $440 million (nearly 50 percent) were recovered from gold-telluride ores.

The total value of silver produced from the principal sources in Colorado from 1858–1957 was about $595 million, of which silver-bearing antimony and arsenic sulfosalt minerals contributed about $200 million, or approximately one-third.

The total value of copper produced from the prinicpal sources in Colorado from 1858–1957 was about $88 million, of which about $25 million (nearly one-third) were obtained from copper sulfarsenides and sulfantimonides.

It is evident from the above figures that arsenic, antimony, and tellurium (and possibly bismuth, cadmium, and perhaps selenium as well) are significantly present in Colorado gold, silver, and copper ores. There is no evidence, however, that Colorado tellurides have ever been used as a source of the element; tellurium is generally considered a nuisance in the processing of the precious-metal ores. Whether the other minor elements are wasted or conserved when the ores are processed is not known; Colorado ores are now sent to smelters outside the State and production figures are not available.

As long as Colorado metallic ores similar to those of past production are mined and treated, the minor elements, antimony, arsenic, bismuth, cadmium, selenium, and tellurium, will be available for recovery in varying amounts. White (1962) estimated that Colorado antimony production plus reserves total between 100 and 1,000 short tons of contained antimony. There are no reserve figures available for the other minor elements.

NONMETALLIC AND INDUSTRIAL MINERALS

ALUNITE

(By J. C. Ratté, U.S. Geological Survey, Denver, Colo.)

Alunite is a hydrous potassium aluminum sulfate ($K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$), which in its pure form contains 11.4 percent K_2O, 37 percent Al_2O_3, 38.6 percent SO_3, and 13 percent H_2O. In most alunite, sodium susbtitutes for part of the potassium and where the sodium exceeds potassium the mineral is called natroalunite. Alunite has been mined as a source of potash (which is used mainly as a fertilizer), and it has been considered as a potential source of aluminum.

Alunite was first used as a source of potash during and following World War I, when the United States lost its German source of supply. About 262,000 tons of alunite ore were produced between 1915 and 1920, accounting for 4 to 7 percent of domestic potash production during that period (Callaghan, 1938). During World War II, interest in alunite switched to its use as a source of aluminum, and a process for the recovery of alumina and potassium sulfate from alunite was patented by Kalunite, Inc. (Fleischer, 1944). A plant operated by Kalunite in Salt Lake City, Utah, processed about 37,000 tons of alunite ore during this period. Since World War II, only 5,000 to 10,000 tons of alunite have been produced for fertilizer. All of the production of alunite in the United States has been from the Marysvale region of south-central Utah.

Characteristically, alunite is a secondary mineral. It occurs in areas of intensely altered volcanic rocks, where it formed principally from the action of acid sulfate solutions related to volcanic processes. Alteration of this type may be pervasive in areas of several square miles, forming replacement or disseminated-type deposits, or the alunite may be deposited along fractures to form vein-type deposits. Vein deposits are generally the richer of the two types and they account for most of the commercial production of alunite to date.

Known alunite deposits of possible economic value in Colorado are located at Marble Mountain (No. 10, fig. 27), Rio Grande County; Democrat Hill and Mount Robinson (No. 15), Custer County, and Calico Peak (No. 1), Dolores County. All are disseminated type deposits formed by the alteration of andesitic breccia and tuff, rhyolite, and monzonite porphyry, respectively. Thoenen (1941) estimated the resources of alunite in Custer County and Dolores County as follows: Democrat Hill, 800,000 tons, 16.6 percent alunite; Mount Robinson, 1,200,000 tons, 6.5 percent alunite; and Calico Peak, 6,000,000 tons, 17.1 percent alunite. Alunite resources at Marble Mountain have been estimated as 5,700,000 tons (L. S. Gardner, written communication, 1942); the alunite content of this deposit is uncertain, but the available Al_2O_3 is estimated to be 15 percent, which is equivalent to an average grade of about 40 percent alunite.

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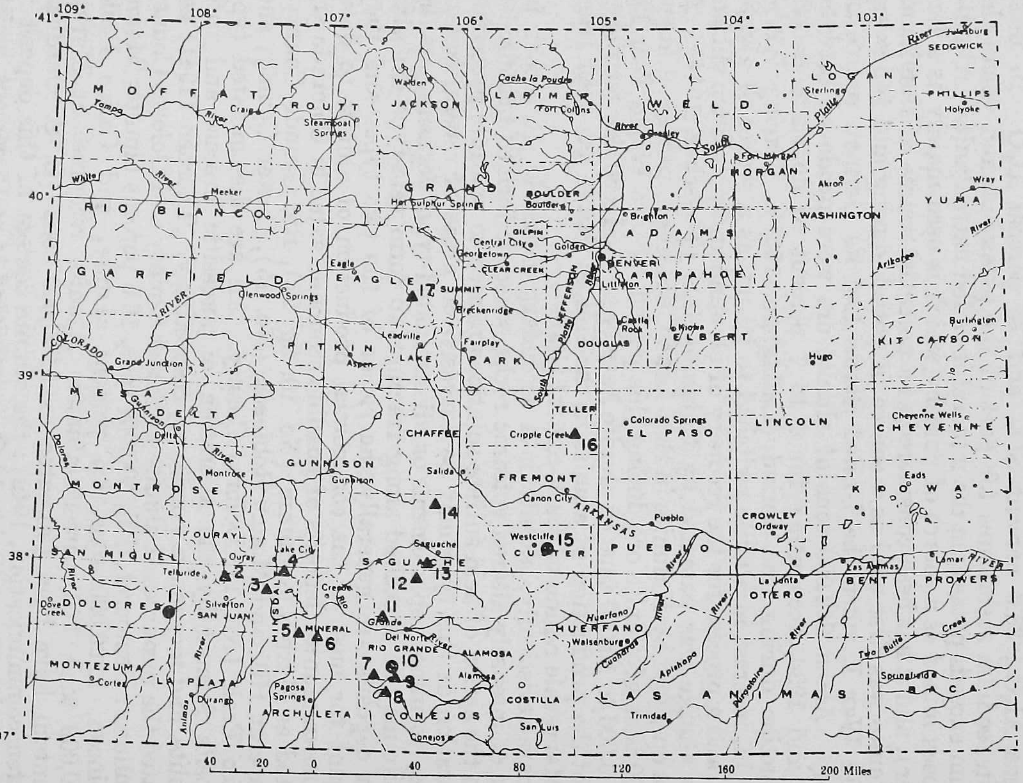


FIGURE 27.—Alunite in Colorado.

EXPLANATION

● Alunite occurrences of possible economic potential

▲ Other alunite occurrences

Areas and mining districts

1. Calico Peak
2. Red Mountain
3. Carson
4. Slumgullion Gulch
5. Head of Piedra Creek
6. Head of South River
7. Summitville
8. Platoro
9. Jasper
10. Marble Mountain
11. Embargo
12. Beidell
13. Tracy Creek
14. Bonanza
15. Democrat Hill and Mount Robinson
16. Cripple Creek
17. Red Cliff

Many other occurrences of alunite have been reported in Colorado and most of them are located in mining districts in the San Juan Mountains volcanic field (fig. 27) (Argall, 1949; Burbank, 1932; Cross, 1891; Larsen, 1912, Steven and Ratte, 1960b; Vanderwilt, 1947). In some of the other districts such as Red Cliff (No. 17), Eagle County, and Cripple Creek (No. 16), Teller County, alunite is a very minor secondary mineral in metallic vein deposits.

The possibility that alunite in Colorado or elsewhere in the United States will be developed extensively as a commercial source of potash or alumina is remote. Extensive bedded salt deposits in New Mexico and elsewhere can supply the nation's potash requirements for the foreseeable future, and large domestic and foreign sources of bauxite can supply the alumina. At present rates of consumption, the estimated total resources of alunite in the United States could supply alumina requirements for only about 6 months.

If alunite should become an economic resource in the future, additional deposits in Colorado would most likely be found in the San Juan Mountains and other volcanic areas, particularly those adjacent to shallow intrusive bodies.

BARITE

(By D. A. Brobst, U.S. Geological Survey, Denver, Colo.)

Barite ($BaSO_4$) is a relatively soft, generally white to gray, heavy crystalline mineral that has a specific gravity of 4.5. It occurs in vein, replacement, and residual deposits either alone or, more commonly, in association with quartz, chert, jasper, fluorite, celestite, and various carbonate and metallic sulfide minerals (Brobst, 1958, p. 82).

The United States has been the world's leading producer and consumer of barite since the years of World War II. The major domestic sources of barite are the large high-grade bedded replacement deposits of Arkansas and Nevada and the extensive residual deposits of Missouri and the southern Appalachian region. Domestic consumption is 1.5 to 2 million tons annually and domestic production of .75 to 1 million tons annually is supplemented by imports, chiefly from Mexico, Canada, Peru, and Greece.

About 90 percent of the barite is ground to minus 325 mesh for use as mud in drilling deep oil wells. The heavy weight of the mud assists in the drilling process and in controlling high oil and gas pressures at depth. The other 10 percent is used both as barite and in the preparation of barium compounds for a great variety of products and industrial processes. Among these are pigments (lithopone); filler in paper, textiles, rubber goods, asbestos products and linoleum; heavy aggregate for concrete paving material; electronic equipment; ceramics; and glass manufacture. The quality standards of the crude barite vary for different uses (Brobst, 1960, p. 62–63). The December 1963 market price for crude mud grade barite (generally having a specified minimum of 4.20 sp. gr.) was $12 to $16 per ton.

Barite production in Colorado is recorded for 1915, 1916, 1939, 1940, and 1941. Complete production figures are not available, but the total output probably has not exceeded a few thousand tons.

Argall (1949, p. 35) reported some production from the Hartsel area, Park County, and from Boulder, Fremont, and Custer Counties during World War I (fig. 28); production in 1916 amounted to 481 tons, valued at $3,005. George (1927, p. 162) reported some barite production from veins in Sunshine Canyon, Boulder County, and from some metal mines in the Aspen area, Pitkin County. Del Rio (1960b, p. 110) reported 500 tons of barite were mined near Ilse, Wet Mountains area, Custer County, in 1940.

The barite deposit 2 miles southwest of Hartsel (No. 1, fig. 28), Park County, was described by Howland (1936). The barite occurs in vertical veins 1 to 2 feet wide and in irregular layers 6 inches to 3 feet thick in gently dipping beds of limestone in the Maroon Formation of Pennsylvanian and Permian age. The ore is described as a porous aggregate of barite crystals mixed with limonitic clay.

Barite has been mined from a vein with galena in gneiss and schist of Precambrian age at the Feldspar mine on Oak Creek, 3 miles north of Ilse (No. 2), Custer County (Argall, 1949, p. 34). The vein is 1 to 7 feet wide, crops out 1,000 feet on a N. 13° W. strike, and dips 73° E. Barite also is a common constituent of thorium-bearing veins in the Precambrian rocks of the Wet Mountains area, Custer and Fremont Counties, but no large deposits of barite are indicated by geologic study to date in this area (Christman and others, 1959, p. 527).

The barite in the Aspen mining district, Pitkin County (No. 3), occurs chiefly as a gangue mineral associated with the silver and base-metal deposits. The barite in Sunshine Canyon, Boulder County (No. 4), was reported by George (1927, p. 162) to occur in "strong veins."

Information about barite mines, prospects, and occurrences in Colorado was summarized by George (1927, p. 162), Larrabee and others (1947), Vanderwilt (1947, p. 255–256), Argall (1949, p. 32–34), del Rio (1960b), and Eckel (1961, p. 64–66). These authors report barite in the following counties: Boulder, Clear Creek, Custer, Douglas, Eagle, Fremont, Gilpin, Grand, Gunnison, Hinsdale, Jefferson, Lake, La Plata, Las Animas, Larimer, Mesa, Mineral, Ouray, Park, Pitkin, Pueblo, Rio Grande, Saguache, San Juan, San Miguel, and Weld.

It is apparent from the production record and the literature of barite in Colorado that, although no large barite deposits are known, barite is common and widely distributed throughout the State, particularly as a minor constituent of veins long known especially for their valuable base and precious metals. For the locations and description of these deposits, see the sections on precious and base metals (p. 77). Barite could be recovered from these veins only as a byproduct of mining for other minerals. These sources are generally unsatisfactory to large barite users because the supplies of barite are limited and always tied to the demand for the major product of the mine.

The presence of barite in the mineral belt of central Colorado suggests that some deposits workable chiefly for their barite-content may yet be discovered. Active prospecting is discouraged, however, because barite is a low-priced commodity and the high cost of transporting it from Colorado to major national markets further reduces

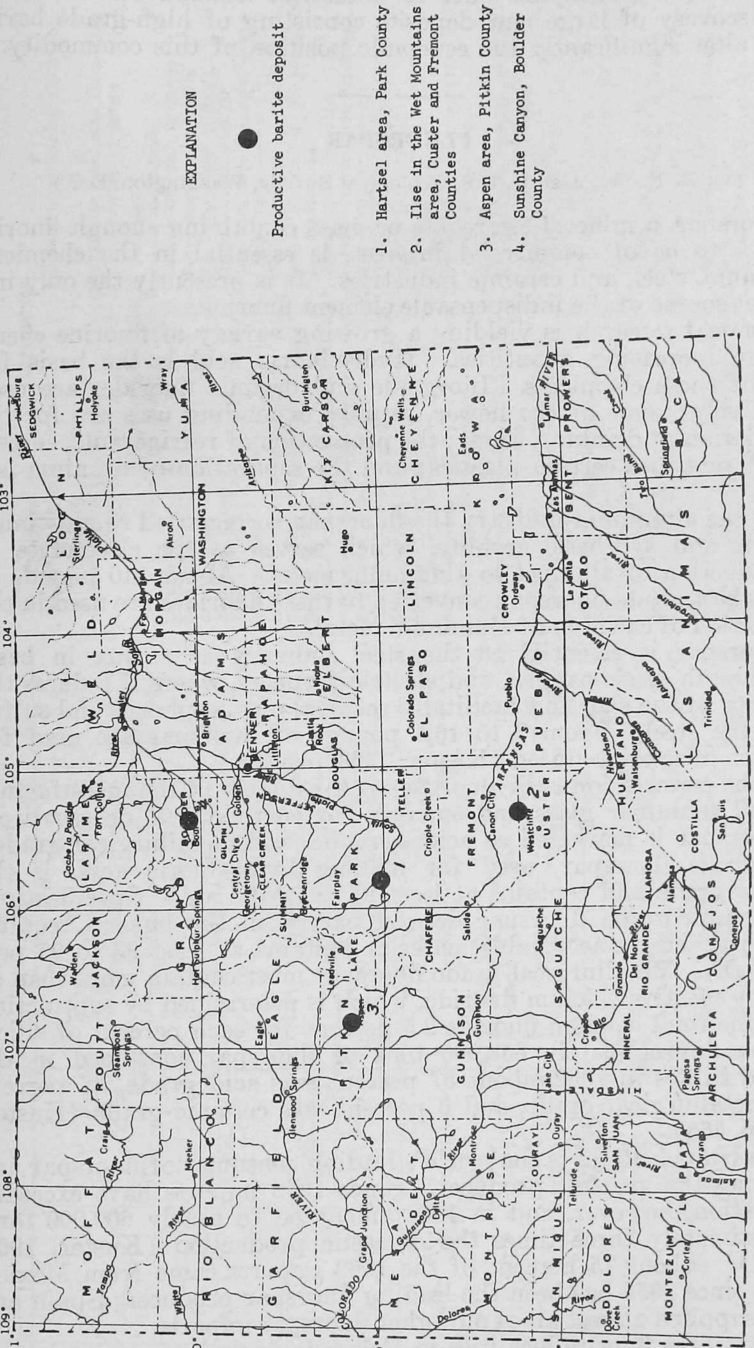


FIGURE 28.—Areas in Colorado known to have yielded commercial barite.

its value. A geographic shift in industrial demand for barite, or the discovery of large new deposits consisting of high-grade barite could alter significantly the economic position of this commodity.

FLUORSPAR

(By R. E. Van Alstine, U.S. Geological Survey, Washington, D.C.)

Fluorspar, a mineral aggregate or mass containing enough fluorite (CaF_2) to be of commercial interest, is essential in the chemical, aluminum, steel, and ceramic industries. It is presently the only important source of the indispensable element fluorine.

Chemical research is yielding a growing variety of fluorine chemicals in increasing quantities. Hydrofluoric acid is the basis for most of these chemicals. Inorganic and organic fluorides are used extensively; some of the newer, rapidly expanding uses are for the fluoridation of drinking water; the production of refrigerants, aerosol propellants, and certain plastics; and the separation of uranium isotopes.

For the aluminum industry the fluorspar is converted to aluminum fluoride and synthetic cryolite, which serves as the electrolyte in the reduction of alumina to aluminum metal. About 140 pounds of the highest grade fluorspar converted to these fluorides are used in the production of each ton of aluminum metal.

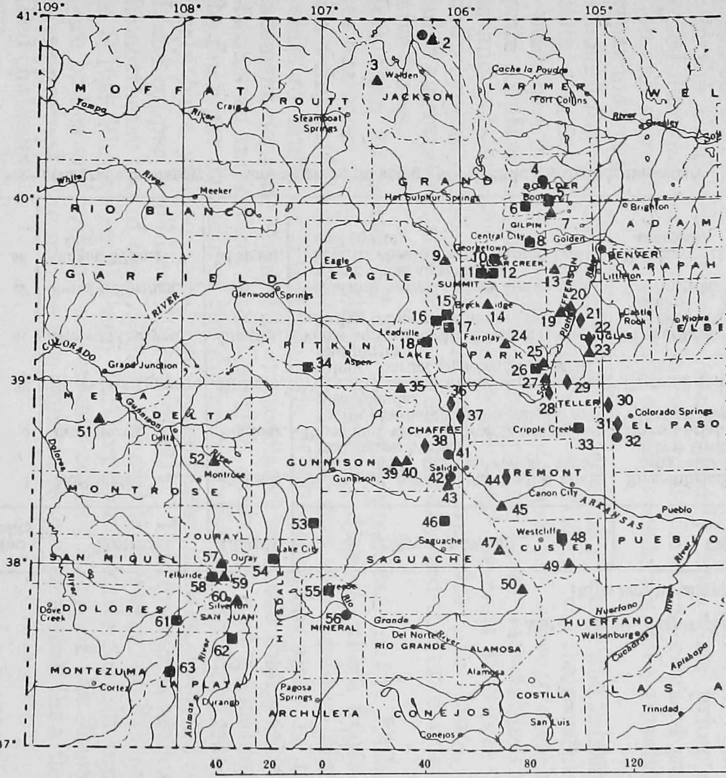
Fluorspar is essential to the steel industry as a flux in basic open-hearth, basic-oxygen, and electric furnaces, where it reduces the viscosity of the slag and facilitates removal of phosphorus and sulfur from the steel. From 3 to 16.5 pounds of fluorspar are used for each ton of steel produced (Kuster, 1963, p. 567).

In the ceramic industry fluorspar is invaluable in the manufacture of opal container glass and enamels for coating steel or cast iron.

Fluorspar is marketed as acid, ceramic, and metallurgical grades. Acid-grade fluorspar, used for making hydrofluoric acid, is the highest grade and contains at least 97 percent CaF_2. Specifications for ceramic-grade fluorspar depend partly on the buyer's requirements; generally acceptable material contains at least 93 to 95 percent CaF_2. Metallurgical-grade fluorspar must contain more than 60 percent effective calcium fluoride, which is determined by subtracting from the total calcium fluoride 2.5 percent for each percent of silica. Of the approximately 653,000 tons of fluorspar consumed in the United States in 1962, about 57 percent was acid grade, 37 percent was metallurgical grade, and 6 percent was ceramic grade (Kuster, 1963, p. 566).

The United States is the world's leading consumer of fluorspar and was long the greatest producer. Since 1952 imports have exceeded production, however, and in 1962 amounted to nearly 600,000 tons, approximately three times the domestic production (Kuster, 1963, p. 561). About 75 percent of the 1962 imports came from Mexico, which since 1956 has been the leading fluorspar producer; Spain and Italy supplied almost all of our other fluorspar imports.

Sixty-three fluorite localities in Colorado, including some mineralogic occurrences which represent types that are productive elsewhere,



EXPLANATION

● Major fluorspar districts

◆ Pegmatites containing fluorite

▲ Districts with smaller fluorspar veins

■ Metalliferous deposits containing fluorite in gangue

Fluorite localities in Colorado.
Productive fluorspar localities are underlined.

1. Northgate district
2. Sand Hills deposit
3. Crystal mine
4. Jamestown district
5. Magnolia district
6. Boulder tungsten district
7. Eldorado Springs district
8. Central City-Idaho Springs dist.
9. Dillon deposit
10. Terrible and Big Chief deposits, Silver Plume-Georgetown dist.
11. Grays Peak area
12. Argentine district
13. Evergreen district
14. Kenosha Pass deposit, Jefferson district
15. Parker-Sheldon deposit, North Star Mountain area
16. Climax molybdenum mine
17. Kentucky Belle and Sweet Home deposits, Alma district
18. Miller and Sweet Home deposits, Leadville district
19. Buffalo district
20. South Platte pegmatite dist.
21. Pine Creek pegmatite
22. Skeleton No. 2 pegmatite
23. C & S deposit
24. Bear Cat deposit
25. Silver Dollar deposit, Tarryall district
26. Badger Flats beryllium deposits
27. Kyner deposit, Lake George area
28. Teller pegmatite
29. Crystal Peak pegmatite
30. Cascade-Ute Pass district
31. Stove Mountain pegmatite
32. St. Peters Dome district
33. Cripple Creek district
34. Lead King mine, Snowmass dist.
35. Clear Creek deposit
36. Yard pegmatite
37. Luella (Crystal No. 8) pegmatite
38. Mt. Antero area
39. Quartz Creek deposits
40. Brittle Silver Basin deposits
41. Browns Canyon district
42. Poncha Springs district
43. Poncha Pass deposit
44. Pine Ridge pegmatite
45. Blue Spar deposit
46. Eagle and Express deposits, Bonanza district
47. Beryl property
48. Wet Mountains thorium deposits
49. Antelope Creek deposit
50. Liberty deposit
51. Unaweep district
52. Vernal Mesa
53. Powderhorn district
54. Galena district, Lake City area
55. Creede district
56. Wagon Wheel Gap district
57. Uncompahgre (Ouray) district
58. Tomboy deposit, Telluride dist.
59. Red Mountain district
60. Aspen mine, Silverton district
61. Rico district
62. Needle Mountains district
63. La Plata district

FIGURE 29.—Fluorite localities in Colorado.

TABLE 19.—*Major fluorspar districts*

[Map locality shown on fig. 29]

Map locality	District	County	Type of deposit	Country rock	Productive period	Main products[1]	References
1	Northgate	Jackson	Veins and replacement bodies along faults and breccia zones; minor manganese oxides.	Precambrian granitic rocks and ashy silts of Oligocene White River Group.	1922–26; 1942–45; 1951–59.	A, M	Steven, 1960.
4	Jamestown	Boulder	Pipes and veins in breccia zones and faults; associated pyrite, galena, and pitchblende.	Precambrian Silver Plume Granite and Tertiary granodiorite.	1873–1963, intermittently.	A, M; galena.	Goddard, 1946. Lovering and Goddard, 1950, p. 255–279.
32	St. Peters Dome	El Paso	Veins and breccia fillings along faults; minor barite, galena, sphalerite, and pyrite.	Precambrian Pikes Peak Granite	1910–11; 1917–18; 1944–45.	A, M	Steven, 1949.
41	Browns Canyon	Chaffee	Veins and mineralized breccias along faults; minor manganese oxides.	Precambrian granodiorite and gneiss; Tertiary rhyolitic volcanics.	1929–49	C, M	Cox, 1945, p. 270–277; Van Alstine, 1947, p. 460–463.
42	Poncha Springs	do	Veins and breccia fillings and replacements along shear zones.	Precambrian granitic rock	1934–54, intermittently.	A	Russell, 1947; 1950.
56	Wagon Wheel Gap.	Mineral	Veins in sheeted zone; minor barite and pyrite.	Tertiary rhyolitic tuffs and breccias.	1911–50; except 1932, 1933, and 1938.	M	Aurand, 1920, p. 61–66; Burchard, 1933, p. 8–10.

[1] A—acid-grade fluorspar; C—ceramic-grade fluorspar; M—metallurgical-grade fluorspar.

are shown on figure 29. Most of the production, however, has come from the six districts indicated by a separate symbol on this map and described in table 19. Fluorspar production, which began about 1873 in the Jamestown district, Boulder County, and near Evergreen, Jefferson County, has been intermittent in most districts in the State; it reached a peak in 1944 when 65,209 tons of concentrates were shipped. Total shipments of all three grades of fluorspar from Colorado through 1963 have amounted to slightly more than one million tons, with an average value of about $34 a ton. The highest annual average value for Colorado fluorspar was reported as $54.01 per ton in 1954 (Holtzinger and Roberts, 1954, p. 462). Most of the fluorspar concentrates have been shipped to the steel industry at Pueblo; to chemical, aluminum, and ceramic plants in other States; and to U.S. Government stockpiles. Shipments since 1950 have consisted almost entirely of acid-grade flotation concentrates.

About 9 percent of the fluorspar produced in the United States since 1880 has come from Colorado, and from 1953 to 1955 Colorado ranked second to Illinois as the largest fluorspar producer. By 1963 shipments decreased to less than 10,000 tons, however, and only the Jamestown district was active. Fluorspar production has been largely discontinued in western United States because of the inability to meet foreign competition, the depressed prices, and the cessation of stockpile purchases by the U.S. Government. In Colorado, however, chemical, aluminum, and steel companies and an independent or non-captive company hold substantial tonnages of unmined fluorspar and several mills in standby condition. The demand for fluorspar in the United States is growing steadily, and when prices of imported fluorspar increase as the foreign demand and costs of production and shipping rise, Colorado should once again have a healthy fluorspar industry.

Although fluorite may be found in most types of rocks and mineral deposits, commercial deposits generally formed at low temperatures and pressures in limestone or silicic intrusive and extrusive rocks. Fluorite displays a wide array of colors and locally crystallizes as cubes and octahedrons. In most commercial deposits it occurs in banded cryptocrystalline form resembling chalcedony, in crusts, in globular aggregates with radial fibrous texture, and in granular and massive forms.

More than 80 percent of the fluorspar produced in the United States has come from the Illinois-Kentucky district, where fluorite-calcite veins and bedding-replacement deposits are localized along and next to faults in limestone beds of Mississippian age. In the replacement deposits sphalerite is associated with the fluorspar and constitutes an important source of zinc, cadmium, and germanium.

The fluorspar deposits of the Jamestown district, Boulder County, similarly have yielded metals as byproducts; namely, lead, silver, gold, and copper (Goddard, 1946, p. 20–21). This district is situated at the northeast end of the Colorado mineral belt, where the Precambrian Silver Plume Granite and Tertiary granodiorite contain pipelike ore bodies and mineralized breccia zones. Much of the fluorite is coarse grained; the main silica mineral is quartz rather than fine-grained chalcedony.

In the other five major fluorspar districts shown in table 19, the fluorspar commonly occupies steep faults in Precambrian silicic igneous and metamorphic rocks and in Tertiary volcanic rocks; none of these deposits is in Paleozoic or Mesozoic rocks. The fluorite generally is fine grained, and the associated silica mineral is chalcedony rather than coarse quartz. Fine-grained pyrite is the rare sulfide mineral. Calcite and clay are locally abundant; barite and manganese and iron oxides generally are rare. Additional details concerning these deposits are given in table 19 and in the references cited therein.

These six major productive fluorspar districts are localized along geologically young faults and breccia zones near the edge of Tertiary uplifts or depressions. Deposits in all of these districts but Jamestown are considered to be of late Tertiary age and epithermal in origin, having formed at relatively low temperatures and pressures near the earth's surface; warm or hot springs are associated with the deposits in three of the districts (Van Alstine, 1947, p. 461, 465). The Jamestown deposits have been classed as early Tertiary (Laramide) and mesothermal (Lovering and Goddard, 1950, p. 43, 64, 258).

The grade of deposits that have been worked ranges from about 20 percent to more than 75 percent CaF_2. Some of the lower grade but larger ore bodies were mined in open cuts. Deposits are as much as 45 feet thick and 2,600 feet long in the Browns Canyon district, and open cuts on a vein zone in the Northgate district have been developed over a length of about 4,400 feet (Steven, 1960, p. 395). Fluorspar is exposed through a vertical range of more than 1,000 feet in the Northgate district and was mined below a depth of 1,200 feet in the Jamestown district.

In addition to the principal producing localities in Colorado (table 19), fluorspar has been mined and marketed from 12 other localities shown on figure 29. Most of these 12 deposits contain small veins, but a pegmatite in the South Platte district (No. 20), Jefferson County, yielded a little fluorspar as a byproduct of feldspar mining.

Fluorite is present as a gangue mineral in various metalliferous deposits; it has been reported in certain gold, lead, zinc, tungsten, molybdenum, beryllium, and thorium deposits of Colorado but has not been recovered from such deposits. Some of these metalliferous deposits, however, are potential sources of fluorspar. In the Cripple Creek district Lindgren and Ransome (1906, p. 122, 218) report the presence of fluorite in almost every vein and as a replacement product in all types of adjacent rocks. According to Loughlin and Koschmann (1935, p. 294–296), veins of dense fluorite and quartz as much as 2 feet thick are persistent for considerable distances. The extensive mine dumps and piles of mill tailings in and near the Cripple Creek district represent a possible future source of fluorspar. Acid-grade fluorspar concentrates are being recovered from vast piles of mill tailings containing 5–20 percent CaF_2 in some zinc-lead-silver districts of Chihuahua, Mexico (Van Alstine, 1963, p. 29–30).

Since an early estimate of 400,000 tons of probable fluorspar reserves in Colorado (Burchard, 1933, p. 24), mining and exploration during periods of high prices have revealed the presence of sizable deposits. Van Alstine (1956) has estimated that Colorado deposits contain 6 million tons of measured, indicated, and inferred fluorspar having a CaF_2-content of at least 35 percent and an additional 4 million tons ranging from 15 to 35 percent CaF_2. Most of this fluorspar is in the Northgate, Poncha Springs, Browns Canyon, and Jamestown districts, and most discoveries are to be expected here, although other deposits may be found elsewhere in Colorado, whenever economic conditions in the domestic fluorspar industry favor further search and exploration.

GEM STONES

(By G. R. Scott, U.S. Geological Survey, Denver, Colo.)

Gem stones and gem materials are naturally occurring substances that combine the properties of beauty, rarity, and durability in sufficient degree to make them prized for decoration and personal adornment.

A wide variety of minerals and rocks has been used as gems. Many of them are found in placers, where their durability and weight permit their concentration. A few are recovered from lode deposits; others are found as float probably transported far from the point of origin.

Prices of gem stones depend on their scarcity, their beauty, and their popularity. Prices range from thousands of dollars per carat for best-quality rubies, sapphires, and emeralds to a few cents per carat for some of the varieties of quartz (Jahns, 1960, p. 435). Certain gem material is also used in industry. Diamond and corundum, because of their great hardness, are used in dies, bearings, abrasives, and as cutting agents. Garnet is a widely used abrasive. Quartz, calcite, tourmaline, and fluorite are used as piezoelectric elements in strain gages.

Colorado contains many deposits and occurrences of gem stones (fig. 30). Seven minerals found in Colorado have the right combination of scarcity and value to be of commercial importance in the gem and mineral specimen trade. They are feldspar (variety, amazonstone), beryl (variety, aquamarine), topaz, gypsum, lazurite, quartz, and turquois.

Amazonstone is found at six areas in the granite pegmatite of the Pikes Peak batholith and at two localities in the Idaho Springs Formation (Eckel, 1961, p. 140–141). Only those in the Pikes Peak Granite provide gem quality material or attractive specimens. A large area near Crystal Peak in Teller County (No. 1, fig. 30) has been most productive of good quality crystals. According to Pearl (1958, p. 108–113), the pegmatite bodies were discovered about 1865 and have produced regularly since that time. In 1909 and 1910 a single miarolitic cavity 15 by 15 by 6 feet produced $3,500 worth of amazonstone, smoky quartz, and fluorite crystals. The value of the annual production from all areas in the Pikes Peak Granite may be as much as $1,000; many of the specimens found, however, probably go into the finder's collection rather than to the market.

Aquamarine occurs in pegmatite in the Royal Gorge district, Fremont County (No. 2), on Santa Fe Mountain and Floyd Hill, Jefferson County (No. 3), and on Mount Antero, Chaffee County

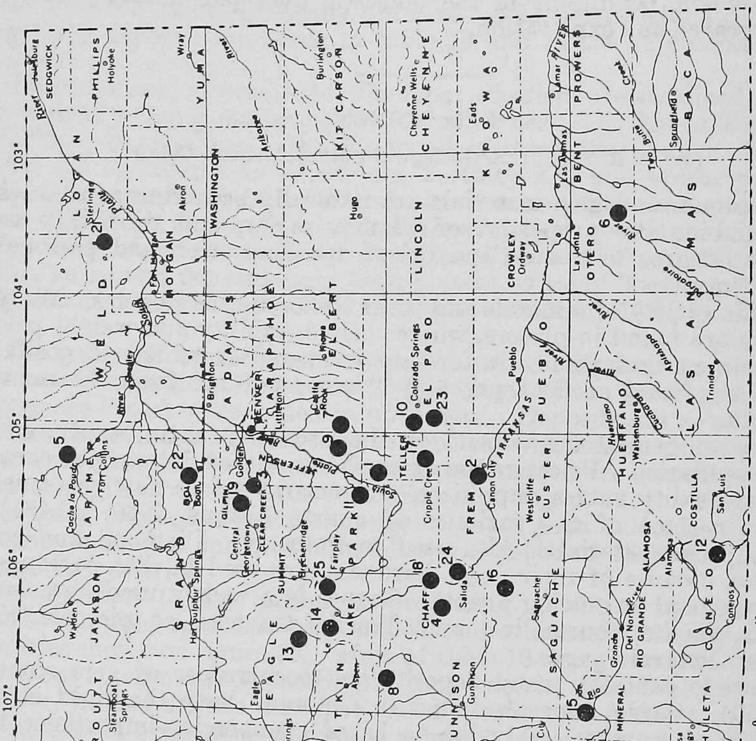


FIGURE 30.—Gem stones in Colorado. Numbered localities discussed in text.

(No. 4) (Eckel, 1961, p. 71–73). Mount Antero produces excellent gem crystals from miarolitic cavities in pegmatites of the Mount Antero Granite of Tertiary age (Dings and Robinson, 1957, p. 54–56). The locality lies above 13,000 feet altitude and is accessible only in the summer. In the 1888–92 period, stones worth $5,000 when cut, were produced. Production records since then are not available, but the pegmatites have been worked steadily during at least seven summers, and many fine crystals have been recovered.

Topaz is widespread and varied in geologic occurrence. The important localities are in miarolitic cavities in pegmatite, but it also occurs in schlieren and greisen zones in granite and in cavities in rhyolitic rocks. The four most productive areas are Devils Head, Douglas County (No. 9), Crystal Park, El Paso County (No. 10) Crystal Peak, Teller County (No. 1), and Tarryall, Park County (No. 11), all lying within the Pikes Peak Granite. Lenticular discontinuous pegmatites contain crystal-lined cavities as large as 4 by 4 by 1 foot. Crystals of feldspar, smoky quartz, and topaz are easily recovered because of the disintegrated condition of the granite surrounding the pegmatites. Most of the topaz crystals are colorless or pale blue. The largest gem quality crystal found in Colorado was 3¼ by 3¼ by 4⅜ inches and came from Devils Head, but all four localities have produced 2-inch gem crystals. Production was high in the first few years at each of these localities, and crystals worth $4,000 were recovered in the first 2 years at Crystal Peak (Pearl, 1958, p. 112); in recent years probably no more than a few hundred crystals a year are recovered from all four localities.

Gypsum in its varieties alabaster and satin spar is used for ornamental and jewelry objects. Alabaster quarries are operated in sedimentary rocks at Owl Canyon near Livermore, Larimer County (No. 5), and south of La Junta, Otero County (No. 6). Ornamental objects from Livermore are shipped to most parts of this country and into foreign lands. Pink and white chatoyant satin spar occurs in the Lykins Formation at Perry Park, Douglas County (No. 7) (Vanderwilt, 1947, p. 242–243).

Lazurite (lapis lazuli) occurs in metamorphosed Paleozoic limestone on the west slope of Italian Mountain, Gunnison County (No. 8). This locality, the most important in North America, produces intensely blue gem material from stringers as much as 8 inches wide in a vein that is 200 feet long and as much as 10 feet wide. The deposit was discovered in 1939 and 100 pounds of gem quality lazurite was produced from the first 15 feet of development work (Eckel, 1961, p. 203).

Quartz is the most varied and widely used semiprecious stone in the State; 20 varieties are listed by Eckel (1961). The most popular probably are plume and fortification agate, agatized wood, agatized dinosaur bone, jasper, chalcedony, and amethyst. Specific deposits are known for some of these stones; other varieties are picked up from stream gravel or from the surface of sedimentary or volcanic rocks. The polished slabs and cabochons cut from them are attractive and are widely distributed in gift, souvenir, and rock shops. The quantity of quartz gems collected each year in Colorado is unknown, but it is undoubtedly large enough to be of considerable value. Eckel (1961, p. 275–280) summarizes the reported collecting localities for the different varieties of quartz.

Turquois, a bluish-green gem stone, was probably one of the first Colorado minerals used by man, for it was apparently mined by Indians long before the coming of the white man (Eckel, 1961, p. 341). It was first reported from southern Colorado by Smith (1870, p. 15) and is the most valuable among the gem stones that have been produced in Colorado. Production data in recent years are not available, but in 1938 Colorado was reported (Pearl, 1941, p. 335) to be second only to Nevada in the production of turquois, having produced 15 percent of the United States output of $30,000.

Six turquois-producing localities are known: the King mine, Conejos County (No. 12); the Holy Cross district, Eagle County (No. 13); the Turquoise Chief mine in the St. Kevin district, Lake County (No. 14); the Creede district, Mineral County (No. 15); the Hall mine at Villa Grove, Saguache County (No. 16); and the Cripple Creek district, Teller County (No. 17). Only the King, Turquoise Chief, and Hall mines have recently produced commercial quantities of turquois. The geology of the three is similar, the turquois occurring in veins and nodules filling preexisting features in weathered felsite or medium-grained granite. The Hall mine is said to produce a bright blue turquois that is relatively free from matrix. Turquois from the Hall mine has sold for $15 to $45 per pound and is said to average the best in the State (Pearl, 1941, p. 337; 1951, p. 40). The production in 1956 was worth $33,000 (Sinkankas, 1959, p. 215).

The King mine has become a major producer since 1942 (Pearl, 1951, p. 37). In 1946 it produced 2,000 pounds of rough turquois worth $30,000 and its production in 1951 was said to be 8 to 10 pounds daily. The Turquoise Chief mine produced 2,000 pounds of gem turquois in two summers in the late 1930's (Eckel, 1961, p. 341).

Other Colorado minerals that have potential value as gem stones are garnet (variety, spessartite) from Ruby Mountain, Chaffee County (No. 18); rhodochrosite from the Moose mine, Gilpin County (No. 19), the Sweet Home mine, Park County (No. 25), and other localities; rhodonite from the Sunnyside vein, Eureka, San Juan County (No. 20); phenakite from Mount Antero, Chaffee County (No. 4) and Crystal Park, El Paso County (No. 10); barite from Stoneham, Weld County (No. 21), and other localities; fluorite from Jamestown, Boulder County (No. 22), and other localities; zircon from the Eureka Tunnel, St. Peters Dome, El Paso County (No. 23); and chrysocolla from the Sedalia mine, Chaffee County (No. 24), and other small deposits.

Faceted and cabochon gem stones have been cut from other minerals, but because of their small quantity or low value they are not considered to be commercially important.

No information is available on resources.

PEGMATITE MINERALS

(By J. W. Adams, U.S. Geological Survey, Denver, Colo.)

Several valuable commodities, chiefly feldspar, mica, beryl, niobium-tantalum minerals, and quartz, are recovered from pegmatites. Pegmatites are commonly dike-like bodies that range from a few inches to thousands of feet in length. They are found in crystalline rocks and are characterized by large, but extremely variable, grain size. Most pegmatites are granitic in composition, having as their dominant minerals quartz, feldspar, and mica, which are the minerals found in ordinary granite. In addition they may contain minerals of such valuable elements as beryllium, lithium, cesium, niobium, tantalum, tin, zirconium, the rare earths, and scandium.

Pegmatites are considered to have formed from late fluid fractions of crystallizing magmas, and as such are enriched in some constituents to a greater degree than are the earlier crystallized fractions or parent rock. The conditions of crystallization in pegmatites permit the development of very large crystals (Jahns, 1953) of individual minerals; commonly these are of sufficient size that they may be recovered by no more complicated procedure than hand sorting. This situation has made pegmatite mining attractive inasmuch as deposits can be exploited for salable products by use of very modest equipment.

Pegmatites are by no means all alike, and may differ not only in shape and size but in internal structure and mineral composition. Some of these differences may be due to the composition of the parent magma, to their rate of cooling, or to the host rocks in which they are found. These differences can have economic significance, as only a very small percentage of pegmatites have the combination of features to make them usable sources of mineral commodities.

The majority of pegmatites of economic interest are zoned; that is, they exhibit roughly concentric layers, each of characteristic mineralogy and texture, which commonly surround a nucleus or "core" of nearly pure quartz or feldspar. In such zoned pegmatites, specific minerals are apt to be more abundant within certain zones rather than being generally dispersed throughout the entire body. Pegmatites showing little or no zoning are, however, much more numerous than the zoned pegmatites.

Pegmatites are widespread throughout the areas of intrusive igneous rocks in Colorado and are particularly abundant in the Precambrian metamorphic and igneous rocks of the Front Range. The location of more important pegmatite areas and of a few individual pegmatites are shown in figure 31 and listed in table 20. The more precise location of a large number of pegmatites is given in Hanley and others (1950) and other cited references, but a great number of such deposits that have been prospected or mined are unrecorded.

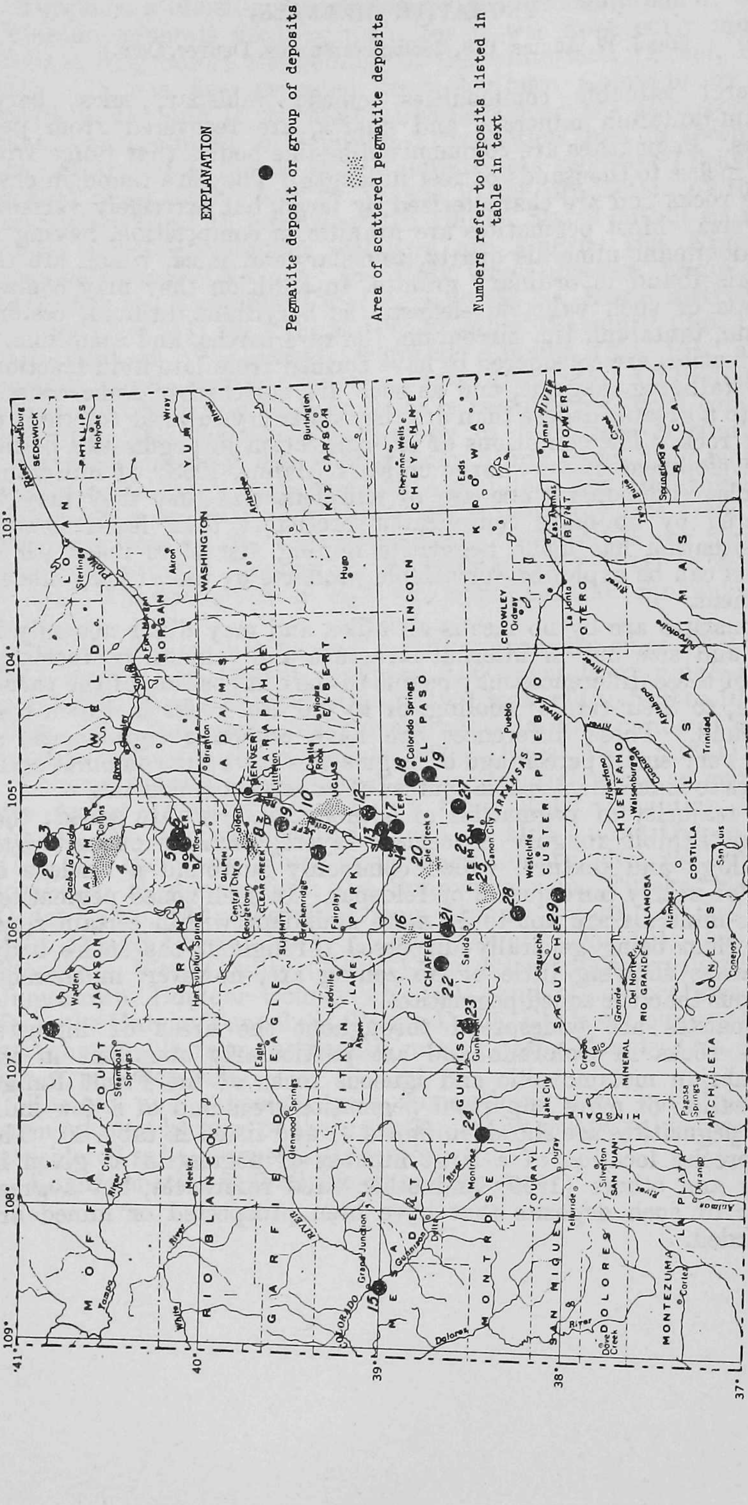


FIGURE 31.—Pegmatites in Colorado.

TABLE 20.—*Pegmatites and pegmatite areas*[1]

[Map numbers on fig. 31]

Map number	Locality	County	Valuable minerals
1	Mica Basin-Mt. Zirkel	Routt	Mica, beryl, uraninite.
2	Red Head prospect, Prairie Divide area.	Larimer	Beryl, fluorite, columbite-tantalite, topaz, rare-earth minerals.
3	Pegmatite near Copper Queen mine, Prairie Divide area.	do	Monazite.
4	Crystal Mountain area	do	Beryl, feldspar, mica, columbite-tantalite (Thurston, 1955).
5	Cerite prospects, north of Jamestown.	Boulder	Rare-earth minerals, uraninite (Goddard and Glass, 1940).
6	New Girl prospects, east of Jamestown.	do	Feldspar, mica, beryl, columbite-tantalite.
7	Beryl No. 1 prospect, near Gold Hill.	do	Beryl, columbite-tantalite.
8	Clear Creek area	Clear Creek and Jefferson.	Feldspar, mica, beryl, chrysoberyl, columbite-tantalite, rare-earth minerals.
9	Bigger mine, Bald Mountain	Jefferson	Feldspar, mica, beryl, columbite-tantalite, bismuth minerals.
10	South Platte area	Jefferson and Douglas.	Feldspar, quartz, fluorite, rare-earth minerals (Haynes, 1958).
11	Lone Lode mine, northwest of Wellington Lake.	Park	Feldspar, topaz, fluorite, monazite.
12	Snowflake mine, northwest of Woodland Park.	Teller	Feldspar, fluorite, rare-earth minerals (Adams, Hildebrand, and Havens, 1962).
13	Florissant area	do	Smoky quartz, amazonite (green microcline), phenakite, topaz in miarolitic pegmatities.
14	Teller prospect, Lake George	Park	Feldspar, rare-earth minerals (Glass, Rose, and Over, 1958).
15	Ladder Canyon, south of Grand Junction.	Mesa	Mica, feldspar (Sterrett, 1923), beryl.
16	Trout Creek Pass	Chaffee	Feldspar, rare-earth minerals.
17	Black Cloud mine, near Florissant.	Teller	Feldspar, quartz, rare-earth minerals (Heinrich and Gross, 1960).
18	Crystal Park area	El Paso	Amazonite, smoky quartz, phenakite, topaz, zircon in miarolitic pegmatities.
19	St. Peters Dome-Mount Rosa area.	do	Thorium, rare-earth, niobium-tantalum, and beryllium minerals, zircon, fluorite (Eckel, 1961).
20	Guffey-Micanite area	Park	Feldspar, mica, beryl, rare-earth minerals.
21	Turret area	Chaffee	Feldspar, mica, beryl, columbite-tantalite.
22	Mount Antero area	do	Beryl, phenakite, fluorite, smoky quartz in miarolitic pegmatites (Switzer, 1939).
23	Quartz Creek area	Gunnison	Feldspar, beryl, mica, lithium minerals, microlite, columbite-tantalite, rare-earth minerals.
24	Black Canyon area	do	Feldspar, mica, beryl.
25	Cotopaxi	Fremont	Feldspar, rare-earth minerals (Heinrich, Borup and Salotti, 1962).
26	Eight Mile Park	do	Feldspar, mica, beryl, columbite-tantalite, bismuth minerals.
27	Phantom Canyon	do	Feldspar, mica, beryl, columbite-tantalite.
28	Villa Grove area	do	Rare-earth minerals.
29	Crestone area	Saguache	Rare-earth minerals, beryl.

[1] Data largely from Hanley, Heinrich, and Page (1950).

Two rather distinct types of pegmatite are commonly mined in Colorado. One of these, prevalent in the South Platte area (No. 10, fig. 31), Douglas and Jefferson Counties, and elsewhere in the Pikes Peak batholith, is primarily a feldspar-rich pegmatite. They are mostly round or oval in plan and section and well-zoned with a biotite-rich wall zone, perthitic microcline and quartz intermediate zone, and a quartz core. The mineral assemblage, which is very coarse grained, may include fluorite, topaz, and rare-earth and thorium minerals as common accessories. Plagioclase feldspar is minor, and muscovite, tourmaline, garnet, and beryl are sparse or absent.

The other type, exemplified by pegmatites of the Eight Mile Park (No. 26) area, Fremont County, also contains much feldspar but in addition may contain local concentrations of beryl, mica (muscovite), columbite-tantalite, and more rarely lithium minerals. Tourmaline and garnet are common, but fluorine minerals, such as fluorite or topaz, and minerals of thorium and the rare earths are unusual. Plagioclase feldspar, rather than microline-perthite may be locally dominant within the deposit. These pegmatites may be quite irregular in shape, but tend to be elongate especially when they occur in layered metamorphic rocks. Zoning may be either lacking, or well defined and complex.

Feldspar, an important raw material of the glass and ceramic industries, has been the chief product of Colorado pegmatites. Until the end of 1957 it was produced from a large number of mines, chiefly in Jefferson, Douglas, Fremont, and Chaffee Counties. At least 250,000 long tons are estimated to have been produced prior to 1945 (Hanley and others, 1950, p. 19), and more recent annual production has been close to 45,000 long tons per year.

Most of the feldspar from the pegmatites is perthitic microline, which is chiefly the mineral microcline with some intergrowth with plagioclase feldspars. The feldspar was largely recovered from zoned pegmatites where it may make up all or most of the core, or together with quartz, forms an intermediate zone surrounding a quartz core. Production of feldspar all but ceased in Colorado after 1957 following a drop in price of the mineral and the closing of an important feldspar grinding plant in Denver.

During the period when feldspar mining was active, little or no demand existed for quartz, and this mineral was avoided as much as possible during mining. Within the past few years, however, the use of crushed quartz in the building trades and for decorative purposes has grown sufficiently to encourage mining of the mineral from a number of pegmatites in the Front Range. Its recovery is facilitated where large quartz cores remain exposed from earlier feldspar mining as in many of the pegmatites of the South Platte area (No. 10).

Two mica minerals, muscovite (white mica) and biotite (black mica), are abundant in Colorado pegmatites. Muscovite is of economic value especially when found in large crystals or "books" that are clear, flat, and free of inclusions and stains; such mica is termed sheet mica and is used in electrical condensers and other equipment where its dielectric properties are needed. Muscovite that does not meet the requirements for sheet is termed scrap mica and, while less valuable, has many important uses, largely in roofing materials and paints. Sheet mica has been found in a few Colorado pegmatites, notably in the Micanite area (No. 20), Park County, and in the Ajax mine in the Clear Creek area (No. 8), Jefferson and Clear Creek Counties, but nearly all of the small tonnage of mica mined annually in Colorado is only suitable for scrap use; recent production has come entirely from Larimer County (Sharps, 1962, p. 11). Mica in large, flat sheets, but containing mineral inclusions has been obtained from pegmatites in Mica Basin, near Mount Zirkel, in the northeastern part of Routt County (No. 1). Biotite is not of current economic importance.

Lepidolite, a lithium-bearing mica, has been mined from pegmatites in the Quartz Creek area (No. 23), Gunnison County, and also occurs in the Meyers Quarry pegmatite (Heinrich, 1948, p. 556) in the Eight Mile Park area (No. 26). The lepidolite reserves in the Quartz Creek area have been estimated at 3,460 tons (Staatz and Trites, 1955, p. 50). More recently a number of pegmatites containing small crystals of spodumene, another lithium mineral, have been found in the same district (Staatz, M. H., oral communication, 1964).

Beryllium minerals, chiefly beryl, are found in a large number of Colorado pegmatites (p. 121). The aggregate production from these deposits has been generally less than 100 tons a year, representing small lots of beryl from several mines, chiefly in Larimer, Jefferson, Fremont, and Gunnison Counties. Beryl of gem quality occurs in miarolitic pegmatites in the granite of Mount Antero (No. 22) in Chaffee County.

In addition to the more important pegmatite commodities, a number of other valuable minerals are recovered sporadically from these deposits. These include niobium and tantalum minerals such as columbite-tantalite and microlite (p. 126), rare-earth minerals such as euxenite, monazite, gadolinite, rare-earth-bearing fluorite (p. 128), and thorite (p. 131).

Pegmatites in Colorado are well known to mineralogists as a source of rare minerals, some of which were first described from these deposits. The area around St. Peters Dome (No. 19) in El Paso County contains many rare minerals (Eckel, 1961, p. 19) in both small miarolitic pegmatites and in larger bodies that have been prospected as possible sources of niobium-tantalum, beryllium, thorium, and the rare earths. A number of uncommon minerals of the rare earths occur in pegmatites of the South Platte (No. 10) and Cotopaxi (No. 25) areas, the Teller (No. 14) and Black Cloud (No. 17) pegmatites near Lake George, and in the Jamestown area (No. 5) (p. 131). The presence of rare minerals of valuable elements in pegmatites is of more than academic interest as the knowledge gained from their study facilitates recognition of these minerals in other environments where they may be less conspicuous yet sufficiently abundant to be of economic value.

The future of pegmatite mining in Colorado depends largely on developments in the feldspar industry, but there is a general trend away from pegmatites as a source of beryllium, rare earths, and niobium-tantalum minerals in favor of other types of deposits, so that production of these commodities from pegmatites probably will never exceed its past importance.

SALTS OF SODIUM AND POTASSIUM

(By O. B. Raup, U.S. Geological Survey, Denver, Colo.)

The commonly occurring salts of sodium and potassium include halite or common salt ($NaCl$) and the potassium minerals sylvite (KCl) and carnallite ($KMgCl_3 \cdot 6H_2O$). These minerals chiefly occur in bedded deposits, commonly with gypsum and anhydrite, and they were formed by precipitation from natural saline waters in undrained lakes or in partly isolated arms of the sea. Precipitation occurs as these bodies of water evaporate and become enriched in dissolved salts. These deposits are commonly called "evaporites" or "salines."

The sodium and potassium salts, however, have quite different uses from those of gypsum and anhydrite, so they are described separately; the salts are described below, gypsum and anhydrite are described on page 190. Alunite is another source of potassium, but its geological occurrence is entirely different from that of potassium salts, so it also is described separately (p. 155).

Annual rate of production and consumption of common salt in the United States is about equal and is approximately 24 million short tons. Michigan is the leading salt-producing State, followed in order by Texas, New York, Louisiana, Ohio, and California (MacMillan, 1960, p. 746).

The greatest use of salt in the United States is in the chemical industry, which used 68 percent of the salt produced in 1958. Chief chemical uses are in the production of chlorine, sodium hydroxide, and sodium carbonate. Other uses of salt include processing food, tanning, textile dyeing, soap making, pulp and paper manufacture, metallurgy, ceramics, rubber, and oil refining. Considerable quantities of salt are used on roads to melt ice and snow (MacMillan, 1960, p. 756).

Potash (potassium salts) is produced and consumed in the United States at an annual rate of approximately 2,200,000 short tons (Ruhlman, 1960, p. 656). Ninety percent of the potash produced in the United States in 1958 came from New Mexico with the remainder coming from California, Utah, Michigan, and Maryland (Ruhlman, 1960, p. 651).

The primary use of potash in the United States is for fertilizer, which consumes 95 percent of the United States annual production. The remaining 5 percent is used by the chemical industry in the manufacture of detergents, soap, glass, ceramics, textiles, dyes, and drugs (Ruhlman, 1960, p. 651).

Common salt occurs in three major areas in Colorado, but potassium salts are known only in the Paradox basin (fig. 32).

In the Paradox basin area, layers of salt and potash minerals are interbedded with anhydrite, limestone, dolomite, and shale, a sequence of beds that compose the Paradox Member of the Hermosa Formation. These beds are all marine and accumulated in the Paradox basin, a partly isolated arm of a sea, during Pennsylvanian time. The basin covered southwestern Colorado and the adjoining parts of Utah, Arizona, and New Mexico. It was deepest along the northeastern edge, where originally the Paradox Member was as much as 7,000 feet thick, and from there these beds thinned gradually to the western and southern edges of the basin. Salt and potash were deposited only in the deeper part of this basin, the part in Colorado and Utah. In these two States, salt underlies about 11,000 square miles, extending in a broad belt from southwestern Colorado northwestward toward central Utah; potash underlies about two-thirds of this area (Hite, 1961, p. D–135). In recent years part of the salt-bearing area of southeastern Utah has been explored for minable layers of potash, and a mine is being developed in an area near Moab to exploit a high-grade body of potash that averages 11 feet thick, is relatively undisturbed by structural deformation, and is buried only 2,400 to 4,000 feet deep (Hite, 1964, p. 210).

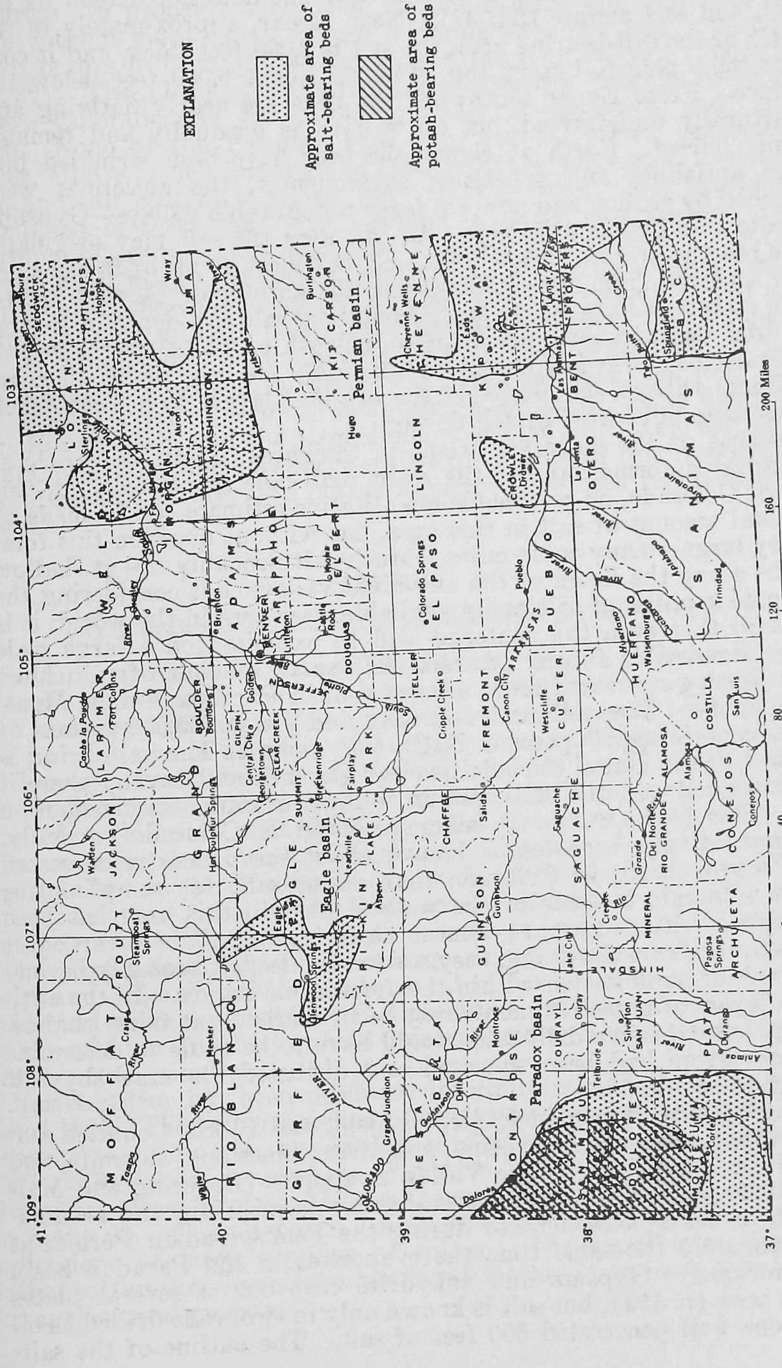


FIGURE 32.—Salt and potash in Colorado.

In Colorado, salt underlies about 4,500 square miles of Mesa, Montrose, San Miguel, Dolores, Montezuma, and La Plata Counties; potash also underlies much of this area but does not extend as far south and east as salt (fig. 32). Near Egnar, approximately in the center of the salt-bearing area, the salt is 2,000 feet thick, and it contains some potash, but its top is buried about 6,000 feet below the surface. From Egnar southward the beds are nearly flatlying and structurally undeformed, but the salt thins gradually and remains deeply buried. North of Egnar the beds have been wrinkled into large anticlines and synclines; subsequently, the anticlines were breeched by erosion and now are large topographic valleys—Gypsum, Paradox, and Sinbad Valleys. In this area the salt may originally have been as much as 5,000 feet thick, but most or all of it has since been squeezed from the synclines into the anticlines. A well drilled as an oil test in Paradox Valley encountered salt at a depth of several hundred feet and remained in it to a depth of 14,000 feet. Potash minerals may also be present at relatively shallow depth in these anticlinal valleys, but probably the original layers have been much squeezed and distorted by salt flowage.

Because of the large variations in thickness of salt due to local structural deformation and the scant drill-hole information in this part of Colorado, no reasonable quantitative estimate can be made of the total amount of salt in this area, but without question this total is very large—many cubic miles. Much salt probably lies at shallow depths along the floors of the anticlinal valleys, but considering the adequate supplies of salt easily available elsewhere in the world, it is doubtful that even this material will be exploited on a large scale in the foreseeable future. A relatively small amount of salt, however, is being recovered from a brine well in Paradox Valley, Montrose County. The well is 90 feet deep and yields 600,000 gallons of brine, containing 22 percent NaCl, per month. The salt brine is pumped to the Union Carbide Nuclear Co. mill at Uravan, where it is evaporated and the salt used in milling uranium and vanadium ores. This is the only salt being produced in Colorado currently.

Quantitatively, even less is known about the potash resources of the Paradox basin in Colorado than about salt, for sampling for potash minerals in some of the wells drilled in this area has been incomplete. Resources are almost certainly large, however. But where the beds are flat-lying, they are buried deeply, probably beyond the reach of exploitation within the foreseeable future. In the anticlines, layers of potash minerals may occur with salt at fairly shallow depths, but extensive drill tests would have to be made to determine if these layers had been squeezed and distorted too much by salt flowage to be minable.

The Eagle basin area in Eagle, Garfield, and Pitkin Counties contains a thick sequence of gypsum, anhydrite, limestone, dolomite, and shale beds, comprising Eagle Valley Evaporite (Lovering and Mallory, 1962, p. D–47). These beds are marine in origin and accumulated in a nearly closed basin during the Pennsylvanian Period, at approximately the same time the evaporites in the Paradox basin were forming. Gypsum and anhydrite crop out at several places in this area (p. 194), but salt is known only in two wells drilled as oil tests; one well penetrated 600 feet of salt. The outline of the salt-bearing area shown on figure 32 is highly conjectural, and is based on the information from these two wells and an interpretation of the local geology (W. W. Mallory, oral communication, 1964). Salt resources are probably large, but no quantitative appraisal can be made without more data. Potash minerals have not been reported.

Salt occurs in beds of Permian age in much of eastern Colorado (fig. 32). These beds accumulated in the extensive Permian basin of eastern Colorado and the adjoining states to the north, east, and south. None of the Permian beds crop out in eastern Colorado; rather, all are buried hundreds of feet, and their character, distribution, and salt content is known only from drilling. Salt is widely distributed in these beds, but it occurs in many separate and discontinuous layers, which have been incompletely correlated, so the extent of salt in any one layer is uncertain. The outlines of the salt-bearing areas shown on figure 32 represent a composite picture of the distribution of all salt layers reported and are only approximate (M. M. Mudge, oral communication, 1964). Large amounts of salt are undoubtedly present in eastern Colorado, but data regarding this salt are too scant to permit a quantitative appraisal. The depth of burial to this salt, and the large amount of easily available salt elsewhere, probably precludes large-scale exploitation of this resource in the foreseeable future. No potash minerals have been reported with this salt.

SULFUR

(By G. N. Broderick, U.S. Geological Survey, Washington, D.C.)

Sulfur, a nonmetallic element, is obtained from a wide variety of sources: native sulfur deposits, pyrite deposits, concentrating plants and smelters treating sulfide ores, oil refineries, sour natural gas, coal-burning plants, and deposits of gypsum and anhydrite.

The uses of sulfur are many and varied. Its largest single use is for the production of sulfuric acid, an acid that is used so extensively in modern industry that it is regarded as an extremely accurate index of a nation's industrial activity. The largest sulfur consuming industry in the United States is the fertilizer industry; other large consumers are the chemical, iron and steel, rayon and film, and petroleum industries. These consumers use the sulfur in acid form. The paper industry uses large amounts of sulfur for sulfite pulp, and large quantities of elemental sulfur are used by the insecticide and rubber industries. In Colorado sulfur is consumed chiefly by the uranium industry, which uses sulfuric acid in the recovery of uranium and vanadium.

Native sulfur has been produced intermittently in Colorado since about 1900. The occurrences are of two types: fumarole deposits, and deposits resulting from the oxidation of metallic sulfides (Wideman, 1957). Reported occurrences of native sulfur in Delta, Dolores, Gunnison, Mesa, Mineral, Montezuma, and Teller Counties are shown on figure 33. These deposits are small and surficial, and none show indications of large supplies of sulfur. The small quantities of native sulfur that have been produced in the State have been used for agricultural purposes.

EXPLANATION

● Native sulfur deposits

1. Delta County
2. Dolores County
3. Gunnison County
4. Mesa County
5. Mineral County
6. Montezuma County
7. Teller County

▲ Precious- and base-metal mining districts containing substantial quantities of sulfur in pyrite and other sulfide minerals

8. Leadville
9. Kokomo
10. Gilman (Red Cliff)
11. Rico (Pioneer)
12. Central City-Idaho Springs

◆ Sulfuric acid plants

13. Denver
14. Rico
15. Uravan

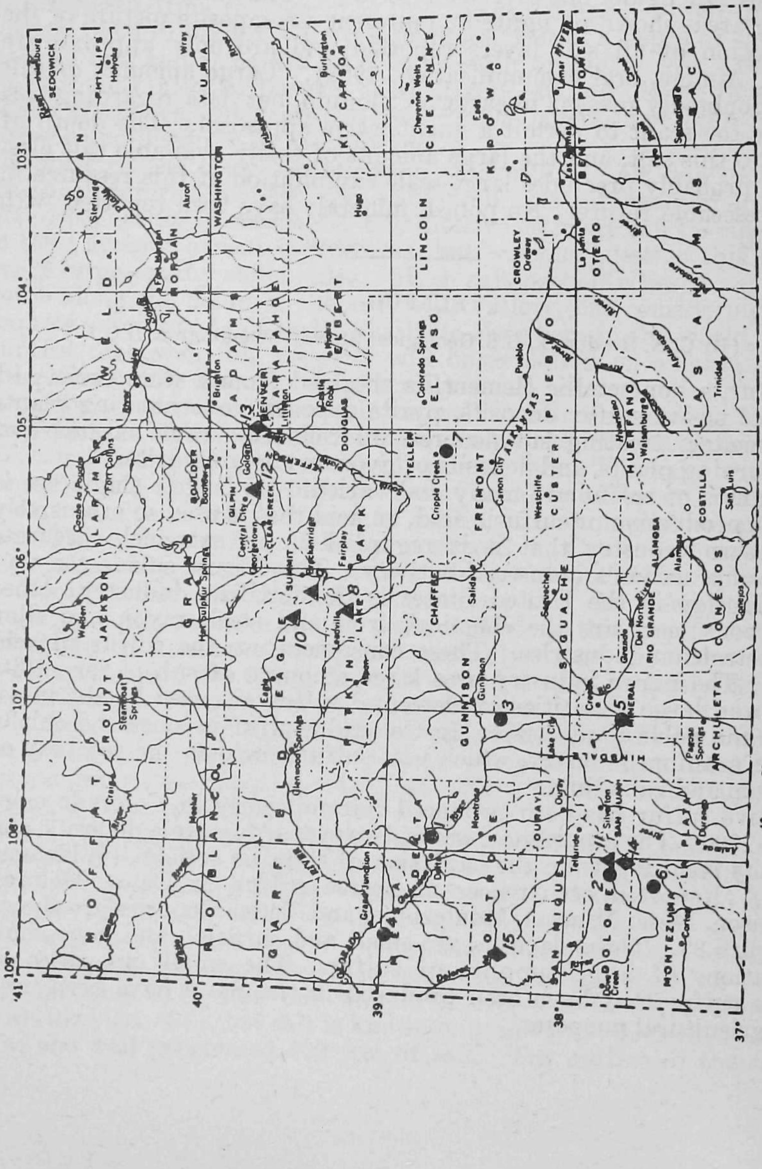


FIGURE 33.—Sulfur in Colorado.

Pyrite and other sulfide minerals are common in many metalliferous deposits in Colorado. Substantial quantities of sulfur in the form of pyrite and other sulfide minerals occur in deposits of precious and base metals in many mining districts, especially those shown on figure 14. The molybdenum deposit at Climax, Lake County, contains abundant pyrite, and pyrite is recovered as a byproduct and used as a source of sulfur for acid. Many tailings ponds and mine dumps also contain additional supplies of pyrite. Acid plants in the State have utilized pyrite, pyrite concentrate, and pyritic mill tailings in the manufacture of sulfuric acid.

Production of sulfuric acid in Colorado was attempted as early as 1875, and in the next several years a few plants were operated for short periods of time. Another plant operated at Louviers, Douglas County, from 1908 to 1930 (Kelly, 1962a).

In 1885, the Western Chemical Works Co., Denver, began manufacturing various chemicals; sulfuric acid was among the products it manufactured. During the early years, most of the sulfur-bearing raw material was pyrite from the Central City-Idaho Springs districts. In 1920 this plant was sold to General Chemical Co. and for a period in the 1920's native sulfur from Texas instead of Colorado pyrite was used in its operation. The plant is now owned and operated by General Chemical Division of Allied Chemical Corp. It consumes pyrite concentrate recovered as a byproduct from molybdenum ore at Climax and, intermittently, pyritic mill tailings from the Red Cliff district, Eagle County.

The Rico Argentine Mining Co. in 1955 began producing sulfuric acid at its plant at Rico, Dolores County. The plant has a capacity of 200 tons of acid per day. It uses pyrite mined by the company from nearby deposits. Its product is used mainly by uranium mills in southwestern Colorado and adjoining States.

The Union Carbide Nuclear Company added a sulfuric acid plant to its uranium mill at Uravan, Montrose County, in 1962. The plant has a daily capacity of 125 tons and uses elemental sulfur from Texas and Wyoming; the plant provides acid for leaching uranium ores at the Uravan plant.

Crude oil in Colorado could conceivably be a source of sulfur supply. A study of the characteristics and analyses of 92 Colorado crude oils indicated that most of the oils contained less than 0.10 percent sulfur (Wenger and others, 1957). However, oil from the Weber Standstone in the Rangely field (Rio Blanco County), the largest producing field in the State, has a moderately high sulfur content (0.7–0.8 percent). Desulfurization plants might be considered if the sulfur content should become a problem in refining the crude oil. Natural gas produced in Colorado contains relatively little sulfur. Continued exploration for oil and gas, however, may result in finding gases containing hydrogen sulfide as well as crude oils with a high-sulfur content.

Colorado oil shale contains sulfur in both the inorganic and organic portions of the oil shale, and, if commercial development of the oil shale were undertaken, it would require removal of the sulfur. In considering the economic effect of a one-million barrel per day shale oil industry upon Colorado and the nation, it has been speculated that the byproducts would include 860 tons per day of sulfur for sulfuric acid (Prien and Welles, 1957). This would constitute an additional supply for use in Colorado or for shipment to markets outside the State.

Gypsum is widely distributed in Colorado, but locally sulfur has not been recovered from this mineral.

Insofar as is known, the salt domes in southwestern Colorado do not contain deposits of sulfur.

Pyrite has been the principal source of sulfur for acid in Colorado. Supplies of pyrite are large, but only a small part of them have been used; many may not be competitive with sulfur obtained from sources in other states. Colorado's known supplies of sulfur from other sources are negligible.

CONSTRUCTION MATERIALS

CEMENT ROCK

(By J. A. Wolfe, Ideal Cement Co., Fort Collins, Colo.)

Portland cement is a complex chemical product manufactured by carefully proportioning amounts of lime, silica, alumina, and iron oxide, grinding them very finely, blending them carefully, and burning them at a temperature of approximately 2,700° F. The resultant "clinker" is finely ground with the addition of gypsum as a retarder to form the commodity which is literally the foundation of civilization. The chemical ingredients can be supplied from various sources. Most of the calcium oxide is supplied by limestone which, in turn, contains varying amounts of clay and free silica. In order to increase the amounts of silica, alumina, and iron present in limestone, it is ordinarily necessary to add argillaceous limestone or clay. In many instances it is necessary to supplement the clay with a small amount of relatively pure silica or iron ore in order to bring the chemical composition to within the very narrow tolerances specified.

The limestones, argillaceous limestones, and clays available to the manufacturer are sedimentary rocks, not chemical compounds. They contain other mineral substances which may be very deleterious in the product if present in more than minimal amounts. The undesirable constituent most frequently found in limestone is magnesia in the form of dolomite. Magnesia is also present in the clay lattice and in ferromagnesian minerals. Specifications require that magnesia not exceed 5 percent in the finished product. Because on burning there is an average loss of 38 percent CO_2 and H_2O, it is highly desirable that magnesia not exceed 2 percent in the raw material. Silica, in the form of chalcedony, is commonly excessive and eliminates many limestones from use. It is not unusual for pyrite to be excessive, the sulfur retained becoming deleterious in the finished product. Gypsum has much the same effect. Also undesirable are the alkalies Na_2O and K_2O. Federal specifications limit the combined amount of these two oxides to 0.6 percent, calculated as soda. Phosphorus is frequently found in limestones, and it is undesirable in excess of 0.5 percent P_2O_5 in the finished product.

In addition to the chemical differences, physical properties may be extremely significant. For example, chalcedony in the limestone may make grinding virtually impossible even though the chemical composition is correct. The mineralogy may make a significant difference in grinding and burning costs. Even thin interbeds of undesirable material, or the influx of ground water, structural deformation, intrusion, or burial under relatively shallow overburden may make an otherwise good deposit unacceptable.

The foregoing illustrates that, while limestone in the generic sense is considered a fairly common rock, limestone suitable for the manufacture of portland cement is restricted to a small proportion of the deposits.

In Colorado, the foremost source of limestone suitable for the manufacture of portland cement is the Niobrara Formation (fig. 39, p. 212). This formation consists of approximately 400 feet of alternating units of limestone and argillaceous limestone. Portions of this formation are presently used at both of the cement plants in the State, (fig. 39). The basal unit, which contains approximately 85 percent calcium carbonate, is 15 to 18 feet thick at the Laporte plant (No. 11, fig. 39) near Fort Collins in Larimer County and approximately 35 feet thick at the Portland plant (No. 2, fig. 39) near Canon City in Fremont County. It is directly overlain by an argillaceous limestone comprising from 50 to 65 percent calcium carbonate; this unit is approximately 120 feet thick at Laporte and 40 feet thick at Portland. The two units contain the additional ingredients essential for cement manufacture in such proportions that by blending to approximately 78 percent calcium carbonate (with the addition of some silica), regular (or Type I) portland cement can be manufactured. These two units make up the light- to dark-gray portion of the formation, which is called the Fort Hays Limestone Member.

Above the Fort Hayes Limestone Member are 200 feet of beds that are quite variable in composition, with locally abundant pyrite, which causes it to weather to buff or brown and form what is considered the "typical" Niobrara outcrop. There is sufficient kerogen in some units of the upper member to make the material equivalent to a low-grade oil shale. The lower 30 to 40 feet approaches a natural cement rock in composition, but because of an abundance of pyrite and other undesirable physical properties, it is not presently utilized.

Throughout most of eastern Colorado, the limestones suitable for the manufacture of cement are deeply buried. From Colorado Springs to the Wyoming border there is only an occasional outcrop of the Niobrara. Some of these outcrops have very little downward extension as a result of thrust faulting along the Front Range, and along much of this band the Niobrara has been faulted out altogether. In northern Colorado, most of the outcrops which appear large enough to supply significant reserves are owned by the present producer and are thought to be adequate to supply the plant for the foreseeable future. In southern Colorado, in the vicinity of Pueblo, the outcrops are extensive (fig. 39).

In the mountainous regions of the State, there are extensive outcrops of the Leadville Limestone. Although this formation has been extensively dolomitized and any local outcrop must be very carefully evaluated, there are portions of the formation which approach chemical grade limestone and are suitable for the manufacture of portland cement. Any cement plant built near a deposit in the mountainous part of the State, however, would be handicapped from having little local market and expensive transportation into the major market area of Denver. Should a major market develop in western Colorado, adequate reserves of this limestone are available to supply portland cement plants.

Locally, there are other small deposits of limestone suitable for the manufacture of portland cement, but they are too small to delineate on figure 39.

In summary, reserves of limestone suitable for the manufacture of portland cement are adequate to supply the foreseeable needs of the State, but some of these reserves are not near the major market centers.

CLAYS

(By S. H. Patterson, U.S. Geological Survey, Beltsville, Md.)

Several types of clays are mined in Colorado, and production began more than a century ago. Fire clays were mined in the Denver-Golden area in the 1860's, and the use of less valuable clays in brick making, which is one of the State's oldest industries, began in the preceding decade or earlier. Bentonite has been produced on a small scale for several years. Current information on the production of fuller's earth and pottery clays, which were formerly mined, is not available.

Clays produced in Colorado in 1962 were fire clay used in the manufacture of refractory and heavy clay products, common or miscellaneous clays used for heavy clay products, and bentonite used chiefly for lining stock ponds and irrigation ditches (Mullen, 1963, p. 242). Most of the clay used for refractory products in 1962 was mined in Fremont and Pueblo Counties, and much of the fire clay produced in Boulder, Douglas, and Jefferson Counties was used in structural clay products. Miscellaneous clays were produced in Arapahoe, Boulder, Douglas, Elbert, El Paso, Huerfano, Jefferson, Las Animas, Mesa, and Pueblo Counties. The small tonnage of bentonite that was produced in Colorado in recent years was mined in Fremont County. The total amount of clay produced in Colorado in 1962 was 801,874 short tons valued at $1,572,720 (Mullen, 1963, table 12), and in that year Colorado ranked as the 21st State in both tonnage and value of clay produced, according to a statistical summary by D'Amico (1963). The tonnage and value figure include clays and shales used for the production of lightweight aggregate, which is discussed in another chapter (p. 197). Yearly tonnage and value totals for the clays produced in the State since 1950, compiled from U.S. Bureau of Mines Minerals Yearbooks, are listed below:

Year	Thousands of tons	Value in thousands of dollars	Year	Thousands of tons	Value in thousands of dollars
1950	310	619	1957	403	978
1951	443	958	1958	449	1,111
1952	569	1,087	1959	417	1,160
1953	778	1,430	1960	490	1,424
1954	855	1,003	1961	556	1,241
1955	464	1,118	1962	802	1,573
1956	523	1,215			

The suitability of clays in Colorado for various uses depends on physical properties, which are controlled by the mineral and chemical composition of the clay. Clays are natural earthy materials composed of very fine crystalline particles (clay minerals) that are principally hydrous aluminum silicates, but may contain small amounts of iron, magnesium, potassium, sodium, calcium, and other ions. The clay minerals that occur in Colorado include kaolinite, halloysite, montmorillonite, and illite. Nonclay minerals and other impurities are present in all clays in varying quantities. Quartz, or other forms of silica, and feldspar are the most common impurities in clay deposits; appreciable amounts of organic matter are present in some sedimentary clays; and most deposits contain one or more iron oxide minerals and titanium-bearing minerals. For most uses the value of the clay varies directly with the purity of the clay mineral present; however, for some products nonclay minerals having certain properties are important. Physical properties of clays, one or more of which makes them suitable for different uses, include: plasticity, bonding strength, color, vitrification range, resistance to high temperature, deformation with drying and firing, gelation, wall-building properties, viscosity of slurries, swelling capacity, ion-exchange capacity, adsorbent properties, etc. The composition, mineral structure, methods of identification, and testing of various clays for different uses has been summarized by Murray (1960) and books by Grim (1953, 1962) contain more detailed information on these subjects.

BENTONITE AND FULLER'S EARTH

Small tonnages of bentonite have been mined in Colorado and used for several purposes. Deposits in the Tertiary Creede Formation, near Creede in Mineral County (fig. 34), were mined on a small scale for several years and used in clarifying oils (Nutting, 1943, p. 151; Larsen, 1930, p. 108–109). This deposit has been altered from rhyolitic tuff. At one locality it is more than 20 feet thick and consists of montmorillonite with minor amounts of biotite, feldspar, and volcanic glass. A few thousand tons of bentonite were mined in Bent County in the 1950's. This clay was shipped to Texas and used for drilling mud. Bentonite deposits also occur in Las Animas and Otero Counties, but there have been no reports of development of these deposits. Bentonitic clay is mined a few miles southwest of Grand Junction in Mesa County and mixed with shale to obtain a common clay having suitable plasticity for making brick and other structural clay products (Van Sant, 1959, p. 125). The Triangle-Lamberg mine, the only bentonite mine currently operated in Colorado, is in Fremont County, 15 miles southeast of Salida. Geologic descriptions of this deposit have not been published; however, volcanic rocks of Tertiary age occur at several places in this area, and the bentonite is probably associated with these rocks. The bentonite is sold chiefly for sealing irrigation ditches and stock ponds (Mullen, 1963, p. 253).

Several large deposits of bentonite occur near Westcliffe and Silver Cliff, one of which is reported to be 30 feet thick and to extend over an area of at least a square mile (Nutting, 1943, p. 152–153). Other deposits are located north of San Luis, between Kiowa and Castle Rock, southeast of Hot Sulphur Springs, and in rocks of Oligocene age in Weld and Logan counties; only the last one is shown on figure 34.

Clay deposits reported to be fuller's earth (Vanderwilt and others, 1947, p. 257) occur at Delta and along the Gunnison River in Delta County; near Grand Junction in Mesa County; at Sterling, Logan

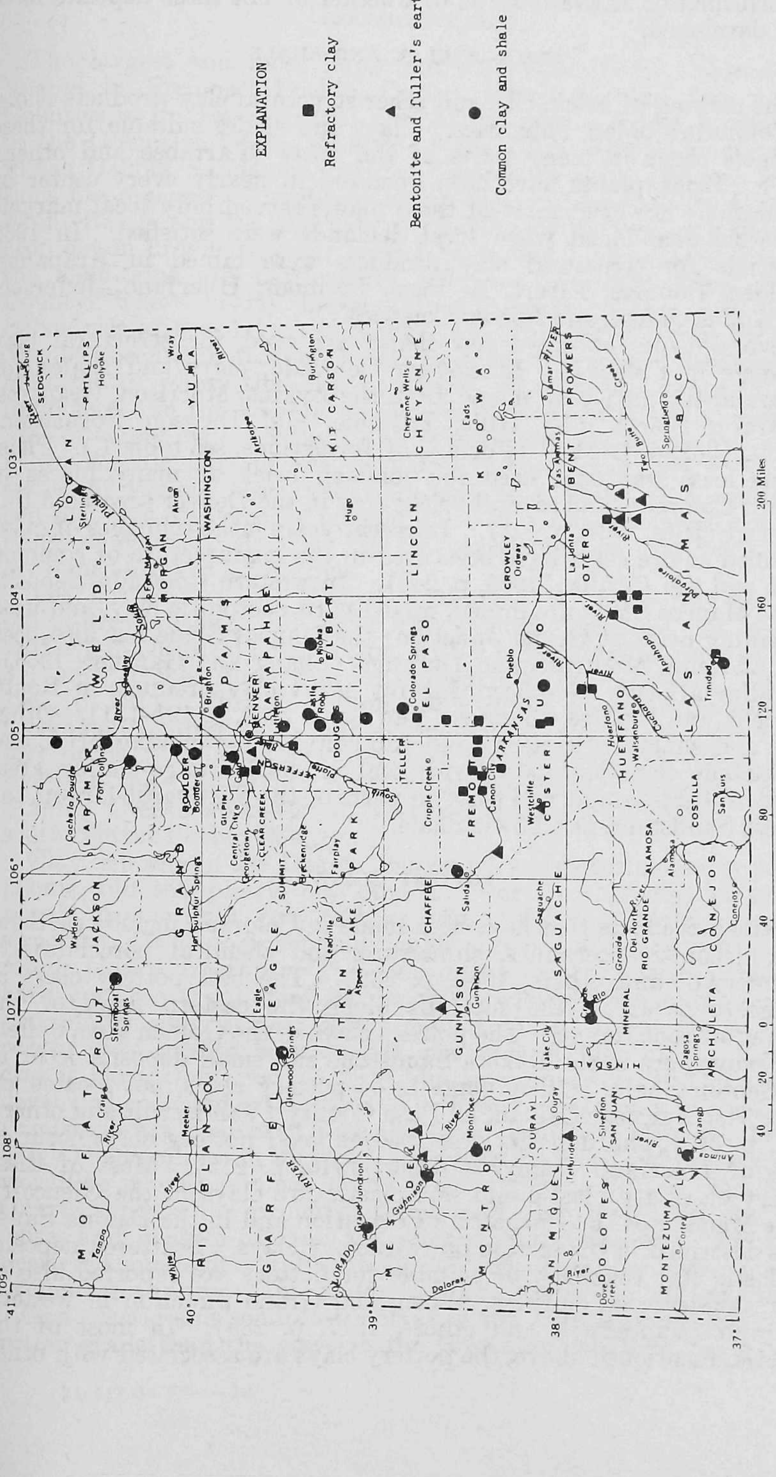


FIGURE 34.—Clay deposits in Colorado.

County; north of Akron in Washington County; and west of Denver. No information is available as to whether or not these deposits have been developed.

COMMON CLAY AND SHALE

The making of brick, tile, and other structural clay products is one of Colorado's oldest industries. Clays and shales suitable for these products occur in many parts of the State (Larrabee and others, 1947). Brick plants have been operated in nearly every center of population; however, most of these plants served only local markets and were abandoned when local demands were satisfied. In 1962 materials for structural clay products were mined in Arapahoe, Boulder, Douglas, Elbert, El Paso, Fremont, Huerfano, Jefferson, Las Animas, Mesa, and Pueblo Counties.

Several types of clays and shales are used for structural clay products in Colorado. In eastern Colorado, clays and shales for brick and tile have been mined from the Lykins, Morrison, Graneros, Niobrara, Pierre, Fox Hills, Laramie, and Dawson Formations (Scott, 1962, p. L–44). (For age of formations, see table 1.) Pleistocene loess was once used for common brick at many places in eastern Colorado, and several brickyards in the Denver area used this material (Ries, 1927, p. 401). In recent years large tonnages of clays classified as fire clays have been used in the manufacture of common brick and tile (Mullen, 1963, p. 242). In western Colorado, deposits in the Mancos Shale are mined, mixed with bentonitic clay, and used in making brick at Grand Junction; the Mancos Shale has also been used at Delta, Montrose, and Durango (Shaler and Gardner, 1906); and alluvial clays have been dug for heavy clay products in Routt, Garfield, and Chaffee Counties (Van Sant, 1959, p. 121–131). Other clays and shales in western Colorado suitable for making brick and tile include clays associated with coal in the Durango-Gallup area, shales of Jurassic age, and clays in parts of the Mesaverde Group, the Dakota Sandstone, and Lewis Shale.

POTTERY CLAYS

Pottery products that have been made in Colorado include earthenware, decorative ceramics, chinaware, and chemical porcelainware (Vanderwilt and others, 1947, p. 239). The best pottery clays in the State occur in the foothills along the eastern flank of the Colorado Front Range. The pottery clays in the Golden area, Jefferson County, are in the Dakota Sandstone and small deposits occur in the Benton Shale. Other deposits of pottery clays, not located on figure 34, occur near Calhan, El Paso County (Vanderwilt and others, 1947, p. 240), and deposits described as good pottery clays occur in parts of Huerfano County (Butler, 1915, p. 215). Most of these pottery clays are plastic and semiplastic fire clays in the Glencairn Shale Member of the Purgatoire Formation and in the Dakota Sandstone described in the section on refractory clays. Scattered deposits of plastic clay that may be suitable for pottery are reported also to occur at Glenwood Springs, Aspen, and Grand Junction in western Colorado (Vanderwilt and others, 1947, p. 239). In most of the localities mentioned above, the pottery clays are associated with other types of clay; no separate symbol is shown for pottery clays on figure 34.

REFRACTORY CLAY

The largest and most important clay deposits in Colorado are located in Fremont, Pueblo, Custer, Huerfano, and Las Animas Counties in the south-central part of the State. These deposits are in the Glencairn Shale Member of the Purgatoire Formation and in the Dakota Sandstone, both of Cretaceous age. The two formations are exposed in hogbacks along the south end of the Colorado Front Range and the east side of the Wet Mountains, and they also crop out in broad irregular belts farther east. The outcrops east of the mountains are particularly extensive in south-central Pueblo County, where nearly horizontal clay-bearing strata are cut by tributaries of the Arkansas River. The clay in the Glencairn Shale Member occurs in tabular lenses near the top of the member. At most places where this clay is mined, its thickness ranges from 5 to 20 feet. In the Dakota Sandstone, the clay is in a discontinuous unit of sandy clay, fire clay, and even-bedded sandstone that occurs in the middle part of the formation. These clays are in isolated bodies of various sizes, and they may be remains of a continuous bed that was dissected by erosion prior to the deposition of the overlying sandstone. Most of the Dakota Sandstone clay bodies that are mined are 3 to 8 feet thick.

The fire clay in the Glencairn Member is bluish-gray to light-bluish-gray, plastic, and parts with a blocky fracture. It is fairly uniform in chemical composition, with a silica-alumina ratio of about 3:1 and fusible impurities of approximately 5 percent (Waagé, 1947, p. 237). This clay is only low grade to semirefractory, but is commonly mixed with higher grade clays to obtain a more refractory product. Clay in the Glencairn Member has been mined extensively in the Canon City district, in the hogback between Oil and Sixmile Creeks northeast of Canon City, and at Capers Spur in south-central Pueblo County.

Clay deposits in the Dakota Sandstone consist of an upper zone of plastic and semiplastic clay and a lower zone of flint clay. The plastic clay is light gray to blue gray and has a blocky to massive structure. It is compact and tough and parts with a splintery to rough blocky fracture. The semiplastic clay is black, moderately hard and has a splintery to poorly developed conchoidal fracture. Semiplastic clay is the least common of the three types, and it occurs only locally between the plastic and flint clay. The flint clay is hard, light gray to light-blue gray, massive, and has a well-developed conchoidal fracture. All three types of clay in the Dakota Sandstone are composed principally of kaolinite (Waagé, 1953, p. 38). The kaolinite in flint clay is fine grained, but plates, books, and wormlike masses as much as 0.2 mm long occur in the plastic clay. Quartz sand is the principal impurity in the flint clay, and small lenses and pockets of sand are present in the clay at a few places. Scattered muscovite grains up to 0.05 mm long and minor amounts of nontronite and organic matter also are present in some of the clay.

The plastic and semiplastic clays in the Dakota Sandstone are of better grade than the clays in the Glencairn Member, being white-

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burning semirefractory to refractory clay. Nonsandy plastic clay contains less than 5 percent of fusible impurities (Waagé, 1947, p. 237) and has an average Al_2O_3 content of 29 or 30 percent. Most of this clay fuses at about cone 29 (2,984° F.), and samples fusing up to cone 31 (3,056° F.) are not uncommon. The flint clay is a white-burning highly refractory clay that fuses between cones 31 and 36 (3,290° F.). It is fairly uniform in composition, and the only major impurity variation is in silica content, which is related to the amount of quartz sand present. The Al_2O_3 content of nonsandy flint clay is approximately 35 percent and the fusible impurities are low.

RESOURCES AND OUTLOOK

Clays in the Dakota Sandstone have been mined extensively in the Turkey Creek district, Pueblo County, where both the Purgatoire and Dakota Formations are exposed on the southeast-plunging Red Creek anticline. Several mines are located in the Stone City area on the southwest limb of this same anticline. Clays in the Dakota Sandstone are also mined in the Canon City district, Fremont County, and in the Rock Creek area, Pueblo County. The largest reserves of these clays are in the Stone City and Hell Canyon areas of the Turkey Creek district, where indicated and inferred reserves of flint clay was estimated to be 2.5 million tons and the plastic clay 1.2 million tons (Waagé, 1953, p. 70). Other reserves of this clay are present in the Beulah, Canon City, and Penrose districts, Fremont County; Wetmore area, Custer County; Capers area, Huerfano and Pueblo Counties; and in the Cucharas Canyon area, Huerfano County (Waagé, 1953, p. 70–90), but no estimates of the amount of clay in these deposits are available.

Refractory clay and clay shale deposits in the northern Front Range occur in the Lower Cretaceous South Platte and Lytle Formations of the locally recognized Dakota Group which are approximately equivalent to the Dakota Sandstone shown in table 1. These deposits extend in a narrow belt from near Boulder, Boulder County, to the northwestern part of Douglas County. The largest and most abundant deposits are in the Van Bibber Shale Member of the South Platte Formation. Other deposits occur in the sandstone unit overlying the Van Bibber Member, and a few scattered deposits are present near the top of the Lytle Formation (Waagé, 1961, p. 1). The best grade clays in the Van Bibber Member are almost pure kaolinite (Waagé, 1961, p. 26), and probably this mineral is abundant in the other clays. Deposits of refractory clay and shale in the Golden area have been mined intensively since the 1860's, and many of the best grade and cheaply mined deposits are exhausted. For this reason, and because many of the remaining deposits are in areas where mining rights cannot be obtained, and others are of low quality due to high-iron content, the Golden area has little reserve potential other than clays left in working mines (Waagé, 1961, p. 88). A considerable tonnage of clay remains, however, in lands where mining rights cannot be obtained, and presumably large resources remain at depths greater than the limits of profitable clay mining. A few refractory clay deposits are mined in southern Jefferson County (Scott, 1962, pl. 1); however, most deposits in this area are small and lenticular and refractory clay potential in this area is not great (Waagé, 1961, p. 69–71). The refractory clay resources in northwestern Douglas County are also not large. Low-grade fire clay is mined in this region, however, from a pit located approximately 6 miles south of Littleton (Scott, 1962, p. L–44). The clay at this locality is in the Dawson Formation. No appraisal of the total resources of low-grade fire clays in this formation have been made.

Clays suitable for low-grade refractory products occur at several places in western Colorado, and some deposits suitable for high heat-duty products may be present. Small quantities of low-grade fire brick for local use have been produced at Glenwood Springs, Delta, Montrose, and Durango. Low-grade refractory clays were found near these towns and at a number of other localities in western Colorado during a reconnaissance by the U.S. Bureau of Mines (Van Sant, 1959, p. 120–135). Two samples from San Miguel County and one from Montezuma County tested by the Bureau of Mines were suitable for high heat-duty refractory products. All three samples were collected from thin strata in the Dakota Sandstone. Though a number of samples were tested by the Bureau of Mines, the fire clay potential in extensive areas of Dakota outcrops have not been examined and valuable fire clay deposits may be present.

Colorado is amply supplied with common clay and shale suitable for making brick, tile, and other structural clay products. Shale resources in formations of Triassic, Jurassic, and Cretaceous ages in eastern Colorado and shale of Cretaceous age in western parts of the State are virtually inexhaustible. Large resources of low-grade fire clays of the type that is presently used for structural clay products are present in the foothills belt east of the Front Range and at several localities in western parts of the State. Total quantities of these clays have not been estimated but are probably adequate to supply Colorado's structural clay products industry for many decades. These resources are not inexhaustible, however, and local supplies will be depleted from time to time and mines will have to be opened at other localities.

The outlook for the use and future value of bentonite and fuller's earth resources in Colorado cannot be appraised because neither type of clay has been adequately investigated, and information on the size of deposits and their quality is not available. Total resources of these two types of clays are undoubtedly very large. The fuller's earth deposits that have been mined in Colorado may not be of superior quality, as is suggested by the lack of production in recent years while deposits in Utah have been mined almost continuously. That the bentonite deposits are also not of superior quality or are otherwise unfavorable for mining is suggested by the low tonnage of the bentonite produced, whereas large tonnages are shipped from northeastern and north-central Wyoming to many states and foreign countries. High-quality bentonite and fuller's earth deposits that could be mined cheaply may be present, however, in undeveloped deposits that have not been tested.

Colorado is the leading producer of refractory clay in the Rocky Mountain Region and can be expected to maintain this position. Though the high-quality fire clays in the northern Front Range are nearing exhaustion, reserves in the south-central part of the State are adequate to supply Colorado's refractory industry for several years. The high-grade flint clay in the Dakota Sandstone is the only present source of refractory clays suitable for high heat-duty products in the entire Rocky Mountain Region. The demand for this clay, which is used both locally and to supply a plant at Lehi, Utah (Mullen, 1963, p. 262), can be expected to continue.

GYPSUM AND ANHYDRITE

(By C. F. Withington, U.S. Geological Survey, Washington, D.C.)

Gypsum and anhydrite are both calcium sulfate minerals. Most commonly they occur in beds formed by precipitation from natural saline waters, chiefly in partly isolated arms of the sea. Precipitation occurs as these bodies of water evaporate and become enriched in dissolved salts. Most deposits of natural salt and potash minerals also form and occur in the same manner, and in places in Colorado they are associated with beds of gypsum and anhydrite. Collectively, these four commodities are commonly called evaporites. Salt and potash minerals, however, have different uses from those of gypsum and anhydrite, and they are also mined differently, so they are described separately. Gypsum and anhydrite occurrences in Colorado are described below and their distribution is shown on figure 35. Salt and potash are described on page 173 and their distribution is shown on figure 32.

Gypsum and anhydrite occur in considerable quantities in many parts of the United States. The resources of both minerals are great, though many of the deposits are in areas too far from consuming centers to be worked profitably. Gypsum is the more useful of the two minerals; about 10 million tons was produced in the United States in 1962. No comparable figures are available for anhydrite production, but probably no more than 200,000 tons were produced in 1962.

Gypsum is hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$); when pure it contains 32.5 percent lime (CaO), 46.6 percent sulfur trioxide (SO_3), and 20.9 percent water. Pure gypsum is generally white or light to dark gray; impurities may color the gypsum pink, black, green, or yellow. It is one of the softest minerals, and may be easily scratched with the fingernail. The most common form is massive rock gypsum, a compact aggregate of small crystals. Alabaster is a compact, very fine-grained gypsum, generally white to light colored. Other varieties include satin spar and selenite. The presence of selenite in gypsum deposits is detrimental for most uses as the selenite crystals cannot be ground fine enough. Gypsite is an impure earthy secondary gypsum, commonly found at the surface of gypsum deposits, and rarely is more than 10 feet thick. Rock gypsum and alabaster resemble both calcite and talc; however, they do not effervesce in hydrochloric acid as calcite does, nor do they have the greasy feel of talc.

Anhydrite is calcium sulfate and when pure contains 41.19 percent CaO and 58.8 percent SO_3. It is slightly heavier and harder than

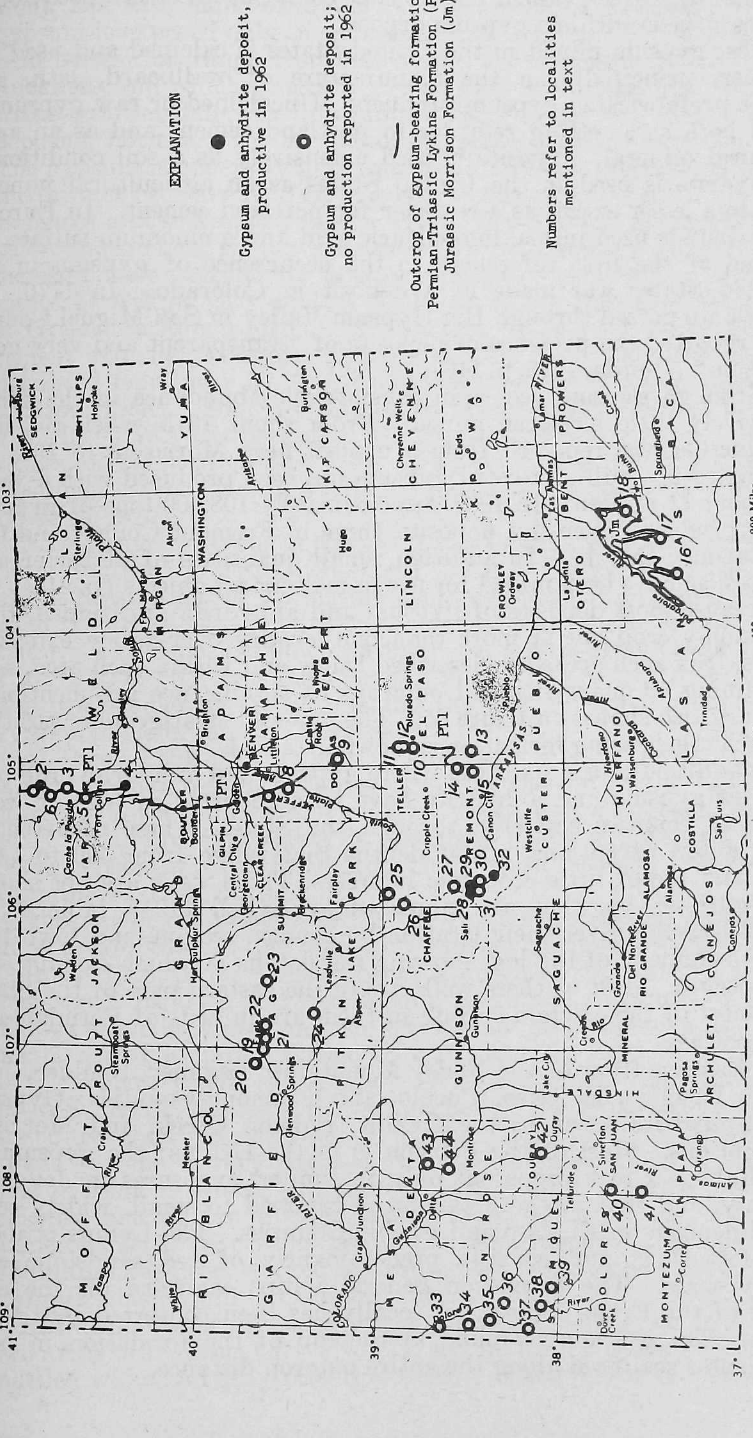

FIGURE 35.—Gypsum and anhydrite in Colorado.

gypsum. Anhydrite may be gray, bluish gray, or white. It occurs as fine- to coarse-grained masses that comprise an entire body, or as lenses or beds within a gypsum deposit.

Most gypsum mined in the United States is calcined and used for plaster, principally in the manufacture of wallboard, lath, and other prefabricated gypsum products. Uncalcined or raw gypsum is used both as a setting retarder in portland cement and as an agricultural mineral. Gypsite is used extensively as a soil conditioner. Anhydrite is used in the United States as an agricultural mineral and to a lesser extent as a retarder for portland cement. In Europe, anhydrite is used in making sulfuric acid and ammonium sulfate.

One of the first references to the occurrence of gypsum in the United States was made of a deposit in Colorado. In 1776, Fr. Escalante passed through Big Gypsum Valley in San Miguel County and reported the presence of deposits of "transparent and very good gypsum" (Bolton, 1950, p. 146).

Although gypsum occurs in considerable abundance in the State, relatively little has been mined. From about 1875, when the first production was reported from a deposit near Morrison, to 1962 an estimated 2½ million tons of gypsum has been produced with a value of about $4 million. In 1962, approximately 108,000 tons of gypsum were produced from five deposits, three in Fremont County and two in Larimer County. In addition, small quantities of alabaster and satin spar have been mined for use in making art objects (p. 215).

Because most deposits of gypsum and anhydrite are bedded, they commonly crop out at more than one locality over fairly extensive areas. Six such areas are described below and within each area, sites of mining or quarrying and outcrops of significance are mentioned and are also shown on figure 35. The age and stratigraphic position of each salt-bearing formation is shown in table 1.

In addition to the six areas where gypsum and anhydrite crop out, beds of gypsum and anhydrite have been reported in logs of wells from 19 counties scattered through the State. These occurrences, with a few exceptions, are at depths that range from 500 to 5,000 feet, and are of little economic interest. These wells are not shown on figure 35, but they are tabulated by Argall (1949, table 83, p. 232–233), who gives their location by county, section, and township, and a summary of the log, showing the depths at which calcium sulfate occurs. Most of these wells are in the eastern part of the State, and most of the calcium sulfate in them are in beds of Permian and Jurassic age.

1. Eastern front of the Rocky Mountains; Larimer, Boulder, Jefferson, Douglas, El Paso, Pueblo, and Fremont Counties: Gypsum and anhydrite occur in the Lykins, Ralston Creek, and Morrison Formations. Most of the gypsum is in the Lykins; the gypsum in the Ralston Creek crops out only in limited exposures in Jefferson County, and that in the Morrison is confined to small, widely scattered deposits in El Paso and Pueblo Counties. The Lykins is about 800 feet thick and consists predominantly of red sandstone and sandy shale. The formation generally dips eastward off the east flank of the Front Range, but locally has been contorted into tight folds. The gypsum is found at the top of the formation in beds and lenses scattered along the entire outcrop distance.

Although the Lykins Formation crops out almost continuously along the east flank of the Front Range across Larimer County, gypsum is exposed only in six areas (Nos. 1–6, fig. 35). The gypsum is in lenses that range from less than 1 foot to more than 50 feet in thickness, and which generally extend only a few hundred feet along strike, grading laterally into impure red gypsum and shale. Larger deposits, however, can be traced for about a mile along the strike. The gypsum is generally gray, massive and finely crystalline; some of the thinner beds are reddish alabaster. Anhydrite is generally found as lenses and scattered crystals within the gypsum at about 30 feet below the surface, deeper it becomes the predominant mineral. Two deposits were worked by open-pit methods in 1962; gypsum was mined at Arkins (No. 4; T. 5 N., R. 69 W.) for making plaster and at Greenacre Ranch (No. 2; T. 11 N., R. 69 W.) for use as portland cement retarder (George, 1920). In the past, alabaster has been produced from near Ft. Collins (No. 5) for use in art objects (Williamson, 1963). Some gypsum from Owl Canyon (No. 3; sec. 7, T. 9 N., R. 69 W.) has been used for portland cement retarder. Occurrences at Table Mountain (No. 1; T. 11 N., Rs. 69–70 W.) and on Deadman Butte (No. 6, T. 10 N., R. 70 W.) have been prospected (George, 1920).

No gypsum crops out in the Lykins in Boulder and Jefferson Counties. South of Morrison, Jefferson County, however, the basal part of the Ralston Creek Formation contains lenses of gypsum, as much as 20 feet thick, associated with gray shale and limestone beds (Scott, 1962). The deposits shown on figure 36 are on Deer Creek (No. 8; T. 6 S., R. 69 W.) and Bear Creek (No. 7; T. 5 S., R. 70 W.), which was worked before 1875, yielding the first reported production of gypsum in Colorado (Wilber, 1883).

At Perry Park (No. 9; secs. 23 and 24, T. 9 S., R. 68 W.) gypsum is in a massive bed 20 to 50 feet thick at the top of the Lykins and crops out for a distance of 4 miles at the base of a hogback that dips 25°E. Anhydrite probably is abundant below a depth of 30 feet. Some gypsum was produced from this deposit between 1898 and 1901 (Santmyers, 1929, p. 10).

Gypsum in the upper part of the Lykins Formation crops out in three areas (Nos. 10–12) west of Colorado Springs, El Paso County (Finlay, 1916, p. 7). The gypsum is in lenses that thicken and thin over short distance, and that have a maximum thickness of 90 feet. The gypsum is white, pinkish white, and pink, massive and dense. north side of Fountain Creek (No. 10; sec. 10, T. 14 S., R. 67 W.), at Glen Eyre where the gypsum is 20 feet thick (No. 11; sec. 27, T. 13 S., R. 67 W.), and in the Garden of the Gods where the beds are 60 feet thick (No. 12; sec. 34, T. 13 S., R. 67 W.). Although some of the gypsum is very pure, much of it contains interstratified clay. The gypsum is white, pinkish white, and pink, massive and dense. Selenite masses are present along fractures in the gypsum, and numerous satin spar veins are in the shales below. The deposit on Fountain Creek was worked intermittently from about 1875 to 1907 to supply a plaster mill in Colorado City.

In Pueblo County gypsum in the Morrison Formation crops out in two areas near Stone City (No. 13; sec. 4, T. 18 S., R. 67 W.). It is mottled white and gray (George, 1920). Some has been used as portland cement retarder. Gypsite occurs in recent lake sediments about 14 miles south of Pueblo, and it has been used locally for plaster. This locality is not shown on figure 35.

White to pink gypsum, in beds 1 to 5 feet thick, occurs in the Morrison Formation along Beaver Creek (No. 14; T. 17 S., R. 68 W.) and at Eight Mile Park (No. 15; sec. 6, T. 18 S., R. 68 W.), Fremont County. Some gypsum has been produced from these deposits for use as a retarder in portland cement (Argall, 1949, p. 229–230).

2. Southeastern Colorado; Las Animas, Otero, and Bent Counties: The Morrison Formation crops out along the Purgatoire River and Muddy Creek and their tributaries in Las Animas, Otero, and Bent Counties. It contains beds and lenses of gypsum in places. Along Chacacua Creek (No. 16; T. 31 S., R. 56 W.), a 17-foot thick bed of white sandy gypsum near the base of the formation is overlain by 20 feet of gypsum interbedded with gray clayey sandstone lenses (Duce, 1924, p. 85). Near Officer (No. 17; T. 30 S., R. 54 W.), a few tons of gypsum with an alabaster texture has been mined for ornamental objects. Thin beds of gypsum are poorly exposed along the Johnnie Branch (No. 18; T. 28 S., R. 52 W.).

3. Eagle basin area; Eagle, Pitkin, and Garfield Counties: Gypsum and anhydrite are abundant in the Eagle Valley Evaporite in the Eagle basin; some salt is also present (p. 176). Gypsum and anhydrite are exposed along the Eagle and Colorado Rivers near Eagle, along Frying Pan Creek north of Aspen, and along Rifle Creek north of Rifle. The Eagle Valley Evaporite has been cut by a few test oil wells in the same general area, but its exact limits are not known. Although the Eagle Valley Evaporite has not been formally correlated with the Minturn Formation evaporites that crop out along the Arkansas River near Salida and Canon City, Brill (1952) suggests that they are the same.

Gypsum is well exposed on both sides of the Eagle River from Eagle to Dotsero; west of Minturn on the south side of the Eagle River; and along Frying Pan Creek near Ruedi. The evaporite beds at Eagle are as much as 4,700 feet thick (Lovering and Mallory, 1962, p. D–48), and consist of anhydritic and gypsiferous mudstone and siltstone with some bedded gypsum and salt; the bedded evaporites increase in amount westward. The gypsum exposed on the surface is dark gray to white, and is interbedded with reddish-brown gypsiferous shale, which is less resistant than the gypsum; the gypsum, although it too is weathered, stands out in rounded hills and small escarpments above the surrounding shale. Much of the gypsum is masked by impure buff to tan, fine-grained gypsite as much as 10 feet thick, but where the gypsum is exposed in gullies, it appears to be in three or more beds, each as much as 50 feet thick associated with thin beds of calcareous shale and limestone. At Deep Creek (No. 20; T. 4 S., R. 87 W.) the gypsum is in six beds, interbedded with shale, through a stratigraphic interval 1,000 feet thick (Brill, 1944). The gypsum has been folded and locally thickened to as much as 150 feet by plastic flowage into the crests of anticlines. Other localities include those near the towns of Gypsum (No. 21; sec. 7, T. 5 S., R. 85 W.) and Avon (No. 23; sec. 1, T. 5 S., R. 84 W.), described by Burchard (1911), and the localities at Dotsero (No. 19; sec. 34, T. 4 S., R. 68 W.) and at Eagle (No. 22; secs. 5 and 6, T. 5 S., R. 84 W.).

Although some prospecting of the gypsum has been done in many parts of the area, the only major production has come from Ruedi (No. 24; sec. 2, T. 8 S., R. 84 W.). The gypsum, which was mined by open-pit methods from 1907 to 1911, is light to dark gray and white, fine grained and massive, in beds about 50 feet thick (Burchard, 1911, p. 363). Williamson (1936, p. 7) reports some production south of the town of Gypsum for use as a retarder.

Although much of the gypsiferous rock exposed on the surface averages more than 85 percent gypsum, masses of nearly pure anhydrite are found near the surface (Burchard, 1911, p. 365), and anhydrite probably predominates at a depth of about 40 feet.

4. Arkansas River area; Chaffee, Fremont, and Park Counties: The Minturn Formation contains some gypsum and anhydrite in places in its drainage area in Chaffee and Fremont Counties and in South Park, Park County, just east of this drainage area.

In the southwestern part of South Park (No. 25; T. 12 S., R. 76 W.) and nearby in Chaffee County (No. 26, T. 13 S., R. 77 W.), the gypsum beds are as much as 50 feet thick. Although readily accessible to U.S. Highway 24 and 285, only a little prospecting and no mining has been done (DeVoto, 1961, p. 235).

The gypsum-bearing portion of the Minturn Formation crops out in a band that extends from 5 miles east of Salida, southeastward along the Arkansas River Valley to Coaldale in Fremont County, a distance of 16 miles. The outcrop of the Minturn Formation is about 4 miles wide throughout the entire distance. To the north these beds are faulted against granite; south of Coaldale the Minturn becomes more clastic, and gypsum is absent. The gypsum is exposed only in isolated masses along the length of the outcrop zone. All localities shown on figure 35 are in Fremont County. Brill (1952, p. 821) has named the gypsum the Swissvale Gypsum Member of the Minturn Formation, after a station on the railroad in the outcrop belt.

Gypsum in the northern part of the belt consists of thin impure brownish-yellow, gray, or black gypsum lenses alternating with brown and black shale at the base, grading upward into white massive gypsum (Brill, 1944; Reeves, 1961). In 1962 gypsum was produced from Maverick Gulch (No. 28; secs. 7, 8, 17, and 18, T. 49 N., R. 10 E.), and Tumble Mountain (No. 29; sec. 9, T. 49 N., R. 10 E.), for use as a soil conditioner. Outcrops of gypsum occur in Badger Creek (No. 27; sec. 10, T. 50 N., R. 10 E.).

Isolated lenses of gypsum crop out along both sides of the Arkansas River between Swissvale (No. 31; sec. 21, T. 49 N., R. 10 E.) and Coaldale (No. 32; SW¼, T. 48 N., R. 11 E.). The gypsum lenses are as much as 15 feet thick and are scattered through a stratigraphic range of 125 feet. Gypsum has been mined from the deposit at Howard (No. 30; sec. 36, T. 47 N., R. 10 E.) for use as cement retarder (Williamson, 1963, p. 7).

At Coaldale at the southern edge of the belt, gypsum was mined in 1962 to make plaster and plaster products for use as a retarder. The gypsum, which is in five beds that dip from 25° to about 72° E., is white to light gray, and is interbedded with bands of gray and black shale, some of which are as much as 15 feet thick. Selenite is scattered through the gypsum as thin seams and isolated masses as much as 1 foot in diameter. Anhydrite occurs with the gypsum at depths of 65 feet below the surface. The gypsum has been folded and thickened locally by plastic flowage to more than 200 feet. Angular fragments of limestone and shale have been plucked from the underlying beds and included in the gypsum.

5. Northeast part of Paradox Basin; Mesa, Montrose, and San Miguel Counties: In Mesa, Montrose, and San Miguel Counties, gypsum in the Paradox Member of the Hermosa Formation crops out along the floors of Sinbad, Paradox, and Gypsum Valleys, each northwest-trending structural valleys, formed by collapse upon the removal of great thickness of salt in the Paradox. The gypsum occurs as cap rock on top of the salt. At the outcrop, the gypsum has weathered to gypsite to as much as 6 feet below the surface, but in exposures seen in gullies, the gypsum is white to gray and granular, and mixed with black shale. No exact measurement of the gypsum is possible, because the gypsum is badly contorted. The resources of gypsum are undoubtedly large but cannot be estimated without detailed drilling.

Sinbad Valley (No. 34; T. 49 N., R. 19 W.), Mesa County, is the smallest of the three valleys. The outcrop of the Paradox Member extends over an area of only about 4 square miles (Shoemaker, 1956).

In Paradox Valley, Montrose County, gypsum is exposed in isolated outcrops in the bottom of the valley over an area at least 8 miles long and 1½ miles wide. East Paradox Valley (No. 36) contains more gypsum at the outcrop than does West Paradox Valley (No. 35). As alluvial material covers much of the rest of the valley floor, as much more gypsum may be present as that exposed (Withington, 1955; Cater, 1955; Shoemaker, 1956).

In Gypsum valley, San Miguel and Montrose Counties, the Paradox Member is exposed in three areas. The largest area is in the southeastern part (No. 37), where the Paradox crops out over an area about 3½ miles long and 2 miles wide; the second area (No. 38), east of the Dolores River, contains considerable quantities of gypsum at the outcrop; and the third, in Little Gypsum Valley (No. 37), is less accessible than the other areas, and the extent of gypsum is uncertain.

Gypsum also occurs southeast of Gateway (No. 38; sec. 35, T. 51 N., R. 19 W.), Mesa County, in the Moenkopi Formation. It is in a bed about 3 feet thick and has an alabaster texture. Some of this material has been used for building blocks and art objects.

6. San Juan Mountains and Black Canyon areas: Scattered occurrences of gypsum are reported in the Hermosa Formation in Dolores and La Plata Counties and in the Wanakah Formation in Ouray County. These occurrences probably have little or no commercial value, but they are interesting because they are host rocks to part of the precious- and base-metal deposits in some mining districts. Along part of the Black Canyon in Montrose and Delta Counties, beds at the same stratigraphic position as the Wanakah Formation, and with similar lithologic characteristics, also contain gypsum and have yielded a small production.

Near Rico (No. 40; T. 40 N., R. 10 W.), Dolores County, gypsum, which occurs near the base of the Hermosa Formation, is found only in the silver mines of the area (Ransome, 1901, p. 337–339). The gypsum is 15 to 30 feet thick and is silvery gray and fine grained. The surface expression of the gypsum is the "Enterprise Blanket" on Newman Hill, which consists of an unconsolidated breccia in a series of shales, sandstones, and limestones.

A small exposure of gypsum near the base of the Hermosa near Hermosa Creek, La Plata County (No. 41; T. 38 N., R. 10 W.), is probably at the same stratigraphic horizon as that at Rico (Ransome, 1901). Other calcium sulfate deposits might be found between the Hermosa Creek and the Rico occurrences, but they would be deeply buried, and would probably be predominantly anhydrite.

Gypsum in Ouray County is found in beds and lenses in the Pony Express Limestone Member of the Wanakah Formation (Burbank, 1930, p. 172–176). The beds, which range from about 2 feet to 50 feet in thickness, occur along the Uncompahgre River Valley at Portland, about 6 miles north of the town of Ouray (No. 42; sec. 35, T. 45 N., R. 8 W.). The gypsum grades laterally into a breccia, which, being porous, seems to form a host rock for the localization of ore. The gypsum is white and banded with crinkly black shale layers. The thicker deposits are in nodular masses, roughly bedded, and contain layers of black interstitial shale beds and partings. Burbank believed that the solution of the gypsum began shortly after the deposition of the overlying sandstone, and that much of the gypsum now missing was removed by ground water by the end of Cretaceous time.

In Montrose and Delta Counties gypsum crops out along the walls of the northern part of the Black Canyon of the Gunnison River. Although published literature on the area (Siebenthal, 1906; George, 1920; and Withington, 1962) places the gypsum in the Morrison Formation, the gypsum-bearing beds are below the Morrison of modern usage and in beds at the same stratigraphic position as the Wanakah Formation and with similar lithology. The gypsum is white and granular and in beds or lenses 1 to 60 feet thick. A bed 4 to 8 feet thick at the base of the gypsum-bearing unit is fairly continuous near the mouth of Smith's Fork (No. 43; T. 15 S., R. 93 W.) and in Red Rock Canyon (No. 44; T. 50 N., R. 9 W.). Some of this gypsum has been used as a soil conditioner.

LIGHTWEIGHT AGGREGATES

(By A. L. Bush, U.S. Geological Survey, Denver, Colo.)

Concretes and plasters are made from a mixture of cement, water, and any one of a large number of aggregate materials. Sand and gravel aggregates are most frequently used and normally weigh from about 150 to 170 pounds per cubic foot; concrete made with these materials ranges from about 140 to 160 pounds per cubic foot, depending upon the proportions of the three ingredients and the specific gravity of the aggregate. Lighter weight concretes and plasters, with better insulating properties, are prepared by substituting lightweight aggregates for sand and gravel. Many widely differing materials have been used (U.S. Bureau of Mines, 1960), such as expanded blast furnace slag; coal ash and cinders; expanded clays, shales, and slates; pumice and scoria; vegetable hulls and fibers; and hailstones and wax pellets. These materials range in weight from about 6 to 70 pounds per cubic foot; they result in concretes and plasters that range from about 25 to 100 pounds per cubic foot (American Society for Testing Materials, 1962), and that have adequate to excellent thermal and acoustical insulating properties. The common uses for lightweight aggregates are in lightweight structural concrete, in curtain walls, floors and bridge decks, roof slabs and shells, in concrete masonry units as blocks and bricks, in thermal and acoustical insulating plasters, and as loose-fill insulation (particularly perlite and vermiculite.)

This report is concerned with the following naturally occurring mineral aggregates: scoria and pumice (which require no further expansion); clay, shale, perlite, and vermiculite (all of which require further expansion by heating); and to a very minor extent, volcanic ash or pumicite (which can be used either raw or expanded). All of these types occur in Colorado, and many of their sources have been described by Bush (1951). Of the other materials, only expanded blast furnace slag and cinders have been widely used.

Prior to World War II only minor amounts of lightweight aggregate were mined in Colorado. Some vermiculite was produced, mostly for use as loose-fill insulation, and sporadic production continued during the war. Total value never exceeded a few thousand dollars a year. The sustained growth of the industry began in 1947, with the mining and processing of perlite from the Rosita Hills district, Custer County. A moderate amount of pumice or scoria was mined in 1949 in Park County, and larger scale scoria production began in 1950 in Costilla County and in 1953 in Routt County. Most perlite was produced for markets in the East and the Middle West, whereas most scoria was used locally. The dollar value of combined production increased until more than $800,000 was recorded for both 1955 and 1956, but it decreased by several hundred thousand dollars in 1957 and amounted to only about $50,000 in 1958 and less than $100,000 in 1959. This decrease resulted entirely from the cutting back of perlite production from a record value of $725,270 in 1956 to the virtual ending of mining and processing in 1958. For the past few years perlite has been produced at an annual rate of a few thousands or tens of thousands of dollars. Scoria production has been rather consistent, ranging from about $40,000 to $60,000 a year since 1956. Production of expansible clay and shale for local markets began on a large scale in 1959 and has increased markedly since, so that total lightweight aggregate production in 1963 (on the basis of preliminary figures) was about $400,000. The value of lightweight aggregate production has ranged from 0.02 percent of Colorado's total mineral production (exclusive of fuels) in 1947 to 0.79 percent in 1955, and was about 0.3 percent for 1962. Known sources of lightweight aggregate in Colorado are shown on figure 36.

Many kinds of clays and shales expand ("bloat") to two or three times their original volume when crushed and rapidly heated to 1,800°–2,200° F. The suitable clays and shales seem to be those that are dominantly montmorillonitic or illitic; the kaolinitic materials generally are unsuitable. Clays and shales of marine, littoral, lacus-

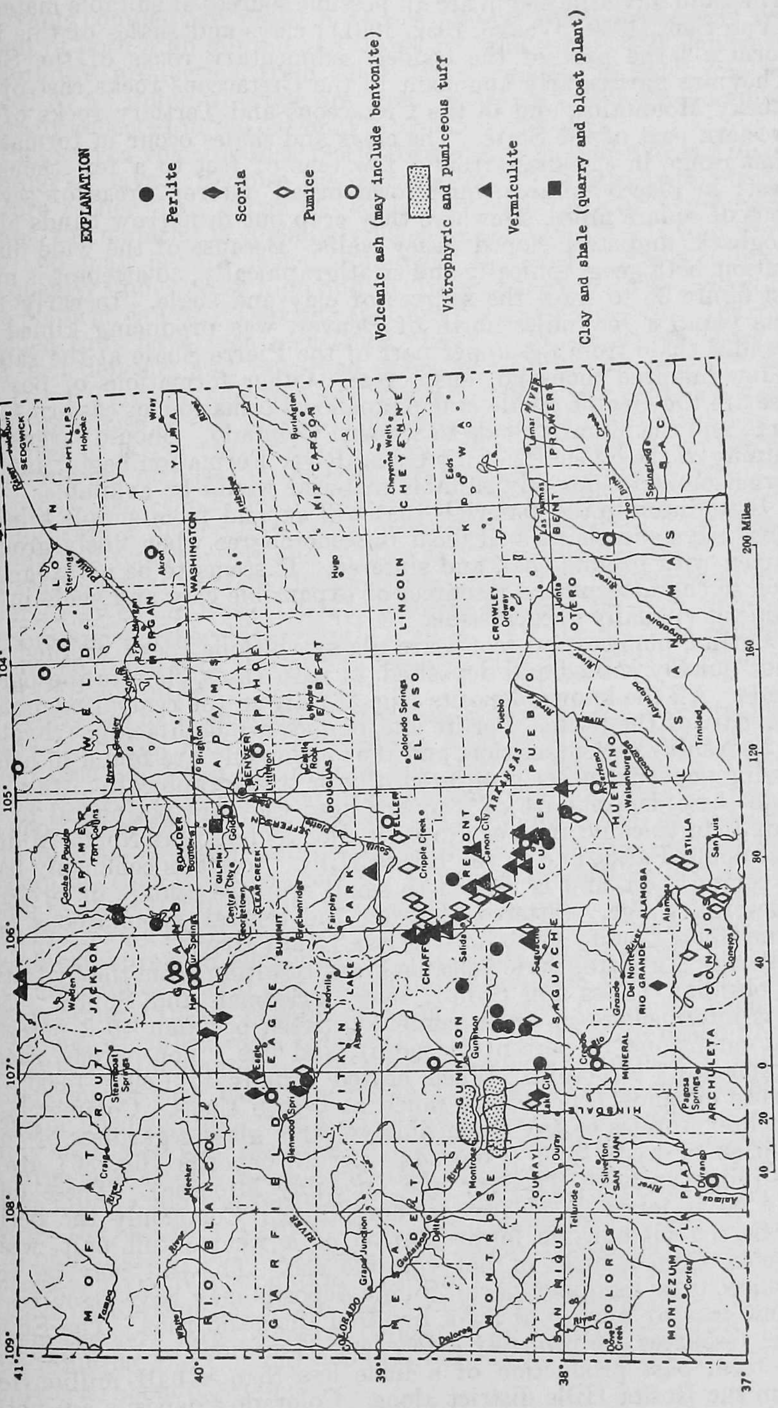

FIGURE 36.—Sources of lightweight aggregate in Colorado.

trine, and fluviatile origin are all possible sources of suitable materials (Van Sant, 1959; Waagé, 1952, 1961); clays and shales of this kind form a large part of the bedded sedimentary rocks of the State. They are particularly abundant in the Cretaceous rocks east of the Rocky Mountains, and in the Cretaceous and Tertiary rocks of the western part of the State. The clays and shales occur in formations that range in thickness from a few tens of feet to a few thousand feet; in places suitable units form broad outcrop areas of several tens of square miles, elsewhere they crop out in narrow bands along hogbacks and steep-sloped valley walls. Because of the wide distribution, both geographically and stratigraphically, no attempt is made on figure 36 to show the sources of clay and shale. In early 1964 one plant, a few miles north of Denver, was producing kilned expanded shale from the upper part of the Pierre Shale at the rate of a few hundred thousand tons a year. Other formations of possible use are the Benton Shale and Arapahoe Formation in eastern Colorado and the Mancos Shale in western Colorado. Should large-scale mining of the oil shales of the Green River Formation begin, another large source of possibly suitable material would be available.

In addition to the materials that will expand from simple kilning, most clays and shales will bloat to some degree when finely ground, mixed with ground coal, and sintered. It seems to be no exaggeration to characterize the resources of expansible clay and shale in the State as virtually inexhaustible.

Perlite, pumice, and scoria are glassy volcanic rocks, erupted and then quickly chilled and deposited, in most cases, close to the parent vents. All the known deposits (fig. 36) are in the central mountainous part of the State. Perlite and pumice are both acidic (rhyolitic to andesitic) in composition, and they commonly are found in neighboring deposits, either geographically or stratigraphically. In Colorado these deposits are of Tertiary age; they are peripheral to the San Juan volcanic area, or are at smaller centers near North, Middle, and South Parks, and in the Rosita Hills. Scoria is commonly basic in composition, and is related to small eruptive centers of probable Quaternary age, scattered through the central mountainous area from Routt County south into the San Luis Valley.

Perlite is a vitrophyric volcanic glass, resulting from the hydration of obsidian (Ross and Smith, 1955; Friedman and Smith, 1958). It is intermediate in water content between obsidian (0–2 percent) and pitchstone (5 percent or more), and has a non-porous, shelly, "onion-skin" structure. When heated rapidly to 1,400°–1,800° F., perlite expands ("pops") as much as 6 to 8 times. Commercially, "perlite" applies to any expansible volcanic glass regardless of composition or hydration. Colorado's perlite deposits (fig. 36) are in flat-lying units of Tertiary age (possibly Miocene). These units may be as much as 75 feet or more thick. Commonly the perlite forms the vitrophyric lower portion of a welded tuff unit, which formed from a mass of hot volcanic ash. The tuff may be very pumiceous in its upper part. Single deposits may have resources of a few tens of tons to about a hundred thousand tons. The State's total resources are probably a few tens of millions of tons, based on the total past production of a little less than a half million tons from the Rosita Hills district alone. Colorado's deposits are not in a strong competitive position at the present time, apparently as a result of both high mining and transportation costs. The removal of Colorado's production from the national market in 1958 was balanced by an influx of crude ore from elsewhere in the West and was scarcely reflected in the national production statistics.

Pumice is a volcanic rock froth, formed by exsolution of gas during cooling of lava. Because the vesiculation of pumice took place in nature rather than under the controlled conditions of a processing plant, the material is commonly heterogeneous in density and porosity and may have a large proportion of shards. Permeability is frequently undesirably high and the inherent compressive strength of the material is low. Deposits that are the pumiceous upper parts of welded tuffs have been mentioned above, and in addition there are ash-fall deposits and reworked deposits. All of the deposits seem to be of Tertiary age, and are related to the same volcanic events that gave rise to the perlite. Resources of pumice in Colorado are as large or larger than those of perlite, but the demand for use as a construction material is considerably smaller. Although production records of both the Federal and Colorado Bureau of Mines would seem to indicate a moderately large production of pumice, both bureaus group and report scoria and pumice as a single item, and the production data actually refers almost entirely to scoria. In addition to the sources given in Bush (1951), possible sources are now known in Grand and northern Huerfano Counties. Of the deposits shown on figure 36, those with the largest resources are in Saguache, Gunnison, and Park Counties.

Scoria has had considerable local use in lightweight concrete, building blocks, and roofing aggregate; a total of about 450,000 tons has been used for these purposes in the past 15 years, and in addition some 200,000 tons has been used for railroad and highway ballast. Almost all of the deposits (fig. 36) are in cinder cones; the remainder are blanket deposits near vents where no cone was developed, or where the cone has been eroded. The most productive deposits have been those in Routt, Eagle, and Costilla Counties. Total resources in the State may be on the order of 1 to 2 million tons; the possibilities for the discovery of additional large deposits are only fair.

Vermiculite, a hydrated magnesium-aluminum silicate, is a micaceous mineral that is capable of being expanded in volume from 10 to 30 times, when heated to 1,600°–2,000° F. It is an alteration product of biotite, phlogopite, and in places hornblende, formed in surficial alteration of such basic igneous rocks as pyroxenite, dunite, peridotite, or hornblendite. Pegmatites and syenite dikes are almost invariably associated with the basic rocks and the vermiculite. Colorado has a large number of small deposits (fig. 36), almost all of them involving high mining and transportation costs. In almost all the Colorado deposits the host rock, pyroxenite or hornblendite, occurs as thin steeply dipping dikes of limited extent. The largest concentration of the deposits is in the Wet Mountain Valley in Custer and Fremont Counties. Local production has never been economically competitive with that from the very large, massive deposit in pyroxenite at Libby, Mont., for example, and Colorado's total production for the last 20 years has only been about 6,000 tons.

Volcanic ash and pumicite are materials that are used sparingly as aggregate in plaster and in some special applications of lightweight concrete. Scattered occurrences are known in northeastern and southeastern Colorado, near Denver (Scott, 1962), in Garfield County (Bass and Northrup, 1963), and in Grand, Montrose, and Mineral Counties. So far as is known, all the deposits are small in areal extent and thickness. Some of the sources shown on figure 36 may be deposits of bentonite, a swelling clay which develops from the alteration and devitrification of volcanic ash. In several cases both terms have been used in published descriptions of the same deposit or area.

In summary, Colorado has abundant resources to satisfy its needs for lightweight aggregate for many years. Supplies of expansible clay and shale are virtually inexhaustible and widely distributed; the economics of treatment plants and transportation costs rather than raw material sources will determine the size and location of the production units. Resources of perlite and pumice, though far smaller than that of clay and shale, are measurable in millions of tons and can satisfy the needs of the State for a great many years. Perlite, so long as the local demand remains small, can probably be supplied more economically from deposits outside the State. Scoria resources are small and confined to the mountainous area, but they are adequate to sustain the local demand for some time to come. Only in the supply of vermiculite is Colorado probably deficient. Although there are a number of deposits, the reserves are small, and the resource outlook is not particularly bright. Montana vermiculite can be sold in Colorado at a price that does not encourage the development of Colorado deposits.

Papers by Bush (1951), Carlson (1956), Kluge (1956), and Valore (1956) contain large bibliographies dealing with both the geology of the raw materials and the manufacture, characteristics, and testing of the aggregates and the mixes in which they are used.

LIMESTONE FOR SUGAR REFINING

(By George Berlin, Great Western Sugar Co., Denver, Colo.)

In Colorado, processors of sugar beets are major consumers of chemical-grade, high purity limestone containing at least 97 percent $CaCO_3$. This material is calcined in vertical kilns to drive off carbon dioxide gas and produce a caustic oxide. Milk of lime produced by dissolving the oxide in water is then added to the diffused juices from the beets where they combine quite selectively with the non-sugar impurities in the sweet juices. Molecular size $CaCO_3$ is reconstituted by bubbling the carbon dioxide gas through the lime and juice liquor, after which the precipitated sludge is filtered out.

In calcining limestone for sugar refining, vertical kilns are preferred to rotary ones because of better fuel economy, less gas dilution, and lower plant costs. However, in vertical kilns the limestone blocks must be at least 2½ inches across to sustain space for draft and escaping gases, and they must have the physical strength to withstand the pressures of 50 to 80 feet of stone piled into the kilns.

Consequently, many types of high $CaCO_3$ rock—such as marble aragonite, calcite, travertine, calc sinters and spars, and marine shells—cannot be used. In quarrying limestone for sugar refining, the rather large amounts of small fragments and rock spalls that cannot be used in the vertical kilns are sold as ballast, road material, smelter flux, or pulverized for special-purpose uses. The discarded sludge from the sugar refineries in Colorado is not used, whereas in California it is re-calcined with new make-up stone in roasters or rotary kilns.

The Ingleside Formation of Permian age has been a major source of limestone since the turn of the century, supplying Great Western and Holly Sugar factories in Colorado and Wyoming. It has been quarried near Livermore, Larimer County, from beds dipping 15° to 20°. The formation contains two seams of limestone, each about 20 feet thick and separated by 20 feet of red sandstone. The limestone is white, nonfossiliferous, and partly recrystallized, containing some mud seams. With careful stripping, partly selective quarrying, and some hand-sorting, limestone averaging 98 percent $CaCO_3$ is obtained. Production of 65,000 tons of limestone a year from the Ingleside quarry (No. 12, fig. 39) also yields a like amount of spalls and chips for high-lime cement feed and road materials.

The Madison (or Leadville) Limestone of Mississippian age contains a dark, high-quality limestone. It is 30 to 50 feet in thickness where it is quarried at Glenwood Springs (No. 8, fig. 39). This quarry yields 35,000 to 40,000 tons of limestone yearly to the Holly Sugar Company's refinery at Delta and the American Crystal Sugar Company's refinery at Rocky Ford. Spalls are utilized at Glenwood Springs in the production of commercial lime. The formation dips at 45°, making quarrying awkward, but the limestone is generally the most acceptable in the State because of its low silica content and excellent calcining characteristics. In the processing of beets into sugar, the speed with which the finely-ground unslaked lime reacts is important and seems to be a surface phenomenon which is variable and unpredictable.

Until recently an underground quarry in the Leadville Limestone at Wellsville (No. 5, fig. 39), a few miles east of Salida, supplied beet sugar processors in the Arkansas valley. Quarry operations at Glenwood Springs now supply the necessary stone and the remaining stone requirements of sugar beet refining in Colorado are supplied from Wyoming.

METALLURGICAL LIMESTONE

(By D. A. Carter, The Colorado Fuel and Iron Corporation, Pueblo, Colo.)

In Colorado, metallurgical limestone sold or used by producers (including metallurgical dolomite and raw dolomite used primarily as a refractory in the steel industry) amounted to 462,868 short tons valued at $1,003,089 in 1961 (Cotter and Jensen, 1962, p. 1157) and to 309,347 short tons valued at $654,580 in 1962 (Cotter and Jensen, 1963, p. 1147). Of these tonnages approximately 85 percent was used at the Pueblo steel plant of The Colorado Fuel and Iron Corporation. The remainder was used by some 45 or more foundries,

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mostly in the Denver area, and by the Globe Refinery of the American Smelting and Refining Company in Denver. The tonnages given above include limestone burned to produce lime at the Pueblo steel plant for use in the Basic Oxygen Steel Process, but do not include burned lime purchased outside of Colorado. Some limestone is burned for production of lime or slaked lime in Colorado and used for what might be considered metallurgical purposes in mills and refineries. However, such lime is largely used for pH control of tailings circuits in uranium mills, hardly a true metallurgical use, and is therefore, not included in the above tonnage. No detailed figures are available for 1963, but consumption of metallurgical limestone apparently increased somewhat over 1962.

The specifications for metallurgical limestone vary, depending on the use. In general, such rock should be in the "high-calcium limestone" category, containing 95 percent or more $CaCO_3$, 2 percent or less $MgCO_3$, and 3 percent or less insoluble (usually silica and alumina). For some uses a very low insoluble content is necessary. For other uses, the magnesium carbonate content is not critical and even true dolomite ($MgCO_3$ approaching 45 percent) can be used. In Colorado about 30 percent of the total metallurgical carbonate rock consumed is dolomite in the raw or unburned state. Of this dolomite more than 75 percent is used as a flux, and less than 25 percent is used primarily as a refractory. Dead burned dolomite, a specialized refractory material, is not produced in Colorado and is outside the scope of this report.

The specifications for high-calcium metallurgical limestone approximate those for limestone used in the beet-sugar industry, for certain limestones used in the cement industry, and for limestone to be burned for agricultural or other uses. Thus, a single deposit may be minable for more than one purpose. The location of the principal limestone quarries in Colorado, and the distribution of some formations containing limestone of possible use, are shown on figure 39.

In Colorado, high-calcium limestones suitable for metallurgical use are found in only a few geologic formations. Near Salida, Chaffee County, one or more beds near the base of the Leadville Limestone are of high purity. On Monarch Pass, the Monarch Quarry (No. 6, fig. 39), a captive operation of the Colorado Fuel & Iron Corp., has operated continuously since 1930 on a bed about 100 feet thick. At Wellsville (No. 5, fig. 39), Fremont County, there is more than one bed of good limestone. The principal bed, about 20 to 25 feet thick, has been quarried in a number of places and even mined underground. Most of this limestone was sold for concrete aggregate and to sugar companies, but some minus 2½-inch screenings were sold for metallurgical use in recent years.

East of the mountains, a small production of metallurgical limestone has come from a deposit near Roxborough Park (No. 9, fig. 39), Douglas County, in recent years. The exact stratigraphic position of this deposit is not known by the writer; the geology of this area has been described by Lee (1927, p. 27). The limestone is sold to foundaries in the Denver area (T. L. Helmer, oral communication, 1964). In the LaPorte area (No. 11, fig. 39), Larimer County, limestone is produced from the Ingleside Formation mainly for sugar refining.

Some of the screenings from this operation also enter the Denver area metallurgical market.

Travertine, a calcium carbonate hot-water spring deposit, usually of Recent age, may also be used for metallurgical limestone. In a captive operation, the Colorado Fuel & Iron Corp., through its contractor, Colorado Limestone Co., has recently maintained a moderate but steady production for use in the Pueblo steel plant, from a travertine deposit at Calcite (No. 4, fig. 39), near Howard, Fremont County. In former years another travertine deposit near Wellsville, Fremont County, produced some metallurgical limestone for the Arkansas Valley Smelter at Leadville. This deposit was, however, better known for dimension stone, as is a similar deposit near Canon City.

The only present source of dolomite is the Dolomite Quarry (No. 3, fig. 39) near Canon City, also a captive operation of the Colorado Fuel & Iron Corp. Production is from massive beds of high-purity dolomite about 130 feet thick, which represent nearly the full thickness of the Fremont Limestone.

In prior years, metallurgical limestone and dolomite have been quarried from other deposits, but they have been worked out or the production of limestone or dolomite for metallurgical use has been discontinued. The geology of these deposits is similar or identical to those mentioned above. One notable occurrence, however, is the Lime Quarry (No. 1, fig. 39) at Lime, Pueblo County, operated by the Colorado Fuel & Iron Corp., and finally closed down in 1948 in spite of its proximity to the Pueblo steel plant. This quarry is in the Fort Hayes Limestone Member of the Niobrara Formation of Late Cretaceous age. This limestone is quarried elsewhere for cement rock and in most places is too impure to be considered for metallurgical purposes.

Actual reserve tonnage figures of metallurgical limestone and dolomite are either undetermined or are not released by the owners. Resources appear to be adequate for local use in the foreseeable future. The Leadville Limestone, which is known to contain beds of high-calcium limestone, crops out widely in the central mountainous part of the State. In some places, however, the formation has been mineralized, dolomitized, or otherwise altered so that it is valueless for metallurgical use. The Fremont Limestone, likewise, crops out widely in the same general area and nearly everywhere contains at least some beds of high-purity dolomite. Dolomite of metallurgical grade is also found in the Leadville Limestone in the Monarch district, Chaffee County, and perhaps elsewhere. Other sections of this report contain information on limestone deposits that may possibly be of future value for metallurgical purposes.

SAND AND GRAVEL

(By W. D. Carter, U.S. Geological Survey, Washington, D.C.)

Sand and gravel are unconsolidated rock fragments formed by the natural disintegration of rocks. Deposits may be mixtures of fragments from many types of rocks or, more rarely, they may be of a single rock type. Sands usually contain a high percentage of quartz and resistant silicate minerals. A deposit may have coarse- or fine-grained, angular or rounded fragments, that are poorly sorted or well sorted, depending on the relative hardness of rock fragments and mode of deposition.

Specifications for sand and gravel differ considerably. Special-purpose materials, especially sand, may have rather rigid specifications, but the bulk of sand and gravel marketed is not required to meet more than general specifications. In general, sand is material that is coarser than 200 mesh and finer than ¼ inch, and gravel is material ranging from ¼ inch to 3½ inches or even larger (Key, 1960, p. 703).

Sand and gravel are low-value, high-bulk commodities which must be mined close to areas of consumption to be profitable. Used mainly for construction purposes, they serve as aggregate for concrete, asphalt, mortar, and plaster, and as road fill. Sand is also used for special industrial purposes such as blast sand, engine sand, filtration sand, hydrofrac sand, molding sand, as metallurgical flux, and as glass sand. Specifications are different for each purpose and for certain special purpose sands, specifications are extremely exact. For example, glass sand must be medium fine-grained quartz sand containing at least 95 percent silica (SiO_2) and less than 0.05 percent iron oxide (Fe_2O_3); more iron would impart a color to the glass.

Hydrofrac sands, consisting of well-rounded quartz grains of uniform size, are used for maintaining or increasing the porosity and, consequently, the production from oil wells. Such sands are pumped under pressure down the well and forced into cracks in the oil-producing layer, generally after it has been broken and fractured by an explosive charge. The sand keeps the fractures open and yet is porous enough to permit oil to flow into the well.

Blasting sand used for cleaning building surfaces is usually composed of angular, fine-grained quartz fragments. Sand, sandstones, and quartzite used as metallurgical flux must be free of impurities that interfere with the metallurgical process or harm the final product. Other clean quartz sands, sandstones, and quartzites are used in the production of ferrosilicon alloys and silicones, a group of silica-based plastics that are being put to ever increasing uses.

Sand and gravel are so common that most people rarely consider them as mineral deposits, yet they constitute the largest volume of mineral raw materials produced from the earth. In the United States 776,701,000 tons of sand and gravel, having a value of $794,-725,000, were produced in 1962 (Cotter and Mallory, 1963). Estimates for 1963 are for about 800 million short tons (Herod, 1964, p. 112). California, the leader, produced approximately 107 million tons, or nearly one-seventh of the total in 1962. That year Colorado ranked twelfth, producing 19,313,000 tons valued at $18,926,000. Of this, 10,650,000 tons were produced by commercial firms and 8,663,000 tons were produced by contractors whose entire production was for Government contracts. Of the total value of mineral production in Colorado ($308,115,000 in 1962), sand and gravel ranked fourth after petroleum, molybdenum, and coal, in that order. Almost half of Colorado's sand and gravel production came from Adams, Jefferson, and Arapahoe Counties and was used mainly in the Denver Metropolitan area (Mullen, 1963, p. 244). Substantial production also came from El Paso, Montezuma, Weld, Pueblo, and Mesa Counties. Preliminary production figures for 1963 show an increase of 5 percent or a value of $1 million.

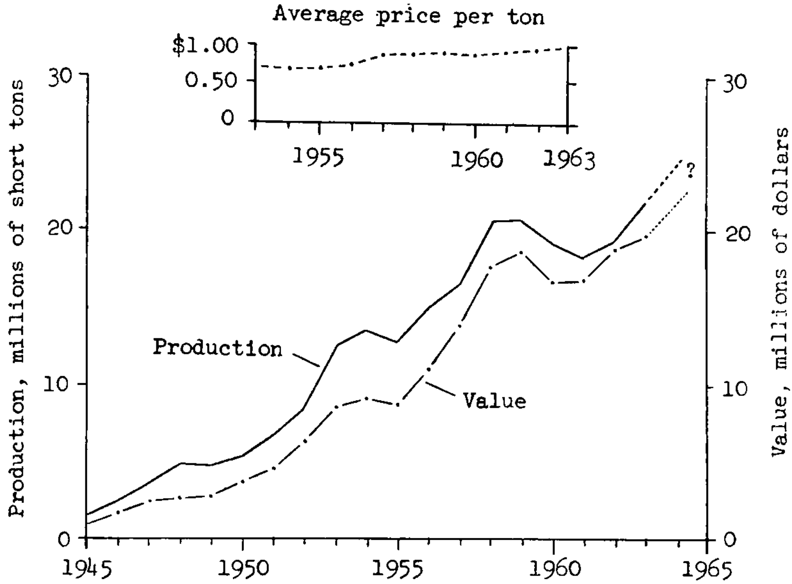

FIGURE 37.—Colorado's sand and gravel production and total value, 1945–63, and average price per ton at the pit, 1953–63.

The growth of the sand and gravel industry in Colorado since World War II has been steady and impressive (fig. 37).

Production in 1945 was less than 2,000,000 short tons, but by 1958 the production and total value had increased tenfold. The total value has increased at a somewhat faster rate, indicating that the unit value has risen steadily. In 1953, for example, the unit value was 69.2 cents per short ton and by 1962 the price had climbed to approximately 98 cents, due largely to the increased demand for higher quality sands for building and highway construction material, to higher labor costs, and, in part, to the development or expansion of industries requiring special purpose sands. Longer haulage distances from mines to points of consumption have also raised the price to the consumer. Average Colorado prices for commercial sand and gravel are, at the present time, below the national average of $1.12 per ton (Herod, 1964, p. 112). Prices for special industrial sands may be as much as $7.00 per ton in certain areas of the nation.

Sand and gravel deposits have been worked in every county of the State, mainly near principal centers of population or industry. Argall (1949) lists many deposits from the records of the Colorado State Highway Commission and presents analyses of each deposit. Studies of the Missouri Basin (Varnes and Larrabee, 1946, Larrabee and others, 1947) and of the Arkansas River Basin (Arkansas-White-Red Basins Inter-Agency Committee, 1955, p. 138–142) provide additional data. Del Rio (1960) briefly described the location of principal deposits of each county. Their general distribution is shown on figure 38.

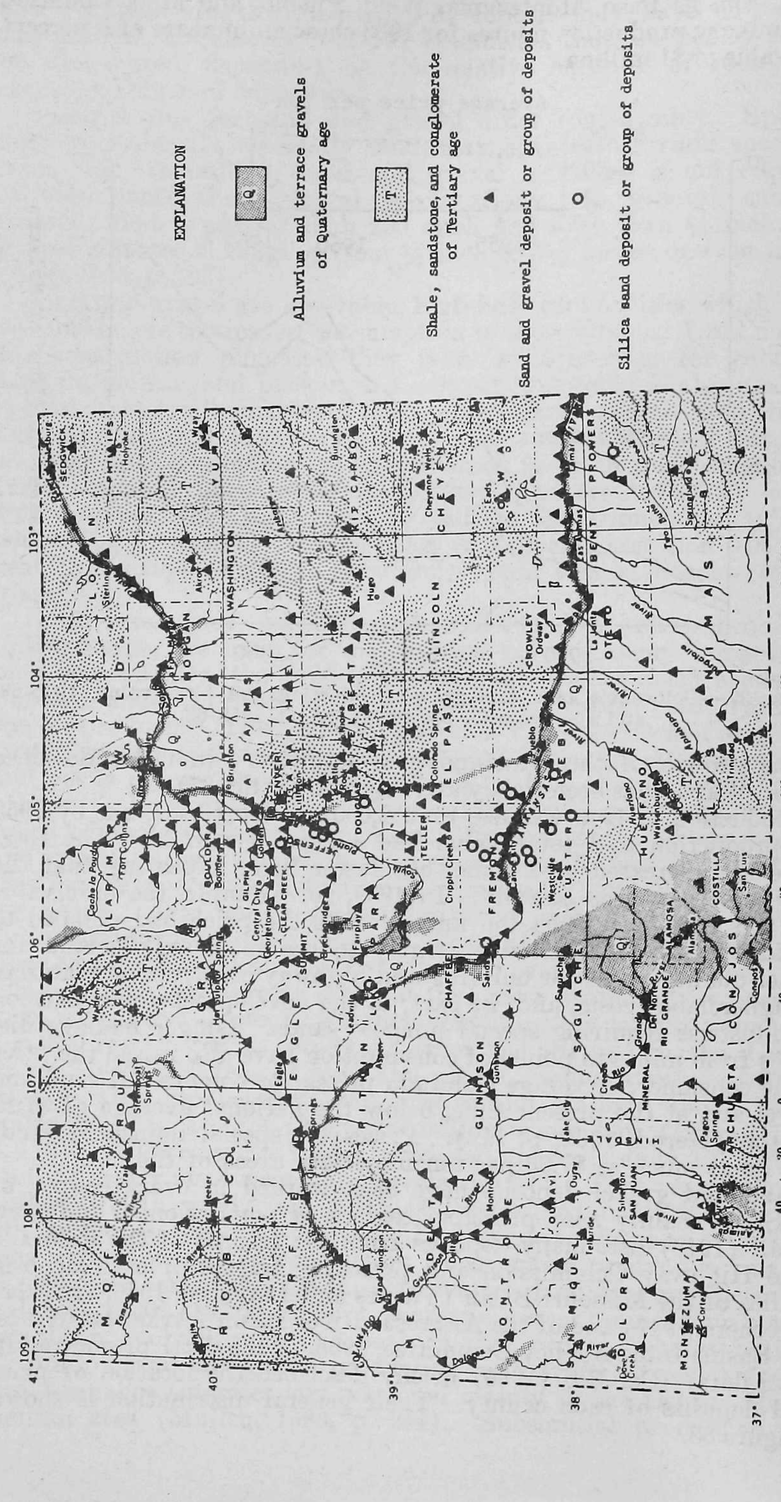

FIGURE 38.—Sand and gravel and silica deposits in Colorado.

Sand and gravel occur as fluvial deposits of Quaternary (postglacial) age in the valleys and marginal terraces of the South Platte, Arkansas, Rio Grande, and Colorado Rivers and their many tributaries. In eastern Colorado, deposits occur as pediments and outwash fans along the foot of the Front Range and extend eastward as narrow ribbons into the valleys of the South Platte and Arkansas Rivers. Large areas are underlain by older more consolidated sands and gravels in the easternmost counties. The Ogallala Formation of Pliocene age has been mined near population centers in Crowley, Washington, and Yuma Counties, mainly where recent weathering has partly disintegrated the formation. The Ogallala and similar sandstone and conglomerate units of Tertiary age constitute a major source of construction materials for the future.

In the mountainous regions of central Colorado, sand and gravel are mined from deposits of fluvial and glacial origin, mainly moraines, eskers, outwash plains, and stream terraces. Large deposits of alluvium are found in the San Luis Valley of south-central Colorado and constitute a major resource of sand and gravel in the State. Smaller gravel deposits lie at the north end of the San Juan Basin near Durango. These are known as the Florida gravel, after Florida Mesa, on which they are found. In the canyon country of western Colorado, the deposits are somewhat more restricted, being confined mainly within the canyon walls or perched as terraces along their narrow margins as along the White, Green, Colorado, Dolores, and San Miguel Rivers and their tributaries. Where the valleys broaden, as in the lower Gunnison and Uncompahgre Rivers, extensive deposits of sand and gravel are found. Deposits of alluvium are also found in West Creek in Unaweep Canyon and in Paradox and Gypsum Valleys, Mesa, Montrose, and San Miguel Counties.

Industrial or special purpose sands of high-silica content have been worked on a small scale since 1907 at 36 different localities within the State (T. D. Murphy, 1953, written communication). Of these, 18 of the operations have been in the vicinity of Canon City, Fremont County; 5 have been in Douglas County; 4 in Pueblo County; 2 in Jefferson County, and 1 each in Weld, Boulder, Powers, Lake, Chaffee, and Custer Counties. The approximate location of these deposits is shown on figure 38. Principal production has been as ganister for acid refractory brick, molding sand for iron foundry work, and silica sand for both colored glass containers and furnace bottoms. Vanderwilt (1947) and Argall (1949) describe several silica sand localities and provide analyses of the raw material. These are summarized below:

Quarry	County	Source rock and thickness	Analysis (in percent)				
			SiO_2	Al_2O_3	FeO_3	CaO	Na_2O
Molding sand	Douglas	Dakota, 10 feet	98.7	0.95	0.25	0.04	0.74
Helmer	do	Dakota, 50 feet	{98.7 98.2	.98 .55	.09 .16	.05 .035	.80 .75
Kassler	Jefferson	Lykins Ss [1]	95.4	4.09	.18	.04	1.08
Little Quarry	do	do.[1]	96.7	.09	.13	.055	.86
Roxborough Park	do	do.[1]	([2])	2.44	.32	([2])	([2])
Colorado Springs	El Paso	Dawson Fm [1]	97.9	1.55	.07	([2])	([2])
Hoover plant	Fremont	Dakota Ss [1]	99.7	.3	[3] .02	------	------
Barrel Springs	Prowers	do.[1]	99.5	([2])	([2])	------	------

[1] Thickness not given.
[2] Data not given.
[3] Flotation product.

Although the Dakota Sandstone and Lykins Formation (see table 1 for ages) crop out extensively in the foothills of the Front Range, Vanderwilt believes that they are in general too thin, and too variable in composition to supply the raw material needed by a glass factory. Washing, screening, froth flotation and other means of beneficiation might, however, make them more suitable.

Other formations that are believed to have been mined on small scales are: the Sawatch Quartzite, Harding Sandstone, Parting Quartzite Member of the Chaffee Formation, certain layers of the Fountain Formation, Lyons Sandstone, Morrison Formation, Lytle Sandstone Member of the Purgatoire Formation, Codell Sandstone Member of the Carlile Shale, Trinidad Sandstone, Fox Hills Sandstone, Laramie Formation, and Dawson Formation (T. D. Murphy, written communication). Very little experimentation, however, has been done and published on the suitability of these units for commercial uses.

Although sand and gravel have been produced from every county of the State, most of the deposits in some counties, especially in the western half of the State, are small and of poor quality. The Colorado State Highway Department has sampled and analyzed many localities throughout the State (Argall, 1949) but no other attempt has yet been made to accurately assess the State's entire sand and gravel resources. W. D. Fish, Chief of Construction Branch, Bureau of Public Roads, believes that there is a critical shortage of suitable material (Lenhart, 1960, p. 745), especially near Denver, the major center of population and consumption. One of the major problems is that Denver is expanding so rapidly that large deposits of sand and gravel are being covered by new construction before they can be exploited.

There are several ways in which this possible shortage may be appraised and perhaps alleviated. Detailed geologic mapping and soil surveys in certain areas of the State will facilitate an accurate appraisal of these resources, especially in the eastern plains counties. Industry will have to increase exploration for new deposits, eventually employing geophysical and drilling techniques in the search. Certain deposits, now considered substandard may have to be utilized by either upgrading the material to meet present specifications or by lowering specifications. Deposits of high-quality material should be conserved for use in industries with high specifications rather than using them in projects of low specification simply because they are nearby. Deposits farther from centers of consumption will eventually have to be utilized. Finally, other sources of raw material, such as sandstone, conglomerate and quartzite, must be found and tested for future use.

To gain some insight into the future needs for sand and gravel in the State, the following data may be of help.

The national average per capita consumption of sand and gravel in 1960 was approximately 4 tons per person. In Colorado, however (1960 pop. 1,754,000), the average consumption for the same year was 11.4 tons per person, reflecting a higher level of construction activity due to the higher-than-average population increase (32 percent between 1950 and 1960), and the high level of highway and building construction taking place within the State. Harold Kirkemo (oral communication) predicts that by the year 2000 the national average consumption may be 17 tons per person, or 4.25 times that of 1960. Assuming an average population increase in Colorado equal to that of the nation as a whole, it is reasonable to predict that sand and gravel production of the State will be approximately 4 times present usage, or on the order of 80 million tons per year by the year 2000. To reach this level a minimum of approximately 1,200 million tons will be needed during this 40-year period. If, on the other hand, Colorado continues to populate at its present rate of 3.2 percent per year, as in the last decade, or even faster, the demand could be much greater.

As the need for ordinary sand and gravel increases there will undoubtedly be a concomitant increase in the demand for special industrial sands. Studies of the various sandstone and quartzite formations that crop out near major centers of population may reveal the necessary resources to satisfy these expanding demands.

STONE

(By R. M. Lindvall, U.S. Geological Survey, Denver, Colo.)

Recorded production of stone in Colorado since its settlement has been relatively modest, totaling $108.6 million through 1963, but this in no way reflects the vast resources of this commodity within the State—resources that far exceed foreseeable consumption. Most parts of Colorado contain deposits of potentially marketable stone (Larrabee and others, 1947) most of which have not been studied or evaluated. Major stone quarries in Colorado are shown in figure 39.

Stone production in Colorado has been mainly in three categories: crushed and broken stone, dimension stone, and, to a lesser extent, ornamental stone.

The principal uses for crushed and broken stone are in concrete aggregate, road stone or "metal," railroad ballast, riprap, terrazzo, roofing granules, and recently in gardens and other types of landscaping work. Large quantities of crushed and broken stone are also used in the production of cement (p. 181), in sugar refining processes (p. 202), and as flux in metallurgical processes (p. 203).

Crushed and broken stone are obtained in Colorado from a variety of sedimentary, igneous, and metamorphic rocks, and the total sources are far more numerous than the localities of the major quarries shown on figure 39. Many quarries, especially those producing concrete aggregate or road metal for highway construction, have been opened to produce stone for a specific project and then abandoned, without general knowledge of their locations. Portable crushing plants are easily moved to new sites as the market demand shifts.

Consumers have developed a variety of specifications for crushed stone; for these specifications, reference is made to reports of the following groups: U.S. Bureau of Public Roads, American Roadbuilders Association, and the American Association of State Highway Officials.

Two varieties of dimension stone quarried in Colorado have attracted widespread markets: the "Colorado Yule Marble" used in

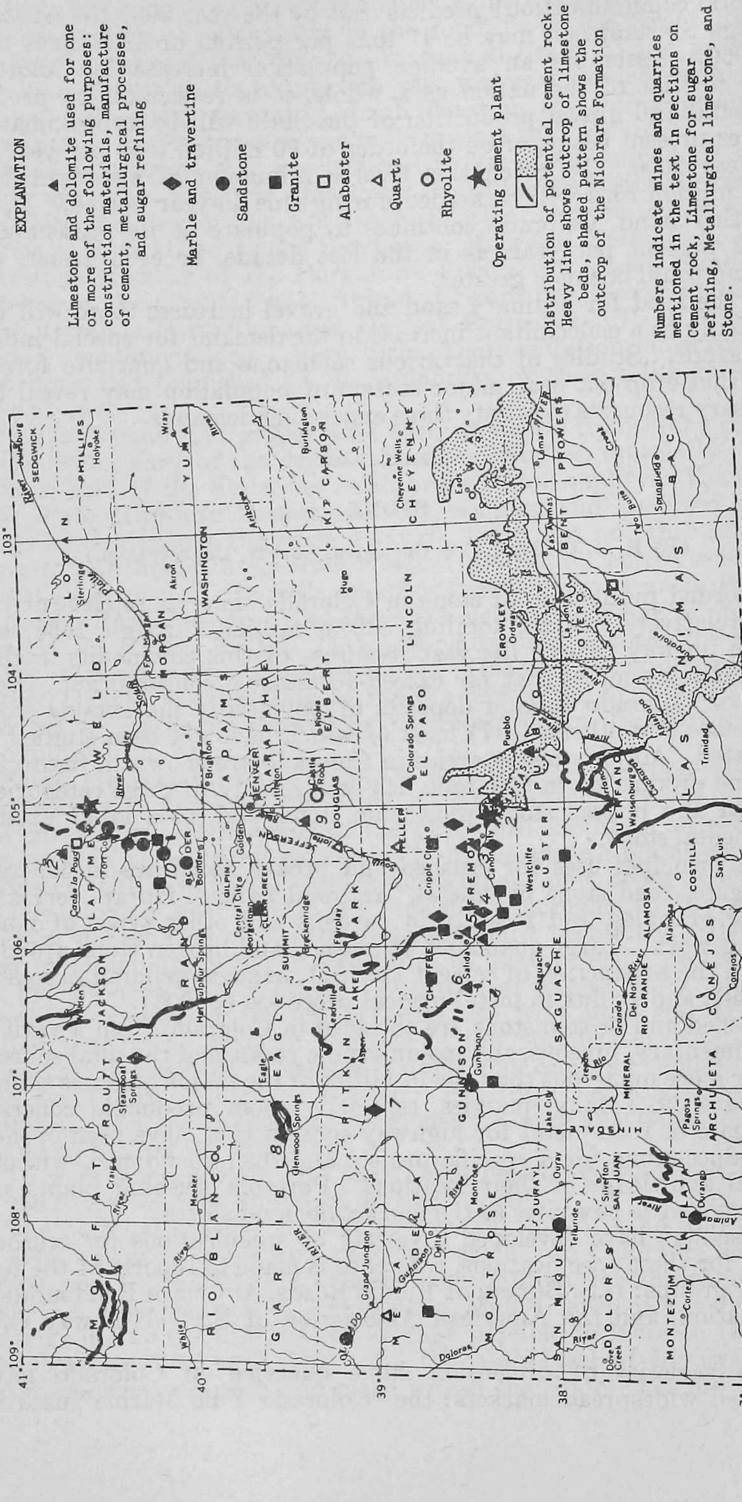

FIGURE 39.—Actual and potential sources of some kinds of stone in Colorado.

the Lincoln Memorial and the Tomb of the Unknown Soldier in Washington, D.C.; and the Lyons Sandstone, used in most of the buldings on the University of Colorado campus at Boulder, and in numerous private and public buildings throughout the Western States.

Production of dimension stone in Colorado extends back to pioneer days, when it was used extensively as building blocks to support the full weight of the structure. More recently, supporting structures are mainly of steel or reinforced concrete, and stone is used chiefly as a decorative veneer.

Other uses for dimension stone include monuments, paving blocks for walks and patios, garden and retaining walls, fireplaces, and in places where special architectural effects are desired.

Uses for ornamental stone include panels for interior and exterior walls, window sills, mantels, tops for furniture and lavatories, lamp bases, bookends, vases, and various art objects. Ornamental stone produced in Colorado includes travertine, onyx, and alabaster. The market for ornamental stone has been extremely variable.

The chief rock types of stone produced in Colorado include limestone, sandstone, granite, and marble. Minor rock types are quartz, alabaster, rhyolite, and travertine.

Limestone leads in both quantity and value of all rock types quarried in Colorado. Much of it is used in the manufacture of cement, the production of lime for sugar refining, and in the iron and smelter industries.

Limestone for concrete aggregate and road metal has been produced throughout the State from small quarries which are opened for short term specific needs and later abandoned. More permanent quarries are in Chaffee, Fremont, and Peublo Counties, in the Arkansas River Valley and its tributaries; north of Colorado Springs in El Paso County; and north of Fort Collins in Larimer County.

Major areas of limestone that have not been fully developed but which seem to have possibilities include north and northwest of Glenwood Springs in Garfield County, northeast of Gunnison along Cement Creek in Gunnison County; in several areas in the San Juan Mountains; along the flanks of the Sangre de Cristo Mountains in Costilla, Huerfano, Custer, and Fremont Counties; along the Wet Mountains at Beulah in Pueblo County; and in several counties in southeastern Colorado (Vanderwilt, 1947, p. 245–246).

Sandstone is currently the most popular dimension stone in Colorado, used chiefly as ashlar blocks in walls, window sills, fireplaces and barbecue pits, and as flagstones for walks and patio paving. Sandstone for building or ornamental use should have an even-grained texture, be free of closely spaced joints, have a pleasing color, and be moderately well-cemented for durability.

Sandstone has been quarried at a number of locations in Colorado—in the southern part of the State the Trinidad and Harding Sandstones have produced building stone of good quality; and in the north-central region the Fountain Formation and the Lyons and Dakota Sandstones have been quarried extensively. In previous years, when large dimension stones with high-bearing strength were in demand, the Dakota Sandstone, which locally is quartzitic, was used widely because of its strength, pleasing color, and favorable bedding.

The Lyons Sandstone is at present quarried extensively in Boulder and Larimer Counties. The pink to red, thin-bedded sandstone formation is over 300 feet thick near the town of Lyons (No. 10, fig. 39) in Boulder County. This beautiful and durable sandstone, which splits well along bedding planes, is used chiefly for veneer facing for buildings, in fireplaces, and in patios and walkways (Sharps, 1963, p. 5).

Other areas where sandstone has been quarried include: Colorado Springs in El Paso County, Stone City in Pueblo County, Glenwood Springs in Garfield County, near Loma in Mesa County, near Placerville in San Miguel County, and east of Basalt in Eagle County.

Crushed sandstone is used in some areas of the State for road surfacing material and in asphalt paving. It is also used as roofing granules and for walkways and other decorative landscaping purposes.

Almost unlimited quantities of sandstone throughout the central and western portions of Colorado are available for production of both dimension and crushed stone if the demand warrants.

Large amounts of marble were quarried in the past near the town of Marble (No. 7, fig. 39) in Gunnison County, and more than 60 public buildings in the United States used "Colorado Yule Marble" in their construction. The "Yule Marble" bed (recrystallized Leadville Limestone), which crops out for a distance of over 4,000 feet along Yule Creek, is about 240 feet thick, but the productive horizon for dimension stone is limited to about 40 feet in the lower half of the formation. The marble is predominantly white, medium grained, with a gray to yellow banding. Large reserves are available.

Other marble deposits are located in Fremont County near Wellsville, Cotopaxi, and Canon City, where small amounts of stone have been quarried for dimension, monumental, and crushed stone uses, and northeast of Salida in Chaffee County, where marble and limestone terrazzo chips have been produced.

Travertine, or travertine marble, has been quarried southeast of Salida. This light-brown and tan mottled stone has been used for decorative purposes on interior walls in the City and County Building in Denver, and in the Department of Commerce Building in Washington, D.C. Another travertine quarry is located near Buelah in Pueblo County.

A large deposit of onyx marble is reported southwest of Steamboat Springs in Routt County.

Many varieties of igneous and metamorphic rock are marketed as granite. Colors vary from light brown and tan through red and pink to gray and black. Colorado contains an abundance of granite, but fracturing and jointing limit the places where stone of dimension quality has been quarried. Only a few quarries are in operation at present, but reserves are large, and any potential demand could easily be met.

Quarries which are producing or have recently produced granite are in the southern part of Larimer County, where red granite for monumental use is quarried; northeast of Salida; and southeast of Cotopaxi in Fremont County. Areas from which granite has been produced and which could undoubtedly be reopened are near Silver Plume in Clear Creek County, near Gunnison in Gunnison County, and south and west of Cripple Creek in Teller County.

Large amounts of weathered granite, which is easily crushed, are quarried in the central and north-central parts of Colorado for use as road metal and for asphalt and concrete aggregate in highway construction.

Rhyolite, a fine-grained igneous rock, is quarried near Castle Rock in Douglas County. It has had limited use as rubble masonry and veneer in private homes and small public buildings, and has been used as riprap on the recently constructed Englewood water reservoir south of Littleton. Resources are large and probably can fill any foreseeable demand.

Alabaster, a fine-grained, dense variety of gypsum, has been quarried near Livermore in Larimer County and near La Junta in Otero County. It can be shaped and polished by machinery and is manutured into vases and other ornaments.

Deposits of quartz have been quarried in pegmatite deposits in Teller and Jefferson Counties. At present there is a growing demand for crushed quartz for decorative use in gardens and landscaping, as surfacing material on cast concrete ornamental panels, as chips in terrazzo, and as roofing granules.

COMMODITIES OF LITTLE IMPORTANCE IN COLORADO

Several mineral commodities that have thus far been of little importance in the mineral economy of Colorado are discussed briefly below. Some of these commodities are largely restricted in occurrence to rocks or geologic environments that do not exist in Colorado, and hence are likely never to be found in workable deposits within the State. Others occur with rocks and environments that do exist in Colorado, but thus far have not been found in promising grade or quantity. For such commodities, there is, of course, always a chance that deposits better than those now known will someday be discovered. Principal uses, common geologic associations, and occurrences in Colorado of both of these kinds of minor commodities are reviewed briefly. Readers interested in more information regarding uses, types of occurrences, and sources are referred to the U.S. Bureau of Mines publication, "Mineral facts and problems," Bulletin 585, 1960. For some of these commodities, additional information on occurrences in Colorado will be found in Vanderwilt and others (1947), del Rio (1960a), and Eckel (1961). The following statements are abstracted largely from these sources.

ALUMINA AND BAUXITE

Aumina (Al_2O_3) is the basic material for producing aluminum, the most widely used light metal. Alumina is abundant in rocks and minerals in the earth's crust, and various rocks are potential sources, but bauxite is virtually the only commercial source. Bauxite deposits form by the weathering of alumina-rich rocks, generally in a tropical or subtropical climate; under favorable conditions, large deposits occur at and near the surface. The largest known reserves are in Australia, Guiana, and Jamaica. Domestic deposits occur chiefly in Arkansas, but are only of moderate size. Commercial bauxite deposits are not likely to be found in Colorado. The alunite deposits in Colorado (p. 155) are possible sources of alumina, but the known deposits are neither large nor high grade.

ASBESTOS

Asbestos is a term applied to several fibrous minerals that can be spun into yarn and made into cloth. Asbestos has many uses, mainly related to its fire-resistance and heat and electrical insulating properties. United States uses large amounts of asbestos, obtained mainly by imports from Canada. The asbestos minerals are calcium and magnesium silicates and they occur in veins in joints in serpentine, a metamorphic rock derived mainly from basic igneous rocks or magnesium-rich limestones. Numerous occurrences of asbestos minerals have been reported in Colorado, but no commerical deposits are known; serpentine, the common host rock for asbestos, is rare in the State.

BORON

Boron and its compounds have numerous uses in many different fields of industry. Most of the world's supply of boron is derived from the beds of dry lakes in southern California, where various boron minerals precipitated from the evaporating lake waters. Dry-lake deposits of this type are not known in Colorado, though conceivably some might be buried by sedimentary beds in some of the older basins in the State.

BROMINE

Bromine is a toxic, corrosive liquid at ordinary temperatures. It is used chiefly as an additive to gasoline. It is widely distributed in trace amounts in rocks and in ocean water, but it is concentrated only in saline deposits and natural brines. Since the mid-1930's most of the bromine used in the United States has come from sea water; before that it was obtained from brines in the Midwestern States. Natural brines from salt-bearing beds in Colorado (p. 173) are the only likely source in the State.

CESIUM

Cesium is a metal that has been used only in small quantity, largely for research; uses may increase substantially in the future, both as a metal and as a rocket fuel. Some cesium has been recovered as a by-product from domestic deposits, but most has been obtained from ores imported from Africa. Cesium occurs most abundantly in nature in some pegmatites, either in the mineral pollucite, a hydrous cesium aluminum silicate, or in lepidolite, a lithium-bearing mica. Lepidolite occurs in several pegmatites in Colorado and is moderately abundant the Quartz Creek area, Gunnison County, and the Eight Mile Park area, Fremont County (p. 169). Cesium is also concentrated in small amounts in some saline deposits and natural brines.

CHROMIUM

Chromium is used chiefly as an alloy metal in stainless steel. The United States is dependent upon imports for most of its supply. Chromium occurs principally in the mineral chromite, which is a common accessory mineral in the most basic igneous rocks. Commercial deposits of chromite occur as pods, irregularly shaped masses, or layers, chiefly in ultrabasic rocks. Such rocks are rare in Colorado, and concentrations of chromite are almost unknown.

COBALT

Colbalt is used chiefly as a ferrous and nonferrous alloy. Domestic supplies are largely imported. The principal minerals of cobalt are sulfides and arsenides, and they commonly occur with similar compounds of copper, nickel, and iron in veins. A little cobalt occurs in the Copper King mine, Gold Hill district, Boulder County.

CORUNDUM

Corundum, a natural aluminum oxide, is a very hard mineral used as an abrasive, most commonly in an impure form known as emery;

ruby and sapphire are gem-quality varieties of corundum. The mineral occurs chiefly in metamorphic rocks and in places in pegmatites. In Colorado, occurrences of corundum are reported in Routt, Jefferson, Clear Creek, and Fremont Counties; a little corundum has been mined from the Turret district, Chaffee County (Eckel, 1961, p. 116).

GARNET

Garnet is a group name for several minerals of like crystal habit but different composition. High-quality garnets are used as gems, but most garnets are used for abrasives. Garnets occur principally in metamorphic rocks and in places are abundant in placer deposits. Garnets are common and widespread in metamorphic rocks in Colorado, but no production has been reported except for mineral and gem collections.

GRAPHITE

Graphite is a mineral form of carbon, and commercial graphite ores contain 50 to 93 percent carbon. It has many uses, but mainly as a refractory, dry lubricant, and electrical conductor. Most of the graphite consumed domestically is imported. The commercial classification of natural graphite is related to the geologic occurrence of the mineral—lump graphite occurs in veins; amorphous graphite develops from the metamorphism of coal beds by igneous intrusion; and flake graphite occurs in metamorphosed sedimentary rocks, mainly in schists. All three types occur in Colorado, and a little amorphous graphite has been mined in Chaffee and Gunnison Counties (Eckel, 1961, p. 174).

KYANITE AND RELATED MINERALS

Kyanite and the related minerals andalusite, dumortierite, sillimanite, and topaz are all aluminum silicates of similar composition and properties. They are used principally as a refractory in lining furnaces and kilns and in making some ceramics. Kyanite, andalusite, dumortierite, and sillimanite typically occur in metamorphic rocks, especially schist, and topaz occurs in pegmatites. Minerals of this group occur in numerous localities in Colorado (Eckel, 1961). Sillimanite is especially common in Precambrian schists and gneisses. No commercial production of these minerals has been made except some topaz as a minor byproduct of the molybdenum ore at Climax. In general the known Colorado deposits are of lower grade or smaller size than some in other states.

LITHIUM

Lithium, the lightest of metals, has some use as the metal and alloy, but its chemical compounds have many uses, especially as lubricants, in ceramics, and storage batteries. It occurs in several minerals commonly found in pegmatites, which are the principal source, and is also recovered from natural brines in California. In Colorado small amounts of lithium-bearing minerals have been mined from pegmatites in the Quartz Creek area, Gunnison County, and the Eight Mile Park area, Fremont County (p. 173).

MAGNESIUM

Magnesium is a light metal that is becoming increasingly useful as a metal; it has long had extensive use as a refractory material and its compounds have many uses. It occurs in many minerals and rocks and in brines and sea water. Magnesite, brucite, and olivine are the principal mineral sources; magnesium-rich dolomite and some ultrabasic igneous rocks are the principal rock sources, but most of the magnesium produced in recent years has been recovered from sea water and brines. Olivine is a common but generally sparse accessory mineral in igneous and metamorphic rocks in Colorado, and no concentrations of commercial grade are known. Magnesite and brucite are rare in Colorado. Dolomite is abundant in Colorado, and some has been used as a refractory (p. 203), but apparently none has been treated as a source of magnesium. Little is known of the magnesium content of brines in the State.

MERCURY

Mercury is the only metal that is liquid at ordinary temperatures, and because of this property it has many uses. Mercury prices have fluctuated widely in the past, and production has also. Domestic production comes from California and other Western States, but generally has not been adequate to satisfy requirements; imports have come from Italy, Mexico, Spain, and Yugoslavia. Commercial sources of mercury are mainly the sulfide, cinnabar, which typically forms at low temperatures in veins near the surface, mainly in areas of rather recent hydrothermal activity. Mineralogic occurrences of cinnabar are reported from localities in Boulder, Clear Creek, La Plata, and Teller Counties, and a small deposit of possible economic interest has been prospected on Cochetopa Creek, Saguache County (Eckel, 1961). Mercury itself has been found in stream gravels in areas where gold has been placered, but this probably represents mercury lost by earlier placer miners, who used it to amalgamate gold. In general, most of the known ore deposits in Colorado cannot be expected to contain commercial deposits of mercury as they formed at temperatures too high and depths too great for cinnabar. Geologically, cinnabar deposits could exist in some areas of young faulting and recent igneous and hydrothermal activity, but except in Cochetopa Creek, none has been found.

NICKEL

Nickel is used mainly as a ferrous alloy and for plating. Most of the domestic requirements are imported. Ore minerals of nickel are either sufides disseminated in basic igneous rocks or in veins, or are silicates resulting from the weathering of nickel-bearing igneous rocks, usually in a warm humid climate. In Colorado, nickel-bearing sulfides occur in the Copper King mine, Gold Hill district, Boulder County (Lovering and Goddard, 1950, p. 70), and in the Gem mine, Pine Creek area, Fremont County (Eckel, 1961, p. 242); both deposits have yielded some nickel ore. Occurrences of nickel-bearing sulfides are reported in a few small copper deposits in the Front Range in north-central Colorado.

PHOSPHATE ROCK

Phosphate rock is the source of phosphate for fertilizer and elemental phosphorus for various chemical uses. Phosphate rock is a sedimentary rock deposited in a certain marine environment. Large deposits of it occur in the Phosphoria Formation of Permian age in southeastern Idaho and the adjoining parts of Utah, Wyoming, and Montana. Equivalent beds extend into northwestern Colorado and perhaps contain a little phosphate rock, but no beds of commercial grade and thickness are known.

PLATINUM-GROUP METALS

The platinum-group metals are used in jewelry and for important but specialized chemical and industrial uses. These metals are chiefly recovered from nickel-copper sulfide ores associated with ultrabasic igneous rocks, and as a minor byproduct from refining gold. No deposits of the platinum-group metals are known in Colorado, though a little platinum may have been recovered from gold produced in the State.

RUBIDIUM

Rubidium is little known outside of the research laboratory, but it has some unusual properties that could be useful in some special applications. In nature it does not form an essential part of any known mineral, but it occurs in minor concentrations in lithium-bearing pegmatites and some natural brines. Lithium-bearing pegmatites occur in Gunnison and Fremont Counties (p. 173).

STRONTIUM

Strontium is used mainly in compound form, principally to obtain red colors in flares and fireworks, but to some extent in the ceramic and chemical industries. Domestic supplies are mainly imported. Geologic sources are the minerals celestite and strontianite, which commonly occur as gangue minerals in veins or in crystals and nodules in sedimentary rocks. Occurrences of these minerals are fairly common in Colorado (Eckel, 1961, p. 92–93 and 313–314), but no commercial deposits are known.

TALC, SOAPSTONE, AND PYROPHYLLITE

Talc, soapstone, and pyrophyllite are minerals and materials of different chemical compositions but like physical properties. Among many useful properties, their softness and chemical inertness make them useful as fillers in many industrial applications. These materials are found mostly in intensively metamorphosed rocks. Large deposits occur in several states, but only occurrences are known in Colorado.

TIN

Tin is used to plate other metals, in solders, and in making bronze and other alloys. Domestic requirements are large and are satisfied almost entirely by imports. Cassiterite, tin oxide, is the principal ore mineral. It occurs in veins, replacement bodies, and pegmatites, and in placer deposits. Considering the geologic variety of rocks and ore deposits in Colorado, occurrences of tin minerals are surprisingly sparse. As a result, much interest has been focused on finding tin deposits in Colorado, and frequently the reported discovery of tin-bearing rocks, or even a mineral specimen of cassiterite, has caused unusual excitement. Several occurrences of tin in the State are recorded by Eckel (1961, p. 91–92), but the only production has been as a minor byproduct from treating the molybdenum ore at Climax, Lake County (p. 105).

TITANIUM

Titanium is used both as a metal in nonferrous alloys and as the oxide in paints. Titanium is widely distributed in the earth's crust and is present in small amounts in many types of rocks. Titanium occurs mostly in the minerals ilmenite and rutile, and in most rocks these are merely accessory, but commercial deposits occur as bodies of titaniferous magnetite, as veins, and as black beach sands. Large deposits of these types occur in many parts of the world, and only those most favorable because of grade, size, and location are competitive. Titaniferous magnetite deposits occur at Caribou, Boulder County; Iron Mountain, Fremont County; and Powderhorn, Gunnison County (p. 97). These deposits have not been productive as titanium ore. Fossil beach sands containing some titanium minerals occur in sandstone beds in the Mesaverde Group in Montezuma and Mesa Counties (p. 132), but the known deposits are small and low in titanium content. Ilmenite and rutile are known as accessory minerals in many vein deposits in Colorado, but no concentrations of commercial grade and size are known.

ZIRCONIUM

Zirconium occurs in a number of minerals, but zircon is practically the only ore mineral. About half of the zircon consumed is used as zircon, as molding sand and as a refractory, and the rest is converted to zirconium and its alloys and compounds. Zircon is widely distributed as an accessory mineral in igneous, metamorphic, and sedimentary rocks; it occurs in small amounts in some pegmatites; and it is most abundantly concentrated in some stream, beach, and dune sands, which are the commercial sources. In Colorado, zircon is an accessory mineral in many rocks and a minor constituent in some pegmatites in Clear Creek, El Paso, and Jefferson Counties; it probably also occurs in the gravels of some streams.

MISCELLANEOUS ELEMENTS RECOVERED ONLY AS BYPRODUCTS

Several elements used only in very small amounts, and mainly for research, are recovered only as byproducts. Gallium is obtained as a byproduct of refining aluminum and zinc; germanium is recovered from zinc sulfides; hafnium is recovered in making hafnium-free zirconium; indium is a byproduct of zinc smelters; rhenium is obtained during roasting molybdenum sulfide concentrates; and thallium is a byproduct of zinc smelters. None are specifically known to have been recovered from Colorado ores, though some of the State's ores are possible sources.

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WATER RESOURCES

(By J. W. Odell and D. L. Coffin, U.S. Geological Survey, Denver Colo., and R. H. Langford, U.S. Geological Survey, Salt Lake City, Utah)

INTRODUCTION

A substantial supply of water is available in most of Colorado, particularly in the mountain areas, adjacent to the major streams, and in other areas underlain by extensive aquifers. Surface-water supplies generally are of good quality in the mountain areas but are variable in both quantity and quality at lower elevations. The quality of water usually deteriorates progressively downstream. Large supplies of good quality water are generally available in the alluvial fill in the upper reaches of the valleys and in the High Plains of eastern Colorado but ground-water supplies are generally limited in the mountain and plateau regions. The alluvial fill in the lower reaches of the valleys contains large supplies of water of poorer quality.

Reservoir storage has greatly increased beneficial use of surface water for irrigation, municipal supplies, and hydroelectric-power generation. Large-scale development of ground-water resources is under way and is expanding rapidly.

The climate and topography of Colorado determines the amount of water available and, to a large degree, its distribution. The mean annual precipitation is about 16 inches and ranges from about 6.5 inches at Alamosa, in the Rio Grande basin, to more than 50 inches in some of the high mountain areas. In the plains, 70 to 80 percent of the annual precipitation occurs as rain during the period April to September. In the mountains, precipitation is well distributed throughout the year with large accumulations of snow during the period December to April. Although extremely rare at high altitudes, cloudburst rainfall has occurred in most parts of the State. The eastern foothills of the Rocky Mountains and the adjoining plains area are particularly susceptible to such storms. Chinooks (warm, dry, downslope, winter winds) often deplete much of the snow storage at the lower mountain elevations and on the plains. In Colorado, chinooks occur primarily on the eastern slope of the mountains and the eastern plains.

An average of about 90 million acre-feet of water falls annually as precipitation in Colorado. A large part is lost by evapotranspiration, and only about 16 million acre-feet appears as runoff in the major streams.

Water is one of the predominant factors in the process of erosion. Streams transport large quantities of material in the form of dissolved solids, suspended sediment, and bedload. For example, the long-term average annual discharge of dissolved solids and suspended sediment of the Colorado River at Cisco, Utah, about 30 miles downstream from the Colorado-Utah State line, is more than 18 million tons. This is equivalent to more than 760 tons annually, per square mile of the drainage basin. However, most of the load comes from the lower part of the basin.

Fresh-water use (exclusive of hydroelectric power use) in Colorado in 1960 was about 9,700 mgd (million gallons per day) or 10.8 million acre-feet per year: for public supply, 250 mgd of surface water and 41 mgd of ground water; for rural supply, 11 mgd of surface water and 29 mgd of ground water; for irrigation, 7,100 mgd of surface water and 1,800 mgd of ground water; for industry, 320 mgd of surface water (of which 200 mgd was for public-utility fuel-electric power) and 35 mgd of ground water. Industry also used about 10 mgd of saline surface water and 10 mgd of saline ground water. Hydroelectric power use was about 3,200 mgd.

The Geological Survey publishes data on streamflow, chemical quality of water, temperature, and sediment loads on a water-year basis. A water year begins on October 1 and ends on September 30 of the year named.

SURFACE WATER

The lofty summit of the Continental Divide in Colorado is the source of five of the West's major streams; the North Platte, South Platte, Arkansas, and Colorado Rivers and the Rio Grande. Altitudes of 53 of the mountain peaks are more than 14,000 feet. The Republican River originates in the High Plains of eastern Colorado. These streams flow outward in all directions from the State, supplying water to 18 other States in this country and two States in the Republic of Mexico. Inflow to the State is small except for the Green River, which enters and leaves the State in a relatively short distance. An unusual feature in Colorado is the substantial amount of water diverted from one drainage basin to another.

The relative discharge of the principal streams is shown schematically on figure 40. The width of the line representing the stream is proportional to the mean discharge in acre-feet per year. The variable width of the line for some streams shows the effect of diversions and return flow.

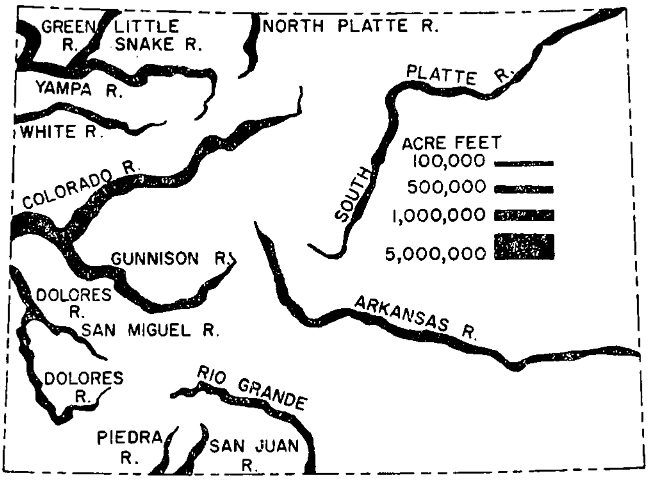

FIGURE 40.—Average annual discharge, in acre-feet, of principal rivers. (Width of river line indicates average annual discharge)

Watersheds in Colorado yield an average of more than 16 million acre-feet of surface water per year, but interstate compacts and Supreme Court decrees limit consumptive use in Colorado to somewhat less than half this amount. The exact allotment to the State under the various compacts and decrees depends upon a great many variables, and is not the same from year to year. In the Rio Grande basin during the period January 1, 1952, to December 31, 1963, deliveries to downstream users have been much less than required by the Rio Grande Compact. Estimates vary as to the amount of unappropriated water in the Colorado River basin, but are as low as 1,250,000 acre-feet per year (U.S. Congress, Select Committee on National Water Resources, United States Senate, 1960, p. 1921). This estimate is based on Colorado's claimed total average annual right to 3,855,000 acre-feet in the basin. Whatever the amount may be, future development of water resources in the State will depend increasingly upon additional storage, reuse of available supplies, and development of management practices that will reduce consumptive use by nonbeneficial plants and increase efficient conjunctive use of surface- and ground-water supplies.

The average annual runoff varies widely and depends upon precipitation, geology, topography, and vegetative cover. It ranges from less than 0.25 inch to more than 20 inches and averages about 4.1 inches for the State. The generalized areal distribution of runoff as equivalent inches in depth over the land surface is shown in figure 41. The

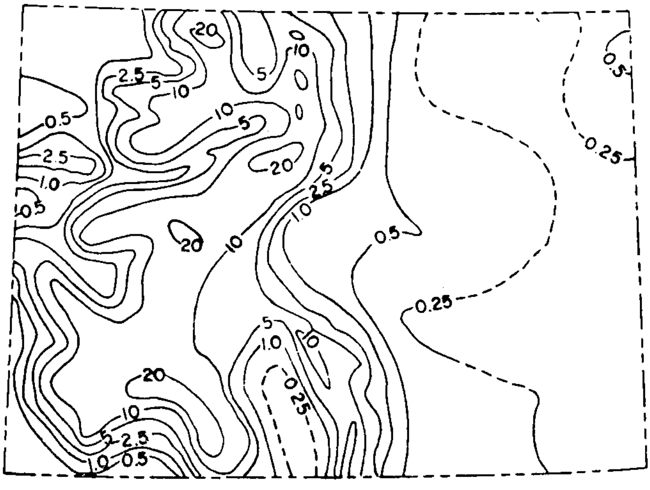

FIGURE 41.—Average annual runoff, in inches, 1921–45.

mountain areas produce the high runoff while the plains and plateau areas, in general, yield less than 1 inch.

The usefulness of streamflow is directly related to its seasonal and annual dependability. The large proportion of annual precipitation that accumulates as snow in the high mountains during the winter months has a marked effect on the runoff pattern. The snowmelt runoff usually occurs during the period April to June, but frequently extends into July during years of large snow accumulation. A large percentage of the total annual runoff occurs during the snowmelt

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period. There is a general recession of streamflow during the summer months with minor fluctuations caused by summer precipitation. The minimum flows of the mountain streams usually occur during the late winter months when ground-water contribution has been substantially depleted and before spring snowmelt replenishes water supplies. Streams originating in the plains area follow a more erratic pattern and usually produce maximum flows during the summer as a result of severe thunder storms. To illustrate this flow pattern, typical annual hydrographs for high- and low-water years for the Blue River above Green Mountain Reservoir and South Fork Republican River near Idalia are shown in figure 42.

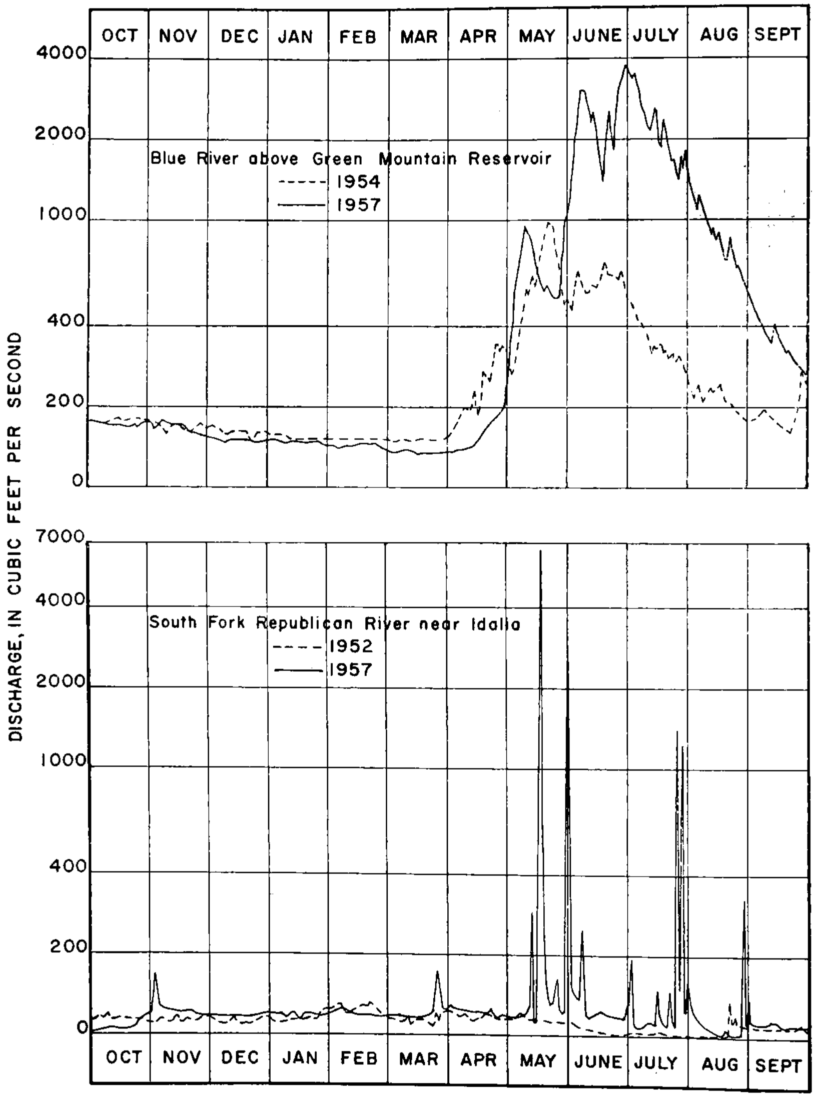

FIGURE 42.—Typical hydrographs of selected streams.

Total annual runoff also varies significantly. Figure 43 shows the variations of the Colorado River at Glenwood Springs and the Arkansas River at Canon City adjusted for significant transmountain diversions. The flow of the Colorado River at Glenwood Springs has been particularly erratic and has ranged from 146 percent of average for the high-water year of 1907 to 50 percent of average for the drought year of 1934. The average discharge for the 31-year period 1900–30 was 37 percent higher than for the succeeding 33-year period 1931–63.

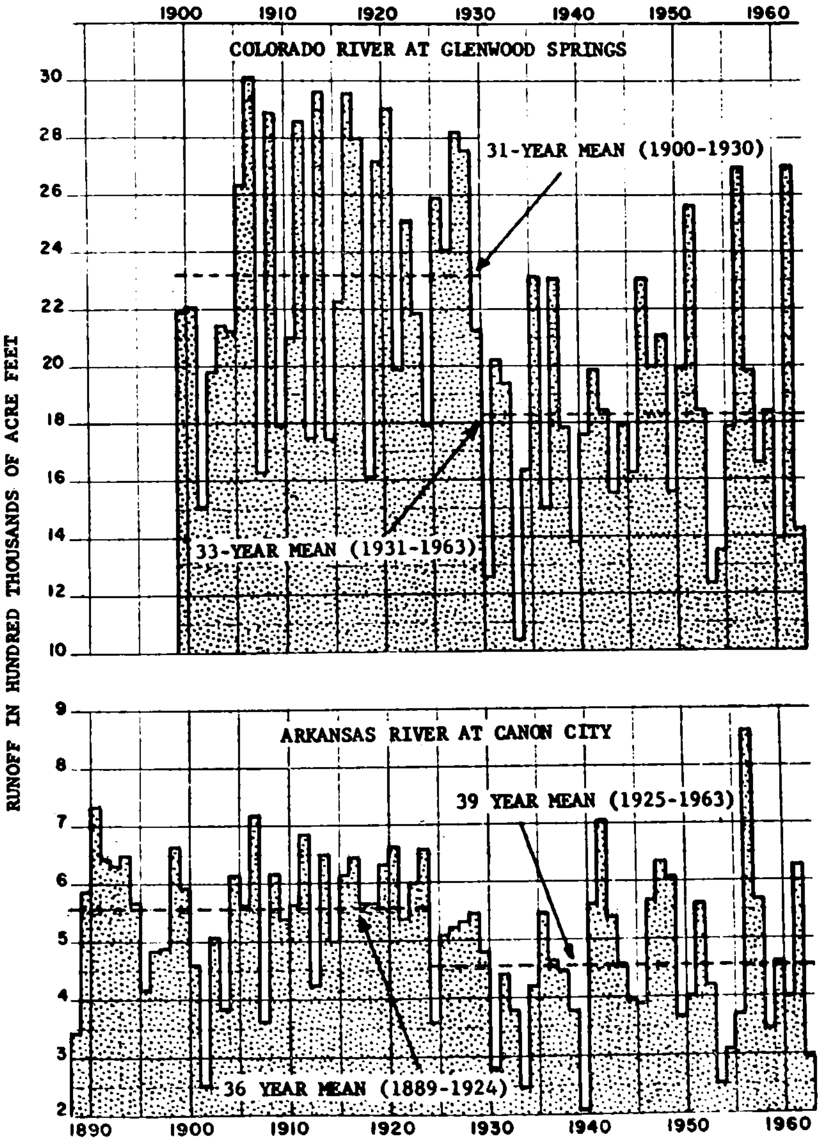

FIGURE 43.—Yearly streamflow (runoff) of selected streams.

Storage reservoirs have been constructed to assist in equalizing seasonal and yearly variations in streamflow. The total number of reservoirs in Colorado, as shown by records of the State Engineer's Office, is more than 1,900 with a total storage capacity of about 4,500,000 acre-feet. Additional reservoirs of substantial capacity are under construction and others are planned. The primary use of most of the reservoirs is storage of water for irrigation and municipal supplies, although many are also used for the generation of hydroelectric power, flood control, and recreation. There are a large number of natural lakes in the State, many of which were formed by glaciation high on the watersheds of streams originating at or near the Continental Divide. Other natural reservoirs are in closed basins in the plains and in some high mountain valleys. Many stock ponds and small detention reservoirs have been constructed in the agricultural and grazing areas. These structures change local runoff patterns to a limited extent but probably have little effect on water yields of perennial streams.

There are numerous springs in Colorado, many of which are hot springs with high mineral content. George and others (1920) have described 254 of these springs. The largest is Glenwood Springs, with a discharge of about 3,000 gpm (gallons per minute).

Runoff from precipitation in the high mountain areas contains small amounts of dissolved salts. Concentrations of dissolved solids are normally less than 100 ppm (parts per million) and in most headwater areas less than 50 ppm. Calcium and bicarbonate are the major constituents, although, in areas underlain by volcanic rocks, silica also is a major constituent. The chemical characteristics of the water change as the streams leave the mountains and traverse the irrigated valleys and the more densely populated areas. Through water use, the dissolved solids concentrations are increased, on the average, to more than 350 ppm and calcium, magnesium, sulfate, and chloride become major constituents.

General information about prevalent chemical type and dissolved solids concentration of water in rivers is depicted in figure 44. The types and concentrations shown usually coincide with low-flow conditions. High flows resulting from precipitation or snowmelt commonly are less highly mineralized and are of a different chemical type than low flows which are made up of a greater proportion of irrigation return flows, industrial and municipal wastes, and ground-water inflow.

The resistant rocks, rugged terrain, high altitude, abundant precipitation, and good forest or grass cover combine to yield abundant runoff but low concentrations of sediment in rivers draining the mountains. Highest concentrations of suspended sediment occur in the ephemeral runoff resulting from intense rains on the Great Plains east of the mountain front. Differences in the suspended-sediment concentrations of rivers of Colorado are shown on figure 44.

PLATTE RIVER BASIN

North Platte River basin.—The North Platte River drains about 1,500 square miles in north-central Colorado, principally in Jackson

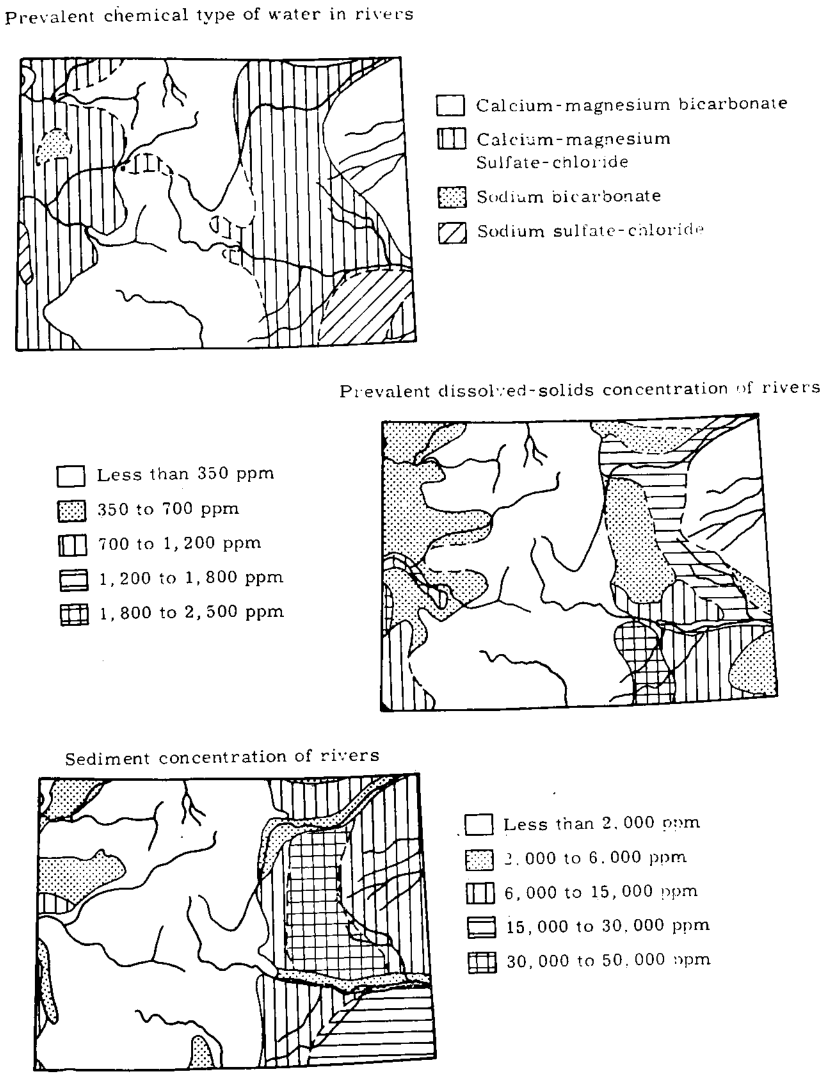

FIGURE 44.—Maps showing chemical quality and sediment characteristics of Colorado rivers (adapted from Rainwater, 1962).

County. The headwaters are in Routt National Forest between the Continental Divide and the Medicine Bow Mountains. The Laramie River drains about 300 square miles in Colorado between the Medicine Bow Mountains and the Laramie Range. It joins the North Platte River after crossing the State boundary into Wyoming. Geography and Supreme Court decrees limit the use of the water in Colorado. There are several diversions to the South Platte River basin.

Summary records of discharge for selected stations in the North Platte River basin are given in table 21.

TABLE 21.—*Summary streamflow records at selected points in the North Platte River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Area-feet per year	Maximum	Minimum daily
Grizzly Creek near Walden	252.	22	52.5	38,010	1,340	0
North Platte River near Walden	463.	25	186.	134,700	1,940	5.2
North Fork Michigan River near Gould	20.2	12	17.8	12,890	290	----------
Michigan River at Walden	185.	24	55.7	40,330	1,070	1.1
North Platte River near Northgate	1,431.	47	441.	319,300	6,720	19.
Laramie River near Glendevey	101.	53	74.1	53,650	2,240	5.

Data concerning sediment and water-quality characteristics of streams in the North Platte River basin in Colorado are sparse, but based on correlation with similar nearby areas, the dissolved-solids and sediment concentrations of streams are known to be low, and the water is of the calcium bicarbonate type (fig. 44).

South Platte River basin.—The South Platte River basin includes about 23,000 square miles in the northeastern quarter of Colorado. It yields an average of about 1,625,000 acre-feet of water per year or approximately 10 percent of the State's average annual supply. The source of the South Platte River is at the Continental Divide near the geographical center of the State. It flows southeast through South Park, swings northward at Elevenmile Canyon and continues in a northerly direction, through Denver, to the Greeley area where it turns abruptly east to Fort Morgan, then northeast through Julesburg and into Nebraska. Numerous left-bank tributaries that head at the Continental Divide and drain the eastern slope of the mountains join the main stream upstream from the Greeley area. The principal tributaries are North Fork South Platte, Big Thompson, and Cache la Poudre Rivers and Bear, Clear, and St. Vrain Creeks. In general, tributaries from the plains area are ephemeral and, although they drain a large area, contribute a small percentage of the total flow.

The South Platte basin is the most heavily populated area of Colorado, having over 60 percent of the State's population. The entire natural water supply has been appropriated and large supplies are imported from other basins. The two largest imports are for the Colorado-Big Thompson project and the Denver municipal water supply, with a combined requirement of approximately 500,000 acre-feet annually. Many smaller imports add materially to the total water available for use in the basin. Existing storage reservoirs have improved greatly the dependability of water supplies for irrigation and municipal uses. Additional storage is planned that will permit more efficient use of the available water supply.

Data for selected streamflow stations with long-term records are given in table 22. Flow at all stations is affected by storage, diversion, return flow, or imports from other basins.

Water in headwater streams of the South Platte River is of very low mineralization and generally is of the calcium bicarbonate type. Available chemical-quality data indicate that dissolved-solids concentrations are about 100 ppm or less in the South Platte River at

TABLE 22.—*Summary streamflow records at selected points in the South Platte River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
South Platte River near Lake George	963	33	69.5	50,320	990	0
South Platte River below Cheesman Lake	1,752	38	156.	112,900	3,020	1.6
North Fork South Platte River at South Platte	479	50	157.	113,700	2,050	[1] 4.
South Platte River at South Platte	2,579	69	358.	259,200	6,320	10.
Plum Creek near Louviers	302	15	22.7	16,430	3,800	0
Bear Creek at Morrison	164	47	54.7	39,600	8,600	.8
Cherry Creek near Melvin	336	23	13.7	9,920	17,600	0
South Platte River at Denver	3,804	67	345.	249,800	22,000	8.8
Clear Creek near Golden	399	52	233.	168,700	5,890	11.
St. Vrain Creek at Lyons	212	71	132.	95,560	10,500	0
Cache la Poudre River at mouth of canyon, near Fort Collins	1,055	79	399.	288,900	[2] 21,000	1.6
South Platte River near Kersey	9,598	59	736.	532,800	31,000	28.
South Platte River at Julesburg	23,138	60	464.	335,900	31,300	0

[1] Minimum observed.
[2] Maximum determined.

Waterton and in major tributaries in the mountains. Near Kersey, just east of Greeley, the water in the South Platte River contains an average of about 1,000 ppm of dissolved solids; sodium, calcium sulfate, and bicarbonate are the major constituents. At Julesburg, the concentration increases to about 1,200 ppm of dissolved solids. Similar changes in mineralization also occur in tributaries draining the eastern slopes of the Rocky Mountains.

TABLE 23.—*Concentration and discharge of dissolved solids for streams in the South Platte River basin*

Stream	Period of record (water year)	Water discharge (thousands of acre-feet per year)	Dissolved solids		
			Weighted-average concentration (ppm)	Discharge	
				Thousands of tons per year	Tons per square mile per year
South Platte River at Waterton	1957	210	120	36	14
South Platte River at Littleton	1951	76	300	31	10
Bear Creek at Morrison	1957–58	56	60	4	26
South Platte River below sewer outfall at Denver	1956	154	550	115	30
Clear Creek near Golden	1957–58	214	87	25	65
South Platte River at Henderson	1955–57	230	370	116	23
South Platte River at Fort Lupton	1950–51, 1955	136	600	111	22
South Boulder Creek near Eldorado Springs	1957–61	51	50	3	30
St. Vrain Creek at mouth near Platteville	1950–56	93	900	114	114
Big Thompson River at mouth near La Salle	1950–56	42	1,420	80	98
Cache la Poudre River near Greeley	1950–56	39	1,270	68	37
South Platte River near Kersey	1950–53, 1955–57	380	1,070	552	58
South Platte River near Balzac	1950–51, 1955–57	146	1,370	273	15
South Platte River near Julesburg	1946–62	317	1,220	526	23

Selected records of chemical quality are summarized in table 23. Except for the Julesburg station, the records summarized in the table are estimates based on correlations between water discharge and dissolved-solids concentrations.

Data are not adequate to appraise fully fluvial sediment in the mountainous parts of the basin. Very low concentrations of suspended sediment have been measured at low and medium flows in the South Platte River at South Platte and in the Cache la Poudre River at mouth of canyon, near Fort Collins. Suspended-sediment records for Clear Creek and North Clear Creek during 1952–55 water years are summarized below. Past mining operations in the Clear Creek drainage basin probably account for the relatively high average concentrations.

Station	Average concentration (ppm)	Discharge (thousands of tons per year)
Clear Creek below Idaho Springs	280	43
North Clear Creek near Blackhawk	690	16

Following intense rainstorms, the basins of the tributary streams east of Denver yield large amounts of sediment. For example, in the 1957 water year, during which there were many intense rainstorms, Kiowa Creek at Kiowa discharged about 100,000 tons of sediment. In contrast, the annual sediment discharge at Kiowa 2 years later, when there were no intense rainstorms, was only about 800 tons.

REPUBLICAN RIVER BASIN

The Republican River system, in Colorado, consists of the North and South Forks, the Arikaree River (designated as the headwaters of the Kansas River), Frenchman Creek, and Smoky Hill River. The system drains about 8,700 square miles in the High Plains of eastern Colorado, much of which contributes little or no surface runoff. The average annual yield is estimated to be about 140,000 acre-feet, less than 1 percent of the State's total supply. An estimated 60,000 acre-feet annually is available for use in Colorado. Altitudes range from about 3,300 feet near the Colorado-Kansas State line to more than 5,500 feet at the headwaters of some of the tributaries. Bonny Reservoir on the South Fork Republican River was completed in 1951 for flood control and for future irrigation of about 6,000 acres in Colorado.

Streamflow data for selected gaging stations are given in table 24 below.

TABLE 24.—*Summary streamflow records at selected points in the Republican River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
North Fork Republican River near Wray		15	22.1	16,000	283	6.9
North Fork Republican River at Colorado-Nebraska State line		32	50.0	36,200	2,110	0
South Fork Republican River near Idalia	1,300	12	34.2	24,760	[1] 14,300	0
Landsman Creek near Hale	450	12	4.91	3,550	4,570	0

[1] Maximum flood known since at least 1865, 103,000 cfs May 31, 1935, prior to establishment of the gaging station.

In the late 1940's periodic data on the chemical quality of water in the South Fork and North Fork Republican Rivers were obtained at 4 sites in Colorado. These data indicate that near the boundary of Colorado with Kansas and Nebraska the water in both streams is of the calcium bicarbonate type, has a hardness of 100 to 250 ppm as calcium carbonate, and contains from 200 to 400 ppm of dissolved solids. During the period 1953–58 data showed that water stored in Bonny Reservoir contained 218 to 330 ppm of dissolved solids and 136 to 189 ppm of hardness. The data probably are representative of water in most headwater streams of the Republican River in Colorado.

ARKANSAS RIVER BASIN

The southeastern quarter of Colorado is drained by the Arkansas River system. It heads near Leadville and flows south and east through mountainous terrain and canyons (the most notable of which is Royal Gorge) and across the eastern plains and into Kansas near Holly. The basin includes 25,410 square miles, of which about 1,708 square miles is probably noncontributing to surface runoff. The average annual yield of the basin is estimated to be 1,095,000 acre-feet, about 7 percent of the total for the State. Natural supplies available for use in Colorado are completely appropriated and an average of approximately 50,000 acre-feet annually is imported from the Colorado River basin. The Fryingpan-Arkansas project, now approaching the construction stage, will import an additional annual average of about 69,000 acre-feet. Of this amount, about 20,500 acre-feet will be used for municipal supplies and the remainder for supplemental irrigation. The project will also provide better regulation of existing supplies, flood protection, and generation of about 500 million kilowatt-hours of electric energy annually. John Martin (Caddoa) Reservoir on the Arkansas River below Las Animas is the largest in the State with a total capacity of 645,500 acre-feet of which 366,600 acre-feet is for conservation and 278,900 acre-feet for flood control.

Streamflow data for selected stations with long-term records are given in table 25. Flow at most gaging stations is affected by storage, imported water, diversion, and return flow from irrigated areas.

Upstream from Canon City water in the Arkansas River has a disolved-solids concentration less than 200 ppm and is predominantly of the calcium bicarbonate type. The dissolved-solids concentration increases to 500–600 ppm at Pueblo, where the water is a calcium-sulfate bicarbonate type. Most of the irrigation in the Arkansas River valley is downstream from Pueblo, and the dissolved-solids concentration of the river increases with distance downstream. Return flow from irrigation is the principal cause of the increase in concentration, though evaporation from the water surface and evapotranspiration also contribute. Figure 45 illustrates the down-valley increase in dissolved solids.

Chemical-quality records have been obtained by the Geological Survey on the Arkansas River below John Martin Reservoir (at Caddoa) continuously since 1951. The average annual dissolved-solids concentration was about 1,500 ppm. The concentration was much higher a large part of the time. It exceeded 2,600 ppm 50 percent of the time, exceeded the annual average 70 percent of the time, and exceeded 1,000

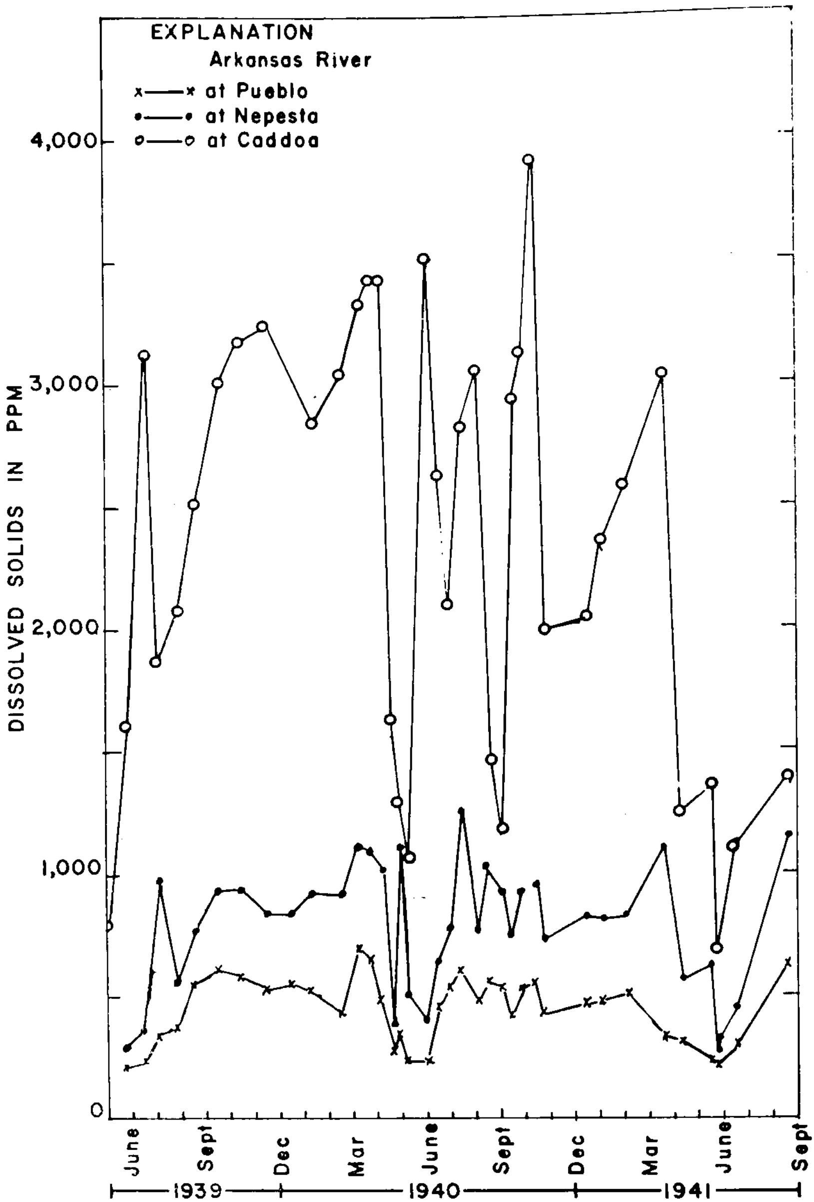

FIGURE 45.—Dissolved-solids concentration of the Arkansas River at Pueblo, Nepesta, and Caddoa. (Data from U.S. Bureau of Reclamation.)

TABLE 25.—*Summary streamflow records at selected points in the Arkansas River Basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Lake Fork above Sugar Loaf Reservoir	18	16	42.	30, 410	610	1. 0
Lake Creek above Twin Lakes Reservoir	75	15	161.	116, 600	3, 150	
Arkansas River at Granite	427	52	353.	255, 600	5, 360	
Clear Creek above Clear Creek Reservoir	59	16	72. 4	52, 420	1, 300	
Cottonwood Creek below Hot Springs near Buena Vista	65	26	59. 5	43, 080	1, 180	[1] 10.
Arkansas River at Salida	1, 218	56	624.	451, 800	9, 220	[1] 100.
Arkansas River at Canon City	3, 117	74	722.	522, 700	19, 000	69.
Arkansas River near Pueblo	4, 686	69	717.	519, 100	103, 000	18.
Fountain Creek at Pueblo	926	25	51. 8	37, 500	[2] 17, 800	0
Huerfano River below Huerfano Valley Dam, near Undercliffe	1, 673	23	40. 3	29, 180	16, 800	0
Arkansas River near Nepesta	9, 345	49	700.	506, 800	180, 000	0
Apishapa River near Fowler	1, 125	26	36. 3	26, 280	[3] 83, 000	0
Arkansas River at La Junta	12, 210	50	261.	189, 000	200, 000	0
Arkansas River at Las Animas	14, 417	23	238.	172, 300	44, 000	1. 6
Purgatoire River near Las Animas	3, 503	23	138.	99, 910	70, 000	0
Arkansas River below John Martin Reservoir	18, 917	24	[4] 355.	[4] 257, 000	40, 000	0
Arkansas River at Lamar	19, 780	45	237.	171, 600	130, 000	0
Arkansas River near Coolidge, Kans	25, 410	12	187.	135, 400	60, 000	0

[1] Minimum observed.
[2] Flood of May 30, 1935, prior to operation of gaging station, discharge 35,000 cfs.
[3] Caused by failure of Apishapa Dam 31 miles upstream.
[4] Adjusted for storage in John Martin Reservoir.

ppm 90 percent of the time. The average annual load of dissolved solids below John Martin Reservoir was 331,700 tons.

Water quality continues to deteriorate below John Martin Reservoir and sparse data indicate that the average annual dissolved-solids content at the Colorado-Kansas State line may be as much as 3,000 ppm. Below John Martin Reservoir the water is predominantly a calcium sulfate type.

The Corps of Engineers, U.S. Army, has obtained data on suspended sediment in the Arkansas River and its tributary streams. Data for the period 1940–53, adapted from a report of the U.S. Army Corps of Engineers (1960, table 22) are summarized below:

Station	Average annual sediment discharge, 1940–53		
	Acre-feet	Thousands of tons	Tons per square mile
Arkansas River at Pueblo	489	806	172
Fountain Creek at Pueblo	374	617	666
St. Charles River near Pueblo	315	519	1, 109
Huerfano River at Undercliffe	604	996	595
Arkansas River at Nepesta	2, 672	4, 405	466
Apishapa River near Fowler	1, 273	2, 099	1, 866
Timpas Creek near La Junta	279	460	1, 010
Arkansas River at La Junta	1, 881	3, 101	254
Arkansas River at Las Animas	1, 754	2, 892	201
Purgatoire River near Las Animas	2, 345	3, 866	1, 104
Arkansas River below John Martin Reservoir	1, 345	2, 218	117

In the same report, the Corps of Engineers estimated that during the period 1940–57, the average annual suspended sediment inflow to John Martin Reservoir was about 4,540 acre-feet and the outflow was 1,160 acre-feet.

RIO GRANDE BASIN

The Rio Grande at the Colorado-New Mexico State line has a drainage area of about 7,700 square miles. A small part of the area is in New Mexico and 2,940 square miles is in a closed basin in the northern part of the San Luis Valley, Colo. The headwaters of the Rio Grande are at the Continental Divide in the San Juan Mountains. Tributaries rise in the Cochetopa Hills on the north and the Sangre de Cristo Range on the east. The estimated average annual surface-water yield of the basin is 1,380,000 acre-feet, more than 8 percent of the total for the State. A large part is used for irrigation in Colorado and the average annual discharge near the State line for 63 years is 458,300 acre-feet. Colorado's portion of Rio Grande water is fully appropriated. During the period 1952–63 there has been a preponderance of years with subnormal runoff, and deliveries to downstream users have been much less than required by the Rio Grande Compact. This situation presents a serious water problem in the basin.

Reservoirs on the main stream and on several tributaries provide storage for better distribution of the available water supply. There are a few transmountain diversions from the San Juan and Gunnison River basins but the quantities imported are small and have little effect on the total water supply.

Streamflow data for selected gaging stations with long-term records are given in table 26.

TABLE 26.—*Summary streamflow records at selected points in the Rio Grande basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Rio Grande at Thirtymile Bridge near Creede	163.	49	219.	158,500	7,500	0.1
North Clear Creek below Continental Reservoir	51.7	33	31.5	22,810	362	0
South Fork Rio Grande at South Fork	216.	38	215.	155,700	8,000	14.
Rio Grande near Del Norte	1,320.	73	922.	667,500	18,000	69.
Rio Grande near Monte Vista	1,590.	36	330.	238,900	18,500	1.5
Rio Grande at Alamosa	1,710.	50	268.	194,000	14,000	1.
Saguache Creek near Saguache	595.	50	71.8	51,980	756	[1] 8.2
Alamosa Creek above Terrace Reservoir	107.	36	117.	84,700	5,200	----------
Ute Creek near Fort Garland	32.	39	21.4	15,490	[2] 630	0
Conejos River near Mogote	282.	53	343.	248,300	9,000	10.
Los Pinos River near Oritz	167.	43	127.	91,940	3,160	[3] 4.
Conejos River near La Sauses	887.	41	197.	142,600	3,890	0
Culebra Creek at San Luis	220.	35	51.8	37,500	654	4.6
Rio Grande near Labatos	7,700.	63	633.	458,300	13,200	0

[1] Minimum daily recorded.
[2] Maximum daily.
[3] Minimum observed.

Only meager data are available to appraise the quality of surface-water resources of the Rio Grande basin in Colorado. Available data indicate that upstream from Del Norte the water contains less than 100 ppm of dissolved solids; concentrations increase downstream. The range and average annual concentration of the major dissolved constituents in the Rio Grande above Culebra Creek near Lobatos for the period 1947–62 are given below. The dissolved-solids discharge is about 77,500 tons per year.

	Maximum observed	Minimum observed	Average annual
Silica, SiO_2, ppm	68	18.	27.
Calcium, Ca, ppm	90	14.	31.
Magnesium, Mg, ppm	24	1.	6.7
Sodium, Na, ppm	183	7.5	25.
Bicarbonate, HCO_3, ppm	321	26.	113.
Sulfate, SO_4, ppm	318	14.	57.
Chloride, Cl, ppm	33	1.9	7.6
Dissolved solids, ppm	805	100.	225.
Specific conductance, micromhos per cm at 25° C	1,110	139.	317.
Percent sodium	72	16.	34.

COLORADO RIVER BASIN

The Colorado River and its tributaries that originate within the State are the major sources of undeveloped surface water remaining in Colorado. The estimated average annual yield of the Colorado River basin in Colorado is 11,150,000 acre-feet, including tributary flow that leaves the State before joining the main stem, about 69 percent of the State's total supply. Large quantities of water are exported to the South Platte and Arkansas River basins. Projects now under construction will increase the exports substantially.

Colorado River and tributaries joining it in Colorado.—The Colorado River heads in Rocky Mountain National Park, flows south for a short distance, then southwest to the approximate midpoint of Colorado's western boundary, where it enters Utah. The drainage area above this point is approximately 17,900 square miles.

Major reservoirs in the upper basin have a combined capacity of more than a million acre-feet. The largest of these is Lake Granby, a part of the Colorado-Big Thompson irrigation and power project, with a usable capacity of 465,000 acre-feet. Other reservoirs are in planning or construction stages for participating irrigation projects of the Upper Colorado River Storage project.

Table 27 contains streamflow data for selected gaging stations in the area. Flow at most of the stations is affected by transmountain diversions, storage, or diversions for irrigation.

TABLE 27.—*Summary streamflow records at selected points on the Colorado River and tributaries joining it in Colorado*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Colorado River near Grand Lake	103.	43	96.7	70,010	1,840	1.7
Arapaho Creek at Monarch Lake Outlet	47.1	18	83.9	60,740	1,300	.2
Fraser River near Winter Park	27.6	52	40.9	29,610	820	2.
Williams Fork near Parshall	186.	49	148.	107,100	2,620	10.
Blue River at Dillon	129.	50	116.	83,980	[1] 1,180	[2] 7.4
Eagle River at Red Cliff	72.2	33	54.9	39,750	1,010	1.
Colorado River at Glenwood Springs	4,560.	63	2,764.	2,001,000	30,100	286.
Roaring Fork at Glenwood Springs	1,460.	56	1,402.	1,015,000	19,000	179.
Colorado River near Cameo	8,050.	29	3,976.	2,879,000	36,000	700.
Buzzard Creek near Collbran	139.	41	48.2	34,900	1,630	0
Plateau Creek near Collbran	604.	27	192.	139,000	3,920	13.
Colorado River near Colorado-Utah State line	17,900.	11	5,970.	4,322,000	56,800	960.

[1] Maximum observed.
[2] Minimum observed.

Average annual concentrations and discharges of dissolved solids in several streams in the Colorado River basin are summarized in table 28, along with data on sediment characteristics of streams. The data in table 28 represent the long-term average that would have occurred if the water-use developments existing in 1957 had been in place and in operation throughout the water years 1914–57 (W. V. Iorns, personal communication, 1962).

The upper reaches of the Colorado River and its principal tributaries are underlain by rocks that are relatively resistant to the solvent action of water, and the dissolved-solids concentration of runoff may be less than 20 ppm. The average concentration of headwater streams seldom exceeds 50 ppm and does not exceed 100 ppm. These dilute waters are of the calcium bircarbonate type and some contain relatively high concentrations of silica dissolved from volcanic rocks.

The concentrations of dissolved solids, sodium, sulfate, and chloride increase downstream, particularly during periods of low and medium flow. The increase is caused by many factors, but principally by the change from igneous and metamorphic rocks in the headwaters area to sedimentary rocks in the middle and lower parts of the basin. The sedimentary rocks contain minerals that are more readily soluble and, therefore, contribute more dissolved solids to the streams. Springs along the 17-mile reach of the Colorado River between the Eagle River and the Shoshone Power Plant contribute about 180,000 tons of dissolved solids annually, mostly sodium chloride. In the reach between Shoshone Power Plant and Cameo, springs add an additional 250,000 tons of dissolved solids to the river annually (W. V. Iorns, personal communication, 1964).

Lake Granby, Willow Creek Reservoir, Williams Fork Reservoir, and Green Mountain Reservoir trap sediment from 1,280 square miles of the drainage basin. A large part of the sediment transported by the Colorado River near Cameo comes from the drainage area downstream from Roaring Fork (table 28). Between Glenwood Springs and Cameo almost 8.8 million tons of suspended sediment is added to the Colorado River each year. This contribution is equivalent to a yield of about 4,200 tons per square mile per year from the intervening drainage area (2,040 square miles) below the mouth of Roaring Fork and above the mouth of Plateau Creek.

Gunnison River and tributaries.—The Gunnison River is one of the major tributaries of the Colorado River. It lies wholly within the State and drains about 8,000 square miles. Taylor River and its tributaries rise on the west side of the Sawatch Range, join East River at Almont and become the Gunnison River. Principal tributaries are Tomichi Creek, Cochetopa Creek, Cebolla Creek, Lake Fork, North Fork Gunnison River, and Uncompahgre River.

Numerous reservoirs have been constructed to regulate streamflow for better distribution of irrigation water. The largest of these is Taylor Park Reservoir, capacity 106,200 acre-feet. Diversions from the Gunnison River to the Uncompahgre River Valley average more than 300,000 acre-feet annually, most of it through Gunnison tunnel. Blue Mesa and Morrow Point Dams, part of the Curecanti Unit of the Upper Colorado River storage project, are currently (1964) under construction. When completed, additional stored water will be provided for irrigation, power development, and recreation.

TABLE 28.—*Concentration and discharge of dissolved solids and suspended sediment at selected points on the Colorado River and tributaries joining it in Colorado and at Cisco, Utah*

[Data represent annual averages for the period 1914–57 adjusted to 1957 conditions]

Stream	Water discharge (thousands of acre-feet per year)	Dissolved solids			Suspended sediment		
		Weighted-average concentration (ppm)	Discharge		Weighted-average concentration (ppm)	Discharge	
			Thousands of tons per year	Tons per square mile per year		Thousands of tons per year	Tons per square mile per year
Colorado River near Grand Lake	71	38	3.7	35			
Fraser River near Winter Park	15	30	.6	22			
Colorado River at Hot Sulphur Springs	177	76	18.	23			
Williams River near Parshall	99	35	4.7	26			
Blue River below Green Mountain Reservoir	379	101	52.	83			
Colorado River above Eagle River near Dotsero	1,165	154	244.	71			
Eagle River at Gypsum	436	303	180.	213			
Colorado River near Dotsero	1,628	199	442.	101			
Colorado River near Glenwood Springs	1,738	270	639.	142			
Colorado River at Glenwood Springs	1,738				200	486	107
Fryingpan Creek at Norrie	99	23	3.1	35			
Roaring Fork at Glenwood Springs	980	225	300.	205	220	287	197
Rifle Creek near Rifle [1]	18	647	16.	112	1,800	44	311
Colorado River near Cameo	2,998	387	1,578.	196	2,300	9,248	1,150
Plateau Creek near Collbran	75	57	5.8	66	180	19	216
Colorado River near Cisco, Utah	5,534	547	4,120.	171	[2] 2,050	[2] 14 351	[2] 595

[1] For the period 1940–46, 1953–57.

[2] For the period 1930–57; average annual water discharge was 5,141,000 acre-feet.

Streamflow data for selected gaging stations in the basin are given in table 29.

TABLE 29.—*Summary streamflow records at selected points in the Gunnison River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Taylor River at Almont	440	52	344	249,000	[1] 3,760	24
East River at Almont	295	40	347	251,200	[1] 6,500	19
Gunnison River near Gunnison	1,010	36	796	576,300	[1] 11,400	90
Tomichi Creek at Gunnison	1,020	25	173	125,200	1,900	13
Lake Fork at Gateview	338	25	248	179,500	2,700	25
Gunnison River below Gunnison tunnel	3,980	59	[2] 1,479	[2] 1,071,000	[1] 19,000	0
North Fork Gunnison River near Somerset	521	29	439	317,800	7,860	17
Uncompahgre River at Colona	437	52	274	198,400	[3] 4,080	12
Gunnison River near Grand Junction	7,870	54	2,631	1,905,000	[1] 37,500	106

[1] Maximum observed.
[2] Unadjusted for Gunnison tunnel diversion.
[3] Maximum daily.

Discharges of dissolved solids range from about 20 tons per square mile per year in the areas underlain by volcanic rocks on the north side of the San Juan Mountains to more than 400 tons in the Uncompahgre River at Delta. Most of the sediment apparently comes from areas underlain by rocks of Cretaceous age.

Most of the headwater streams yield water that is of the calcium bicarbonate type. The interior of the basin below Cimarron Creek is underlain by rocks of Cretaceous age, and as the streams pass through this area, sodium, magnesium, and sulfate are brought into solution increasing the dissolved-solids concentration greatly. The Uncompahgre River contributes about 30 percent of the dissolved-solids discharge of the Gunnison River near Grand Junction.

Average annual concentrations and discharges of dissolved solids and sediment in streams of the Gunnison River basin are summarized in table 30.

Dolores River and tributaries.—The Dolores River and its main tributary, the San Miguel River, head in the San Miguel and Uncompahgre Mountains in southwestern Colorado. Their combined drainage area is approximately 4,350 square miles. About 7 percent of the State's contribution to runoff in the Colorado River basin originates in the Dolores River basin.

Streamflow is regulated to some extent by storage in reservoirs and lakes, and decreased by export of water to other basins. Planning is in progress to provide additional storage and further development of the water resources of this basin.

The following table 31 contains summary data for selected streamflow stations in the basin.

TABLE 30.—*Concentration and discharge of dissolved solids and suspended sediment for streams in the Gunnison River basin*

[Data represent annual averages for the period 1914–57 adjusted to 1957 conditions]

Stream	Water discharge (thousands of acre-feet per year)	Dissolved solids			Suspended sediment		
		Weighted-average concentration (ppm)	Discharge		Weighted-average concentration (ppm)	Discharge	
			Thousands of tons per year	Tons per square mile per year		Thousands of tons per year	Tons per square mile per year
East River at Almont	243	147	49.	165	------	------	------
Gunnison River near Gunnison	546	126	94.	93	------	------	------
Tomichi Creek at Gunnison	131	176	31.	31	------	------	------
Lake Fork at Gateview	192	85	22.	66	------	------	------
Gunnison River above Gunnison Tunnel	1,281	------	------	------	105	183	46
Gunnison River below Gunnison Tunnel	944	111	142.	36	------	------	------
Smith Fork near Crawford	40	------	------	------	224	12	287
Iron Creek near Crawford [1]	12	1,160	19.	289	986	16	245
Surface Creek at Cedaredge [2]	20	95	2.5	59	112	3	70
Uncompahgre River at Colona	201	376	103.	236	------	------	------
Uncompahgre River at Delta [3]	207	1,610	453.	408	------	------	------
Gunnison River near Grand Junction	1,884	592	1,519.	189	806	2,067	258

[1] For the period 1948–52. [2] For the period 1918–57. [3] For the period 1939–57.

TABLE 31.—*Summary streamflow records at selected points in the Dolores River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Dolores River below Rico	105	11	133	96,290	2,120	7.0
Dolores River at Dolores	556	51	440	318,500	10,000	8.
San Miguel River near Placerville	308	26	232	168,000	[1] 10,000	26.
San Miguel River at Naturita	1,080	34	360	260,600	7,100	5.8
Dolores River at Gateway	4,350	18	938	679,100	15,400	23.

[1] Result of failure of Trout and Middle Reservoir Dams in September 1909.

The Dolores River basin is underlain chiefly by sedimentary rocks of Cretaceous age. In the headwaters, surface water is mainly of the calcium bicarbonate type. At Dolores, the river contains 100 to 300 ppm of dissolved solids 90 percent of the time. At Bedrock, above the confluence of the Dolores and San Miguel Rivers, the dissolved solids concentration at low flow has exceeded 1,200 ppm and the water is of the sodium chloride type. The dissolved-solids concentration at the mouth of the Dolores near Cisco, Utah, ranges from 200 to 6,000 ppm and is more than 1,000 ppm 60 percent of the time.

The Dolores River basin produces about one-sixth of the suspended sediment discharge of the Colorado River at the station near Cisco which is just below the mouth of Dolores River.

Average annual concentration and discharge of dissolved solids and suspended sediment for the Dolores River basin are given in table 32.

Yampa River.—The Yampa River heads in Routt National Forest and drains about 7,500 square miles, part of which is in Wyoming. The high elevations on the western slope of the mountains receive relatively high precipitation, and water yields from this part of the basin are high. The lower areas in the plateau region contribute little to the total runoff.

Water is used principally for irrigation and small storage reservoirs have been constructed to provide better distribution of the available supply. Proposed projects are being studied to determine the feasibility of developing the water supplies that are excess to current use.

TABLE 32.—*Concentration and discharge of dissolved solids and suspended sediment for streams in the Dolores River basin*

[Data represent annual averages for water years 1914–57 adjusted to 1957 conditions]

Stream	Water discharge (thousands of acre-feet per year)	Dissolved solids			Suspended sediment		
		Weighted-average concentration (ppm)	Discharge		Weighted-average concentration (ppm)	Discharge	
			Thousands of tons per year	Tons per square mile per year		Thousands of tons per year	Tons per square mile per year
Dolores River at Dolores	356	125	61	109	245	119	214
Lost Canyon Creek at Dolores	22	57	1.7	21			
San Miguel River near Placerville	188	157	40	130			
San Miguel River at Naturita	254	316	109	101			
Dolores River at Gateway	684	475	442	102			
Dolores River near Cisco	681	496	460	99	[1] 3,370	[1] 2,524	[1] 545

[1] For water years 1952–57.

Summary data for selected streamflow stations in the basin are given in table 33.

TABLE 33.—*Summary streamflow records at selected points in the Yampa River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Yampa River near Oak Creek	227	11	85.9	62,190	1,400	10
Yampa River at Steamboat Springs	604	55	473.	342,400	6,820	4
Elk River at Clark	206	44	344.	249,000	[1] 4,470	23
Yampa River near Maybell	3,410	46	1,571.	1,137,000	17,900	2
Little Snake River near Lily	3,730	41	570.	412,700	14,200	0

[1] Maximum daily.

Most of the water comes from the mountainous parts of the basin but most of the dissolved solids comes from the lower, more arid parts. Water in the Yampa River is of the calcium bicarbonate type from the headwaters to Maybell; that in the Little Snake River changes from a calcium bicarbonate type in the headwaters to a calcium sulfate type in the lower reaches, except during periods of high flow in the spring.

The Little Snake River above Lily produces about 3½ times as much sediment as the Yampa River basin above Maybell, although the two basins are nearly the same size. Most of the sediment carried by the Little Snake River comes from the more arid parts of the basin.

Average annual concentrations and discharge of dissolved solids and suspended sediment in streams of the Yampa River basin are presented in table 34.

White River.—The White River and its tributaries drain about 4,000 square miles in western Colorado. It heads in the mountains of White River National Forest, and flows generally west into the Green River in Utah.

Diversions are made for irrigation of about 30,000 acres. Feasibility studies are in progress on proposed further development of water in the basin.

TABLE 34.—*Concentration and discharge of dissolved solids and suspended sediment for streams in the Yampa River basin*

[Data represent annual averages for the water years 1914–57 adjusted to 1957 conditions]

Stream	Water discharge (thousands of acre-feet per year)	Dissolved solids: Weighted average concentration (ppm)	Dissolved solids: Discharge: Thousands of tons per year	Dissolved solids: Discharge: Tons per square mile per year	Suspended sediment: Weighted-average concentration (ppm)	Suspended sediment: Discharge: Thousands of tons per year	Suspended sediment: Discharge: Tons per square mile per year
Yampa River near Oak Creek	63.	221	19.	84			
Yampa River at Steamboat Springs	342.	74	34.	57			
Elk River at Clark	258.	40	14.	67			
Elk River near Trull	394.	47	25.	61			
Fortification Creek near Craig	9.7	774	10.	298			
Williams Fork at Hamilton [1]	158.	234	50.	148			
Yampa River near Maybell	1,152.	140	219.	61	196	308	90
Little Snake River near Slater	188.	78	20.	70			
Slater Fork near Slater	61.	101	8.4	52	212	18	109
Little Snake River near Lily	451.	196	120.	36	1,790	1,099	295

[1] For 1905–06, 1910–27 water years.

Table 35 gives summary data for selected streamflow stations.

TABLE 35.—*Summary streamflow records at selected points in the White River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
White River below Trapper's Lake	21.4	6	29.3	21,210	481	7
White River at Buford	254.	17	321.	232,400	[1] 3,150	90
South Fork White River at Buford	170.	12	265.	191,900	3,000	60
White River near Meeker	762.	58	633.	458,300	[2] 6,370	112
White River near Watson, Utah	4,020.	39	720.	521,300	[1] 8,160	53

[1] Maximum daily.
[2] Maximum observed.

The headwater area of the White River is underlain by rocks of Pennsylvanian and Permian age which are capped in many areas by volcanic rocks of Tertiary age. The waters draining this area are generally a calcium bicarbonate type, and the average dissolved-solids concentration usually does not exceed 300 ppm. The middle and lower reaches of the basin are underlain by sedimentary rocks of Cretaceous and Tertiary age which contain more readily soluble minerals. Streams draining these areas have a higher dissolved-solids content and increased quantities of sodium, sulfate, and chloride, especially during low and medium flows.

Average annual concentrations and discharge of dissolved solids and suspended sediment for the White River basin are given in table 36.

San Juan River.—The San Juan River and several of its tributaries drain the southwestern part of Colorado. The Navajo River, Rio Blanco, and Piedra River join the San Juan River before it flows into New Mexico at Rosa. These tributaries and the San Juan River originate in the San Juan Mountains at the Continental Divide. This part of the basin drains approximately 2,000 square miles most of which is in Colorado. Average annual runoff for the area is about 880,000 acre-feet. Water use in the basin is principally for irrigation. Small quantities of water are exported to the Rio Grande basin in Colorado and recently authorized projects provide for additional exports to the Rio Grande basin in New Mexico.

TABLE 36.—*Concentration and discharge of dissolved solids and suspended sediment for streams in the White River basin*

[Data represent annual averages for the water years 1914–57 adjusted to 1957 conditions]

Stream	Water discharge (thousands of acre-feet per year)	Dissolved solids			Suspended sediment		
		Weighted-average concentration (ppm)	Discharge		Weighted-average concentration (ppm)	Discharge	
			Thousands of tons per year	Tons per square mile per year		Thousands of tons per year	Tons per square mile per year
White River at Buford	240	164	54	211	102	33	131
South Fork White River near Buford	205	144	40	258			
White River near Meeker	462	244	153	201			
White River near Watson, Utah	554	439	331	82			

Summary data of streamflow stations in the area are given in table 37.

TABLE 37.—*Summary streamflow records at selected points in the San Juan River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
East Fork San Juan River near Pagosa Springs	86.9	27	121.	87,600	2,070	5.5
San Juan River at Pagosa Springs	298.	31	380.	275,100	25,000	9.7
Rio Blanco near Pagosa Springs	58.	27	85.9	62,190	1,600	3.
Navajo River at Banded Peak Ranch near Chromo	69.8	26	105.	76,020	1,340	8.4
Navajo River at Edith	172.	50	160.	115,800	2,840	8.
Piedra River near Piedra	371.	25	324.	234,600	[1] 6,870	17.
San Juan River at Rosa, New Mexico	1,990.	53	1,215.	879,600	25,000	39.

[1] Maximum determined.

Los Pinos River (locally known as Pine River), a major tributary of the San Juan, rises in the San Juan Mountains at the Continental Divide. It is joined by Vallecito Creek at Vallecito Reservoir and flows south to New Mexico in the vicinity of La Boca. The drainage area at this point is about 568 square miles. Vallecito Reservoir (capacity 126,280 acre-feet) regulates the flow from 270 square miles and provides control of water for irrigation of about 33,000 acres in Colorado.

Streamflow data for two gaging stations in the basin are given in table 38. Flow at both stations is affected by storage in Vallecito Reservoir and exports to the Rio Grande basin and at the La Boca station by diversions for irrigation.

TABLE 38.—*Summary streamflow records at two stations on the Los Pinos River*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Los Pinos River near Bayfield	270	35	352	254,800	13,800	3.2
Los Pinos River at La Boca	510	12	196	141,900	6,400	14.0

The Animas River heads in the San Juan and Uncompahgre Mountains and flows into New Mexico in the vicinity of Bondad and thence in to the San Juan River. The drainage area at the State line, which includes the Florida River, is about 1,100 square miles. Water is diverted for irrigation of about 20,000 acres. Completion of the Florida project will further the development of the water supply. Lemon Dam and Reservoir, on Florida River, will provide storage for water to irrigate about 5,700 acres of new land and to furnish supplemental water for about 13,700 acres now under irrigation.

Summary data for selected streamflow stations are given in table 39.

TABLE 39.—*Summary streamflow records at selected points in the Animas River basin*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
Animas River at Howardsville	55.9	27	106	76,740	1,980	9
Hermosa Creek near Hermosa	172.	34	143	103,500	2,980	4
Animas River at Durango	692.	57	862	624,100	25,000	94
Florida River near Durango	96.	42	110	79,640	[1] 3,200	0
Animas River at Cedar Hill, N. Mex.	1,090.	29	912	660,300	13,100	90

[1] Maximum determined.

Except during high flows in the spring when the water is a calcium bicarbonate type, the water of the upper Animas River is a calcium sulfate type. Although most of the headwater area is underlain by volcanic rocks, beds of limestone and calcareous shale probably are responsible for the calcium sulfate water. Five springs with a total discharge of about 1 cubic feet per second contribute about 4,000 tons of dissolved solids annually to streams in the Animas River basin.

The southwestern corner of the State is drained by three streams; La Plata and Mancos Rivers and McElmo Creek.

La Plata River drains about 331 square miles. The prinicpal use of water in the basin is for irrigation of about 15,000 acres. The Animas-La Plata project, authorization pending (1964), proposes diversion of substantial quantities of water from the Animas to La Plata basin for development of new irrigated acreage in Colorado and New Mexico.

Water in the La Plata River is of the calcium bicarbonate type in the La Plata Mountains. But in the lower reaches, which are underlain by sedimentary rocks, the sodium and sulfate content increases during and following the irrigation season.

The Mancos River drains about 550 square miles. Water is used principally for irrigation of about 10,000 acres and although 10,000 acre-feet of storage has been provided in Jackson Gulch Reservoir, additional development of the available water supply will depend upon more storage to obtain better seasonal distribution of runoff.

In western Montezuma County, McElmo Creek drains about 350 square miles including Montezuma Valley, which is irrigated with water imported from the Dolores River basin. Return flow from the irrigated area sustains a relatively high mean annual flow at the gaging station near the Colorado-Utah State line. Additional irrigation development in the basin will depend upon increased imports of water from other areas.

Summary data for streamflow stations in the three basins are given in table 40.

TABLE 40.—*Summary streamflow records at points on minor streams in southwestern Colorado*

Stream	Drainage area (square miles)	Years of record	Average discharge		Extremes of discharge (cubic feet per second)	
			Cubic feet per second	Acre-feet per year	Maximum	Minimum daily
La Plata River at Hesperus	37	46	46.0	33,300	1,880	----------
La Plata River at Colorado-New Mexico State line	331	42	34.6	25,050	4,750	0
Mancos River near Towaoc	550	34	54.2	39,240	5,300	0
McElmo Creek near Colorado-Utah State line	350	11	38.0	27,510	1,700	0.1

Most of the flow in McElmo Creek near Cortez is irrigation return flow that has a high dissolved-solids concentration and is of the magnesium sulfate type. The average dissolved-solids concentration near Cortez is about 2,200 ppm (see table 41), and at the lowest flow the concentration may exceed 5,000 ppm.

Average annual concentration and discharge of dissolved solids and suspended sediment are summarized in table 41 for streams in the San Juan River basin. Water in the headwater streams is of the calcium bicarbonate type and contains less than 100 ppm of dissolved solids. In the middle and lower reaches of these tributaries, especially below irrigated lands, the magnesium, sodium, and sulfate content of the water resources progressively downstream. Water from thermal springs enters the San Juan River at Pagosa Springs and contributes about 7,000 tons of dissolved solids to the river each year.

GROUND WATER

Colorado's ground-water resources are largely east of the Continental Divide, in contrast to the surface-water supply, of which two-thirds is in the Colorado River basin, about the western third of the State. As in other Western States, the aquifers with highest yields are largely unconsolidated alluvial sand and gravel. The principal aquifers of this type include deposits in the San Luis Valley, the Ogallala Formation of the High Plains, and the valley-fill deposits in the Rio Grande, Platte, and Arkansas River basins. Sandstone forms extensive and useful but only moderately productive aquifers in the Denver artesian basin and in the Arkansas Valley artesian area. West of the Divide a few stretches of valley-fill deposits along the principal streams are aquifers. The largest aquifers west of the Divide are the sandstones of the Colorado Plateaus and Wyoming Basin, which generally yield less than 50 gpm to individual wells. The general availability of ground water is shown in figure 46.

Irrigation is the largest single use of ground water; most of the 1.6–2.2 million acre-feet discharged by wells in the South Platte and Arkansas basins and the San Luis Valley is used for irrigation. The total pumpage ranges from 500,000 to 1,000,000 or more acre-feet in the San Luis Valley. In 1962, it was about 900,000 and 150,000 acre-feet in the South Platte and Arkansas basins, respectively.

TABLE 41.—*Concentration and discharge of dissolved solids and suspended sediment for streams in the San Juan River basin*

[Data represent annual averages for the water years 1914–57 adjusted to 1957 conditions]

Stream	Water discharge (thousands of acre-feet per year)	Dissolved solids			Suspended sediment		
		Weighted-average concentration (ppm)	Discharge		Weighted-average concentration (ppm)	Discharge	
			Thousands of tons per year	Tons per square mile per year		Thousands of tons per year	Tons per square mile per year
San Juan River near Pagosa Springs	98	77	10.	118			
West Fork San Juan River near Pagosa Springs	64	42	3.6	89			
San Juan River at Pagosa Springs	292	73	29.	97			
Navajo River at Edith	119	113	18.	111			
San Juan River near Arboles	542	104	77.	57			
Piedra River near Piedra	275	126	47.	127			
Los Pinos River near Bayfield	288	62	24.	85	5	1.8	6
Los Pinos River at La Boca	201	108	30.	58			
Spring Creek at La Boca	26	231	8.	139	940	32.	552
Animas River at Howardsville	85	111	13.	229			
Mineral Creek near Silverton	76	78	8.	183			
Hermosa Creek near Hermosa	107	219	32.	185			
Animas River at Durango	622	183	155.	224			
La Plata River at Hesperus	35	84	4.	109			
La Plata River at Colorado-New Mexico State line	28	356	14.	41	740	28.	85
Mancos River near Towaoc	45	629	39.	70			
McElmo Creek near Cortez	39	2,180	115.	494	2,600	141.	605

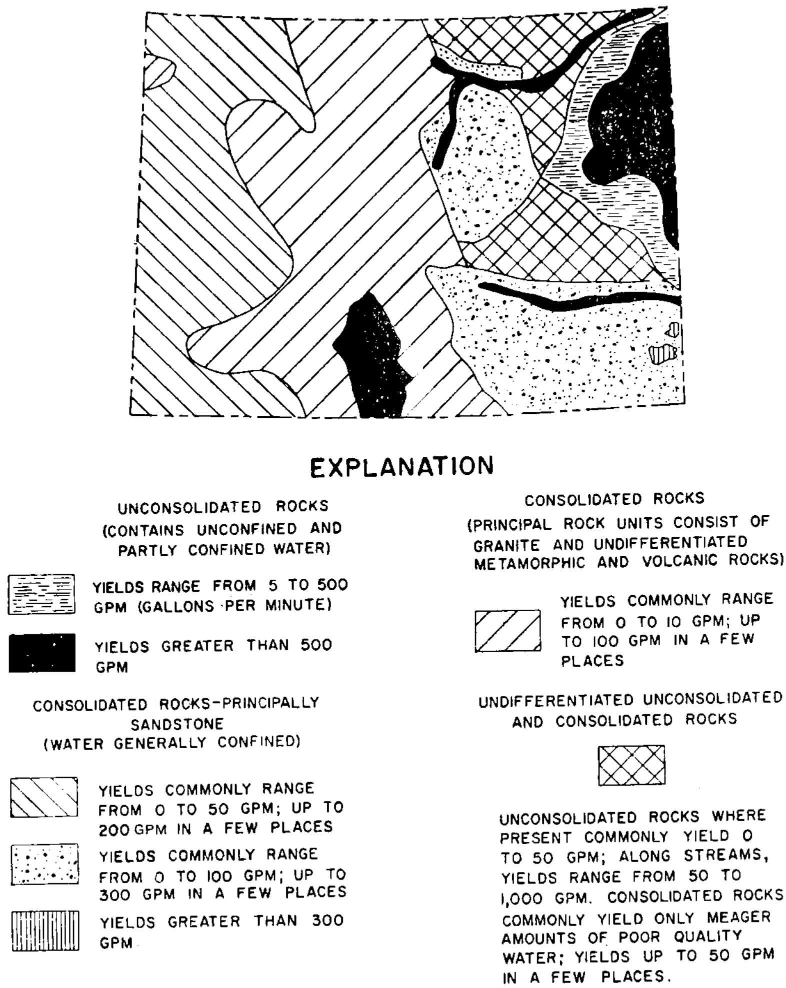

FIGURE 46.—Availability of ground water in Colorado.

Ground water is becoming increasingly important. About 20,000 wells were drilled in the State in 1953–59 and development is continuing at a rapid rate, especially in the High Plains and Arkansas Valley. Most of the water is pumped in the areas that have the smallest surface-water supply; only about a quarter of the State's surface-water supply is in the three basins in which most of the ground water is pumped. In these areas, irrigation water diverted from streams increases the recharge to the ground-water reservoirs; pumpage from these reservoirs makes possible the reuse of this water but also decreases return flow by the amount of pumpage that was consumptively used. It becomes apparent in these areas that surface and ground water constitute one resource and that the interrelation must be considered in devising rational legal and management approaches to obtain maximum beneficial use of the limited supply.

GROUND-WATER AREAS

1. High Plains
2. South Platte River basin
3. Arkansas River basin
4. Arkansas Valley artesian area
5. Denver artesian basin
6. San Luis Valley
7. Valley-fill deposits of the Colorado River and its tributaries
8. Mountainous region
9. Colorado Plateaus
10. North, Middle, and South Parks

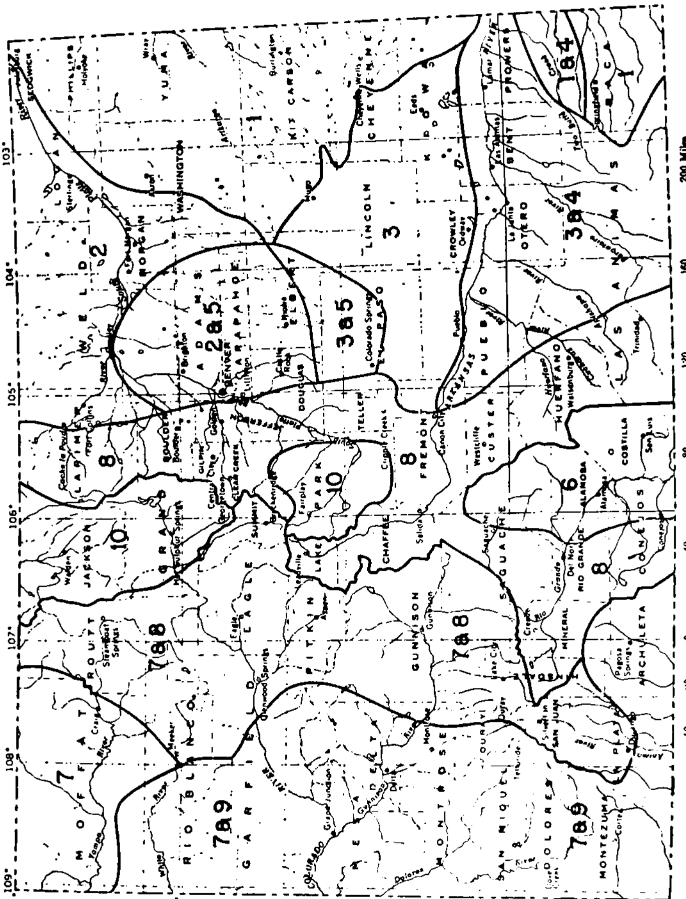

FIGURE 47.—Ground-water areas.

For description of the ground-water conditions, Colorado can be divided into 10 somewhat overlapping areas or groups of areas (fig. 47). These are: (1) the High Plains; (2) the South Platte River basin; (3) the Arkansas River basin; (4) the Arkansas Valley artesian area (part of the Arkansas River basin overlaps with the High Plains); (5) the Denver artesian basin (part of both the South Platte and the Arkansas River basins); (6) the San Luis Valley in the Rio Grande basin; (7) valley-fill deposits along the Colorado River and tributaries; (8) the mountainous region; (9) the Colorado Plateaus area; and (10) North, Middle, and South Parks in the Rocky Mountains. The areas of greatest present and potential development are in the first six groups. As to the seventh group, large supplies possibly could be developed from the valley-fill deposits in short stretches along the Colorado River and its tributaries; but, except for the pumping of locally salvaged water which is now discharged by evapotranspiration, practically all the water would come from the streams and would have to be considered a part of their supply. Similar interference between ground-water and surface-water development also exists or is a possibility along some of the streams of the first six groups.

HIGH PLAINS

Precipitation is virtually the only source of water in the High Plains. The South Platte and Arkansas Rivers have cut to bedrock where their courses cross the Ogallala Formation in eastern Colorado, and so cannot contribute to the replenishment of the water in the Ogallala. Thus, even though alluvium along the streams crossing the High Plains is an important source of water for the immediately adjacent areas, the uplands of the region are "on their own" so far as ground-water recharge is concerned. Recharge in the High Plains of Colorado ranges from less than 0.5 to 1.0 inch per year and averages about 0.8 to 0.9 inch. The higher rates of recharge are in areas where the Ogallala Formation is covered by highly absorptive dune sand. Lower rates of recharge are in areas covered by loess or other beds that impede infiltration.

The part of the High Plains areas south of the Arkansas River that is in southern Prowers and northern Baca Counties is a part of the Arkansas Valley artesian area as well as the High Plains. The Ogallala Formation is underlain by the same artesian sandstones that are tapped by wells along the Arkansas River farther west.

The Ogallala north of the Arkansas River generally ranges in thickness from 200 to 300 feet but is more than 400 feet thick in some places. It abruptly thins to the vanishing point at the edges of the Plains. The lower one-third to one-half of the formation is saturated in most places, and the total amount of water in storage north of the Arkansas River is estimated to be 80 million acre-feet. Only about two-thirds of this quantity is available for use, because (1) it would be physically impractical to dewater the entire aquifer, (2) most of the areas that are underlain by less than 50 feet of saturated material probably will not be developed for irrigation from wells, and (3) excessive declines in heavily pumped areas would make pumping economically infeasible.

About 525 irrigation wells tap the Ogallala north of the Arkansas River, yielding 300 to 3,000 gpm and averaging 1,000 gpm. About 72,500 acre-feet of water was pumped from them in 1962. Municipalities pumped about 5,000 acre-feet. Domestic and stock wells have an average yield of about 5 gpm and produced about 5,000 acre-feet in 1962.

The water is of good quality for irrigation and most other uses. The dissolved-solids content ranges from 100 to 500 ppm and the hardness ranges from 60 to 400 ppm and averages 100 ppm. In a few areas a moderately high silica content limits the usefulness of the water for some industrial processes.

The present total withdrawal from the Ogallala Formation in Colorado is less than the recharge, though pumping is exceeding replenishment locally. In the long term, however, development could easily increase beyond total replenishment. Much of the plains area is irrigable, and if a quarter of it were irrigated, as might ultimately be the case, the withdrawal even at 1 acre-foot per year per acre of crops obviously would exceed the total recharge. Ground water would then be mined, as in the High Plains of Texas, New Mexico, and parts of Kansas.

The Ogallala Formation constitutes a very large and only partly filled ground-water reservoir which could absorb tremendous quantities of surface water if the water were available. The landowners in the vicinity of Cope are considering capturing some of the floodwater and using it to recharge the Ogallala Formation. Some of the water forming ephemeral lakes and ponds in wet weather could be similarly recharged, as the water in many of the ponds is not tributary to streams and hence is not subject to the appropriative rights in effect on the streams.

The High Plains, in view of the potential economic importance of the ground-water supply, has received much of the attention of the U.S. Geological Survey and the Colorado Water Conservation Board in their cooperative studies (fig. 48). Fieldwork for descriptive reports has been completed in all the High Plains areas except northern Lincoln County. Reports on Baca County, the lower South Platte River valley, Frenchman Creek basin, and the area adjacent to Big Sandy Creek in Lincoln, Elbert, and El Paso Counties have been published (McLaughlin, 1946 and 1954; Bjorklund and Brown, 1957; Cardwell and Jenkins, 1963); reports on Washington County, Cheyenne and Kiowa Counties, and Yuma County have been completed (McGovern, 1962; Boettcher, 1963b; Weist, 1960); and a report on Kit Carson County is in preparation. Cardwell (1953) describes irrigation-well development in the Kansas River basin in Colorado as of 1950 and McGovern and Coffin (1963) summarize ground-water conditions in the Ogallala north of the Arkansas River.

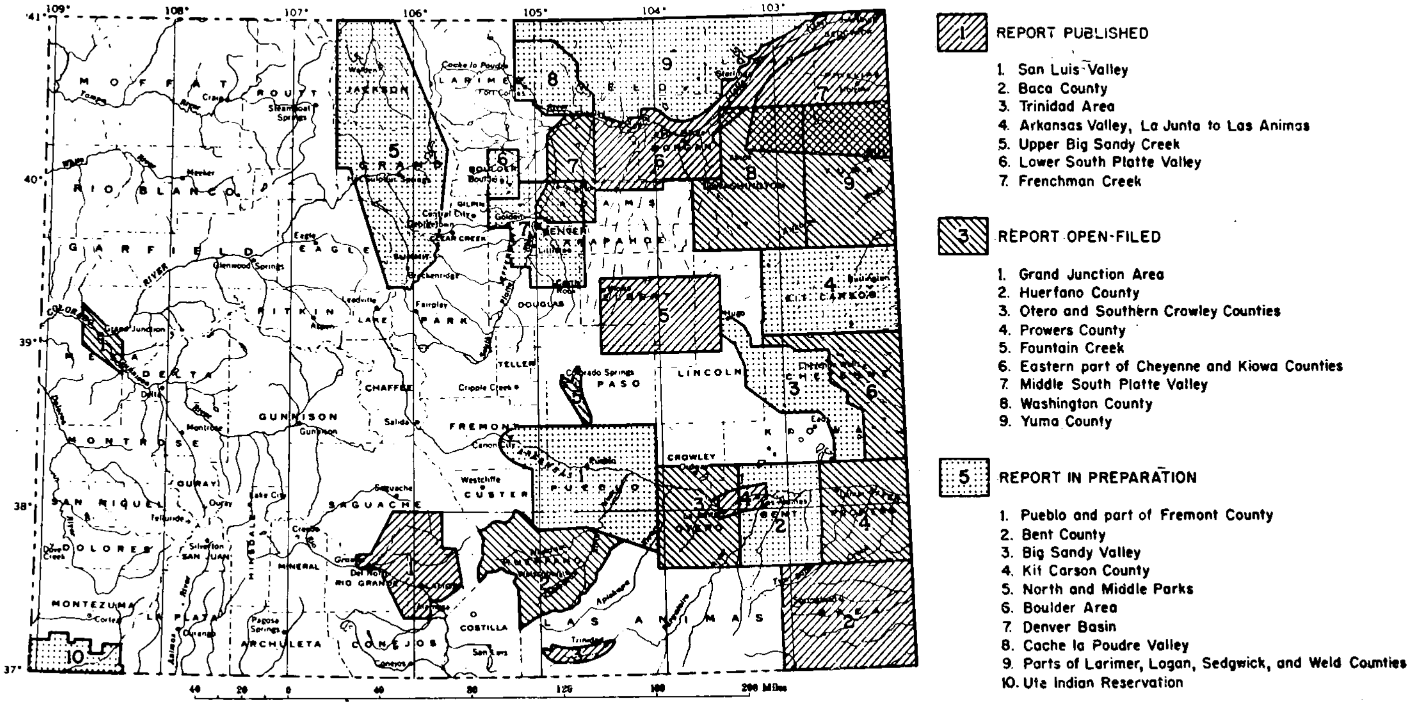

FIGURE 48.—Areas of ground-water reports in Colorado. (Reports prepared principally in cooperation with the Colorado Water Conservation Board, but also with many Federal, State, and local agencies.)

SOUTH PLATTE RIVER BASIN

The South Platte River basin east of the Rocky Mountain front (fig. 47) is one of the most intensively developed irrigated areas in Colorado. Ground water is used principally for irrigation but meets many domestic, stock, municipal, and industrial demands. The ground water used for irrigation chiefly supplements surface water, but during dry years it is the principal supply in many places.

The chief aquifer is the valley-fill deposits along the river and its principal tributaries, and the ground-water supply is closely related to that of the streams because the ground water alternately feeds the streams and is fed by them, either directly or by seepage from canals and irrigated land. Studies show that the same water may be used, either as ground water or as surface water, as many as seven times in the 65-mile stretch from Denver to Kuner, Colo. (Thomas, 1952, p. 43; see also Waite and others, 1949, p. 25–26, 78–79).

There are about 7,500 irrigation wells in the basin. The wells in the river valley yield 400 to 2,000 gpm and average about 900 gpm; wells in tributary valleys yield 50 to 1,800 gpm and average about 800 gpm.

About 900,000 acre-feet was pumped for irrigation in 1962. Industrial pumpage was about 30,000 acre-feet and municipal pumpage about 21,000 acre-feet in 1959. Smaller quantities were used for rural domestic and stock supplies.

The ground water in the valley-fill deposits in the main valley tends to deteriorate in quality downstream. The average dissolved-solids content near Denver is about 1,300 ppm; at the State line it is about 1,800 ppm. The water is usable for irrigation but some of it has a high "salinity hazard" (U.S. Salinity Laboratory Staff, 1954, p. 76). It is generally undesirable for domestic and municipal supplies, though it is so used in the absence of better water. The ground water in tributary valleys is generally of somewhat better quality.

A problem of increasing concern is contamination of ground water by household detergents, inadquately treated domestic wastes, and industrial wastes. Industrial waste from the Rocky Mountain Arsenal near Henderson, northeast of Denver, has contaminated ground water in an area of several square miles (Walker, 1961, p. 489–494; Petri and Smith, 1959; and Petri, 1962). The discharge of the waste into pits from which it could leak to the water table has been stopped, and since December 1961 the waste has been discharged into a deep well tapping fractured Precambrian rocks below 11,975 feet. The well is reported to be 12,045 feet deep and to be cased to 11,975 feet.

Ground-water development has reached the practical maximum in some areas, especially in tributary valleys south of the river, which have only small surface-water supplies and low natural recharge. In the main valley, recharge, principally from surface water diverted for irrigation, is greater and ground-water levels have remained high.

Better water management will alleviate some of the problems and increase the usable water supply both in the main valley and in tributary valleys such as those of the Cache la Poudre River and Beebe Draw. For example, lowering the water levels in some areas by pumping will reduce waterlogging and nonbeneficial evapotranspiration, thus increasing the water supply.

The principal published reports of the South Platte are those by Code (1943), by Bjorklund (1957), and by Bjorklund and Brown (1957). The 1957 reports covered only the valley downstream from Hardin. A report on the area between Denver and Hardin has been released in open file and is pending more formal publication (Smith, Schneider, and Petri, 1961); a report on the Cache la Poudre valley is in preparation. Additional studies are needed for further evaluation of the factors affecting the hydraulic system. The knowledge gained from the studies will allow the use of management techniques to make the best possible use of the water supply.

The Denver artesian basin is partly in the South Platte and partly in the Arkansas drainage area. It is described separately.

ARKANSAS RIVER BASIN

The Arkansas River basin is similar hydrologically to the South Platte basin. East of the Rocky Mountain front, it is second only to the South Platte basin in overall development for irrigation. Ground water is used extensively for irrigation, mainly as a supplement to surface water but also as a sole supply in some areas during dry periods. The ground-water pumpage is about one-fourth as large as that in the South Platte basin.

The principal aquifer is the valley-fill deposits along the Arkansas and its principal tributaries, especially Fountain Creek. As in the South Platte valley, percolation from irrigation water recharges the aquifer, which provides return flow to the river. Pumpage intercepts water that would have reached the river and, therefore, reduces the surface-water supply.

There are about 1,500 irrigation wells in the main valley in Pueblo, Otero, Bent, and Prowers Counties. They yield 100 to 3,000 gpm and average 800 gpm. The tributary valleys, except for that of Fountain Creek, are sparsely developed; the few wells yield 200 to 1,000 gpm and average about 300 gpm. Irrigation wells in the Fountain Creek valley yield as much as 1,300 gpm and average about 700 gpm.

Pumpage from the valley-fill deposits in 1962 was about 150,000 acre-feet for irrigation, 4,000 acre-feet for industrial use, and 8,500 acre-feet for municipal supply. Rural domestic and stock wells pumped a few hundred acre-feet.

As in the South Platte valley the quality of the ground water generally deteriorates downstream. The dissolved-solids content and hardness in the Pueblo area average 1,200 to 590 ppm, respectively; at the State line the corresponding values are 3,700 and 1,600 ppm. The water is undesirable for domestic and municipal supply, though some of it is so used. The poor quality of the water is partly responsible for the slow growth of several towns in the valley.

Waterlogging has occurred in some areas near the State line, although it is not severe because it is confined mainly to the flood plain, which is little used for crop growth. The terraces above the flood plain, where most of the crops are grown, are waterlogged in only a few places even though water is being applied to some fields during the nongrowing season to build up soil moisture. Water-management studies now underway suggest that increased application of water to the terraces, coupled with increased pumping of ground water, could both increase overall water supplies and provide better regulation, to the mutual benefit of all water users in the valley.

In some reaches the quality-of-water problems will need to be considered carefully to attain the most beneficial management of available water resources. The river receives irrigation return flow, sewage effluent, and industrial wastes. The water in the alluvium in both the main valley and tributary valleys north of the river is of poor quality; that in tributary valleys south of the river in eastern Bent and Prowers Counties is of better quality.

Concentrated pumping has caused temporary shortages in the Fountain Creek valley between Colorado Springs and Fountain. Under present conditions surface water is overappropriated. In heavily pumped areas and some lightly pumped upland areas in Pueblo and Otero Counties, substantial ground-water storage space is available for possible recharge from flood flows.

The principal reports published to date are by Moulder and others (1963), by McLaughlin (1946) and by Code (1945). Reports on Fountain and Jimmy Camp Valleys in El Paso County, Prowers County, and Otero and Crowley Counties have been completed (Jenkins, 1961b; Voegeli and Hershey, 1962; and Weist, 1963a and 1963b), and fieldwork for ground-water studies in Pueblo and Bent Counties and the Middle Big Sandy Creek valley have been completed. Water management practices and their effects in a reach of the valley between La Junta and Las Animas were evaluated in the report by Moulder and others (1963). Field work is underway for a comprehensive study of the entire valley bellow Canon City.

ARKANSAS VALLEY ARTESIAN AREA

Artesian water is available from consolidated rocks, principally sandstone, in the Arkansas River basin from Canon City to the State line. The water, which is used mainly for domestic and municipal supplies, is generally softer and less mineralized than that in the valley fill. The hydrogen sulfide, iron, or fluoride content is locally excessive.

The principal artesian aquifers are the Cheyenne Sandstone Member of the Purgatoire Formation and the Dakota Sandstone, both of Early Cretaceous age. They underlie almost the entire Arkansas River basin east of the mountain front. The principal areas in which they are moderately to highly productive and at feasible drilling depth are shown in figure 46 and in area 4 of figure 47. Few wells tap the aquifers north of the Arkansas River because these beds are generally over 1,000 feet below the surface and probably contain saline water. In the southeast corner of the State, older aquifers of Triassic and Jurassic age yield moderate supplies of fresh water in a small area.

The aquifers generally are fine- to medium-grained sandstone and yield small to moderate supplies to wells. Large yields have been obtained from poorly cemented zones in the sandstone in the Bear Creek area of Baca County, in southern Prowers County, and near Penrose in Pueblo County. Yields range from 50 gpm to more than 3,000 gpm from a well in Baca County. The irrigation pumpage is not known but presumably totals several thousand acre-feet per year. Domestic and stock wells generally are widely scattered and the yearly withdrawal is probably a few hundred acre-feet. Municipal withdrawals in the artesian area were about 2,400 acre-feet in 1959.

Additional water can be pumped for domestic, stock, and municipal uses in areas not yet developed. Information on the long-term yield of the aquifers is needed, especially in areas where they are pumped for irrigation.

A report by Weist (1963b) describes the water in the Dakota and Purgatoire Formations in Otero and southern Crowley Counties. Information on the artesian aquifers is found also in county reports which deal mainly with unconsolidated aquifers, such as the report on Baca County in the High Plains (McLaughlin, 1954).

DENVER ARTESIAN BASIN

The Denver artesian basin surrounds the city of Denver, extending a short distance to the mountains on the west and 50 to 75 miles to the north, east, and south (fig. 47). The water supply of this most heavily populated and fastest growing part of Colorado is obtained mainly from streams, including tributaries of the Colorado River. However, ground water is of considerable importance for industrial, irrigation, and municipal supplies. As population increases, the need for ground water of acceptable quality will increase.

The major sources of ground water are aquifers in the "bedrock," some of which is only slightly to moderately consolidated. Valley-fill deposits of the South Platte River and tributaries also furnish large quantities of water, as discussed in the section on the South Platte basin. The principal bedrock aquifers are sand, sandstone, gravel, and conglomerate in the Fox Hills Sandstone and the Arapahoe, Dawson, and Denver Formations, all of Late Cretaceous or Tertiary age. The Fox Hills contains three beds of sandstone that yield an average of about 40 gpm to individual wells. The Arapahoe, Denver, and Dawson Formations contain beds of arkosic sand, gravel, and conglomerate that yield from 1 to 100 gpm to individual wells.

The Fox Hills Sandstone, the deepest of the water-bearing formations, underlies nearly the entire basin, or about 5,000 square miles; the Arapahoe Formation about 1,000 square miles; and the Dawson Formation about 3,000 square miles, including about 1,000 square miles where it interfingers with the Arapahoe and Denver Formations.

Withdrawal from the artesian aquifers as of 1959–60 was about 2,000 acre-feet per year for municipal use and about 10,000 acre-feet for rural domestic and stock supply. A relatively small amount was withdrawn for irrigation.

The water is mostly of the sodium bicarbonate type, soft but not well suited for irrigation. Water from the Fox Hills, lower and middle parts of the Dawson, and lower part of the Arapahoe is generally of good quality and is suitable for most uses. Locally the mineralization is higher because of structural conditions that impede ground-water circulation. The water of the upper part of the Arapahoe Formation and of the Denver Formation generally contains more dissolved minerals than that of the other principal aquifers, reflecting lower permeability and yield. In places, water from the middle and upper parts of the Dawson has an excessive content of the radioactive gas radon, a decomposition product of radium (McConaghy and others, 1964). Excessive iron is found locally in water of the upper parts of the Dawson and Arapahoe and in water of the Denver Formation.

As of 1963 the Arapahoe Formation at Denver had been pumped for 80 years. In the center of the cone of depression the artesian head has declined more than 600 feet. Substitution of water from the municipal supply and dispersal of industries and housing developments have reduced or spread the withdrawal and lessened the rate of decline in recent years. Withdrawals from the Fox Hills Sandstone during the last 30 years have created local cones of depression as much as 350 feet deep in the piezometric surface of the aquifer.

There are no undeveloped aquifers, but additional water can be removed from storage in all the aquifers to the extent that the pumping lifts can be tolerated. The Dawson Formation has been tapped by relatively few wells so far.

SAN LUIS VALLEY

The San Luis Valley (Powell, 1958; McLaughlin, 1962), the site of Colorado's largest single ground-water development, is a 2,800-square-mile structural basin interrupting the southern Rocky Mountains just north of the New Mexico State line. The basin has been partly filled with alluvial and lake deposits and some lava flows and other volcanic deposits. The maximum thickness of the valley fill, which is of late Tertiary and Quaternary age and comprises the Santa Fe Group and the Alamosa Formation, is at least 8,000 feet.

The valley is nominally drained by the Rio Grande, but actually the northern 1,500 square miles is in the "Closed Basin," an area of internal drainage. Shallow ground water, some artesian water, and surface water are applied for irrigation (most of the surface water diverted from the Rio Grande in Colorado is used in the Closed Basin) and that which is not consumptively used moves into the basin and evaporates in a 250-square-mile "sump area." A little of the return flow from irrigation is diverted from the Closed Basin by drains and reused elsewhere, but most of the water that enters the Closed Basin evaporates there, so that the water beneath and near the sump area is saline.

Large quantities of both artesian and shallow ground water are used for irrigation, and smaller quantities for other purposes. Flowing artesian wells yield an average of 47 gpm, but one artesian well was pumped at rates as high as 4,400 gpm. The yearly withdrawal from the artesian aquifers was estimated at 570,000 acre-feet in 1953. Irrigation wells producing from the unconfined aquifers have an average yield of about 1,000 gpm, and the total withdrawal was about 500,000 acre-feet in 1951. Although recent figures are not available, it is estimated that the combined discharge of wells ranges from 500,000 to 1,000,000 or more acre-feet a year, depending on the availability of surface water. In 1959, about 2,900 acre-feet was withdrawn by municipalities, and 340 acre-feet for industrial use.

Large additional quantities of both artesian water and, in lightly developed areas, unconfined water remain to be developed. To the extent that increased withdrawal salvages water that is now being evaporated in the sump area of the Closed Basin, it will not be competitive with use of surface water. Water can be salvaged by pumping it out before it reaches the area of saline water. In the vicinity of saline San Luis Lake, eradication of phreatophytes might improve the quality of the water and increase the amount of water available for salvage.

The detailed study of the valley (Powell, 1958) was undertaken principally to evaluate the proposal to collect shallow ground water in the Closed Basin, now lost by evapotranspiration, by means of a drain and discharge it into the Rio Grande in partial fulfillment of the requirements of the Rio Grande Compact. The study showed that the water that would be collected by the proposed drain would not be of suitable chemical quality unless it could be diluted with a much larger quantity of water of better quality. Consideration is still being given to means by which to achieve the desired end of salvaging water now wasted by evapotranspiration, for use in meeting compact requirements.

Outside the sump area the ground water is of good to fair quality. It is generally best in the artesian aquifers, whose water contains 70 to 450 ppm of dissolved solids and has a hardness of 8 to 230 ppm. The unconfined water has been concentrated by evaporation and by solution of mineral salts by irrigation water. The quality is best at the west side of the valley where the average dissolved-solids content is about 130 ppm. In the eastern part of the valley, in the vicinity of San Luis Lake, the average concentration is about 2,700 ppm.

VALLEY-FILL DEPOSITS OF THE COLORADO RIVER AND TRIBUTARIES

The Colorado River drains about the western third of Colorado. Surface water is the principal source of supply and is of better average quality than the ground water. Ground water is used for many domestic and stock supplies and by a few municipalities and industries.

No studies have been made of the valley-fill deposits along the Colorado River and its tributaries. Meager data indicate that the water is of poor quality locally, probably in part as a result of evapotranspiration of water along the valley bottoms. The valley-fill deposits are a potential source of water that could be salvaged from evapotranspiration, and some unappropriated surface water could be made available by induced infiltration to wells. Reconnaissance and, in places, detailed studies of the occurrence and quality of ground water and its relation to surface water are needed to facilitate the future developments of ground water.

COLORADO PLATEAUS AREA

The Colorado Plateaus area, of which a part is described in an open-file report by Waring (1935), comprises the Colorado part of the Colorado Plateaus-Wyoming Basin ground-water region. It lies mostly in the Colorado Plateaus physiographic province but includes a segment of the Wyoming Basin in the northwestern part of the State. It is drained by the Colorado River and its tributaries. Except in the few stretches of valley-fill deposits along the principal streams, discussed in the previous section, the aquifers are consolidated strata, principally sandstone. In order of importance they are the Dakota Sandstone of Cretaceous age; the Entrada and Junction Creek Sandstones and the Salt Wash Sandstone Member of the Morrison Formation, all of Jurassic age; and the Wingate Sandstone of Triassic age. Older rocks generally yield no water or water that is too highly mineralized for ordinary uses.

The aquifers generally yield less than 50 gpm to individual wells, although a few have yielded as much as 200 gpm.

The low productivity, and yet great value, of some aquifers in areas where they are the only ones available is exemplified by the Entrada and Wingate Sandstones and sandstone of the Morrison Formation in the Grand Junction area (Jacob and Lohman, 1952; Lohman, 1964). The aquifers have been developed intensively in an area of less than 5 square miles near Grand Junction. Wells originally flowed at rates of 1 to 30 gpm, but because the sandstones are of very low permeability the drawdown to produce a given yield is large, and the artesian head has declined greatly. Many wells have stopped flowing and the flow of others has lessened. Most are now pumped, at rates ranging from a few gallons to a few tens of gallons per minute. The rate of decline of head could be reduced by spacing wells more widely, shutting off flowing wells when they are not in use, and repairing or plugging wells having leaky casings.

The Colorado Plateaus area is one in which present use of ground water is small, mostly for domestic and stock supply but also for a few towns. The population and water demand will increase in the future. Surface water will be the principal source of supply, but ground water will be sought for many small to moderate demands for which surface water is unavailable or treatment is too expensive. Reconnaissance studies of the whole area are needed, and detailed studies will be needed in areas of more intensive development as they come into being.

MOUNTAINOUS REGION

The mountains are sparsely settled, and water demands are small. The rocks are mostly hard, dense, igneous and metamorphic rocks of low permeability, carrying small quantities of water principally in fractures and weathered zones. Consolidated sedimentary rocks underlie small areas and are not much better as water bearers. Valley-fill deposits are present along streams and in some basins that are not large enough to be described separately.

Stock-raising, mining, lumbering, and recreation are the chief activities. Water demands are generally small and are met largely with surface water, but ground water is obtained locally from wells and springs for domestic, stock, and municipal supplies.

Reconnaissance studies of the mountainous areas are needed to locate promising areas and aquifers for future development. Some problems of mine drainage will require detailed study. The only area covered by a descriptive study to date is Huerfano County (McLaughlin, 1964).

NORTH, MIDDLE, AND SOUTH PARKS

North, Middle, and South Parks are structural basins within the mountainous region. They are similar to but smaller than the San Luis Valley. The basins contain valley-fill and terrace deposits of

Quaternary age beneath which are older valley-fill deposits of Tertiary age which are semiconsolidated or consolidated and which crop out in large areas, especially at the edges of the basins. The Quaternary deposits are the most productive aquifers but the Tertiary strata supply water to many domestic and stock wells.

The parks are sparsely settled and are used principally for stockraising. The largest water needs are met from streams, but ground water is used for many rural stock and domestic supplies and for a few municipalities. Wells penetrating the younger valley-fill deposits yield 5 to 300 gpm but possibly could yield more in some places. Wells penetrating the Tertiary rocks yield generally smaller supplies which probably do not exceed 50 gpm.

The water from the younger valley-fill is generally suitable in quality for most uses. That from the Tertiary rocks probably averages higher in mineral content, though most of it is acceptable for domestic and stock uses; locally it is probably rather highly mineralized owing to low permeability and slow ground-water circulation.

A reconnaissance of North and Middle Parks was made by Voegeli (1964). No especially serious problems were revealed, but the reconnaissance shows the need for further studies to locate good aquifers and to determine ground water-surface water relationships.

UTILIZATION AND STORAGE

Water uses in Colorado that require withdrawals from streams or aquifers can be classified in four general categories: irrigation, public supplies, domestic and livestock, and industrial. Irrigation not only accounts for most of the withdrawals but is responsible for most of the consumptive use of water in the State. The estimated irirgated acreage for 1960 was 3,200,000 acres for which about 10,000,000 acre-feet of water was delivered, about 5,400,000 acre-feet consumptively used, and about 1,000,000 acre-feet was lost in conveyance channels between points of diversion and delivery to cropland (MacKichan and Kammerer, 1961).

The total estimated withdrawal uses of water in Colorado in 1960 are shown in table 42.

TABLE 42.—*Total estimated withdrawal uses of water in Colorado in 1960 (after MacKichan and Kammerer, 1961)*

Use	Surface water		Ground water		Total	
	Acre-feet per year	Million gallons per day	Acre-feet per year	Million gallons per day	Acre-feet per year	Million gallons per day
	Fresh water					
Public	280,000	250	45,900	41	326,000	290
Domestic and livestock	12,300	11	32,500	29	44,800	40
Industrial:						
Public-utility fuel electric power	224,000	200	2,200	2	226,000	200
Other	134,000	120	39,200	35	173,000	160
Irrigation	8,000,000	7,100	2,020,000	1,800	10,000,000	9,000
Total	8,650,000	7,700	2,140,000	1,900	10,770,000	9,700
	Saline water					
Industrial, total (none for public-utility fuel-electric)	11,200	10	11,200	10	22,400	200

Recreational uses of water, until recent years, have been largely incidental to other uses. However, recreation associated with Colorado's streams, lakes, and watersheds has become a major industry and is regarded as an integral part of all water-resource planning and development. The State's nationally famous scenery is greatly enhanced by the lakes, watercourses, and mountain snows. The innumerable streams and lakes are used extensively for fishing, boating, and water skiing. Expanding resort and camping facilities provide a substantial source of income in the State. The accumulation of winter snow on the mountain watersheds provides excellent skiing and participation in this sport has increased greatly in recent years. Development and operation of ski areas with attendant winter resorts is becoming a major enterprise.

The unequal distribution of runoff, resulting from storage of precipitation in mountain snowpack during the winter season, requires storage of water during the spring snowmelt period to assure adequate water supplies for all water use. Production of firm hydroelectric power is dependent upon adequate storage to regulate variations in streamflow. Water requirements for irrigation, municipal supplies, and industrial use also require regulation by storage to provide the water when it is needed. The first storage facilities, in general, were constructed for a single purpose, usually irrigation or power supplies. The most economical storage sites were developed first to provide water for a specific use but recent developments are usually for multipurpose use and thus can be economically justified on a broader basis. Many of the early storage facilities are being expanded for multipurpose use to further the overall development of the water resources.

The reservoirs with capacities in excess of 50,000 acre-feet are listed in table 43. Reservoirs that provide storage for irrigation, municipal

TABLE 43—*Reservoirs in Colorado with capacities exceeding 50,000 acre-feet*

Reservoir:	*Usable capacity (acre-feet)*
Adobe	70,000
Blue Mesa [1]	[2] 914,000
Bonny	168,700
Carter Lake	113,500
Cheesman Lake	79,060
Cherry Creek	95,960
Dillon	[2] 252,000
Elevenmile Canyon	97,780
Green Mountain	146,900
Horsetooth	143,500
John Martin	645,500
Lake Granby	465,600
Morrow Point [1]	[2] 122,000
Nee Gronda	58,800
Nee-Noshe	73,360
Platoro	60,000
Point of Rocks	81,351
Rio Grande	51,110
Riverside	57,510
Sanchez	103,000
Sterling	81,350
Taylor Park	106,200
Twin Lakes	53,259
Vallecito	126,300
Williams Fork	96,820

[1] Unit of Upper Colorado Storage Project (under construction, 1964).
[2] Approximate.

supplies, power development, and flood control or that provide a combination of these features are included.

SOURCES OF DATA

Much of the above data on surface- and ground-water resources in Colorado were taken from the references cited in the text, from McGuinnes (1963), from a report by Iorns and others (1964, in press), and from the report of the U.S. Department of the Interior (1963). Additional references of general or local interest are cited in the list of selected references. In addition, detailed records of streamflow, ground-water levels, and quality of water are published by the Geological Survey in various Water-Supply Papers. Streamflow data are given in a series "Surface Water Supply of the United States." Before 1961 this was an annual series but beginning with 1961–65 a 5-year series will be used. Records for Colorado are in Parts 6–B, 7, 8, and 9. Notable floods are summarized annually in a report "Floods of 19__." Beginning with the 1961 water year, streamflow records and related data are released for limited distribution by the Geological Survey in annual reports on a State-boundary basis. Ground-water levels and artesian pressures in observation wells in Colorado are given in a 5-year series of Water-Supply Papers "Ground-Water Levels in the United States, Northwestern States." Ground-water levels are also released each spring by the Colorado State University Experiment Station. Quality-of-water data are given in two annual series of Water-Supply Papers: (1) "Quality of Surface Water in the United States"—data for Colorado are in Parts 5–6, 7–8, and 9–14; and (2) "Quality of Surface Water for Irrigation, Western United States."

WATERPOWER

(By Arthur Johnson, U.S. Geological Survey, Washington, D.C., and W. C. Senkpiel, U.S. Geological Survey, Denver, Colo.)

The gross theoretical waterpower of Colorado at its developed and potential sites has been estimated at 2478 MW (megawatt=1,000 kilowatts) which is 2.0 percent of the national total and places in ninth in order of rank of the States. The State ranks 28th in installed capacity with 326 MW at developed sites.

The waterpower resources of Colorado are summarized in table 44. The gross theoretical power has been evaluated for the several flow conditions recommended by the World Power Conference, based on 100 percent efficiency and utilization of the full head available at each site. All developed sites have been included regardless of size, but the undeveloped sites include only those having at least 1 MW potential based on the flow available 50 percent of the time (Q50). For these sites, flow available 95 percent of the time (Q95) suggests the firm or continuous power potential on streams lacking storage for equalizing irregular flow. The Q95 evaluation indicates in general the minimum potential power for comparative purposes.

TABLE 44.—*Developed and undeveloped waterpower in Colorado, Dec. 31, 1962*

Principal drainage area and subdivisions	Drainage basin index number	Developed waterpower sites: Number of sites	Developed: Gross theoretical power (MW), gross head (100-percent efficiency) flows at— Q95	Q50	Q mean	Developed: Installed capacity (MW)	Undeveloped waterpower sites: Number of sites	Undeveloped: Gross theoretical power (MW), gross head (100-percent efficiency) flows at— Q95	Q50	Q mean	Total gross theoretical power (MW), developed and undeveloped sites, based on mean flow
South Platte River basin	6O	12	2.0	7.5	161.6	186.6	11	11.7	35.7	109.3	270.9
Arkansas River basin	7A	5	1.1	2.2	7.5	9.4	11	49.2	75.9	153.2	160.7
Rio Grande basin	8A	------	------	------	------	------	2	1.5	3.9	10.0	10.0
Colorado River basin:											
Green River basin	9B	------	------	------	------	------	8	55.0	124.9	281.6	281.6
Yampa River basin	9C	------	------	------	------	------	2	5.7	18.5	72.7	72.7
Colorado River basin	9D	8	19.7	42.7	87.1	59.5	42	181.6	394.4	903.3	1,002.0
Gunnison River basin	9E	3	95.	23.8	54.4	61.8	16	56.1	202.4	474.4	528.8
San Juan River basin	9G	2	1.0	2.3	7.8	8.2	8	31.2	55.5	154.7	162.5
Total	------	30	33.3	78.5	318.4	325.5	100	392.0	911.2	2,159.2	2,477.6

MW = megawatt = 1,000 kilowatts.

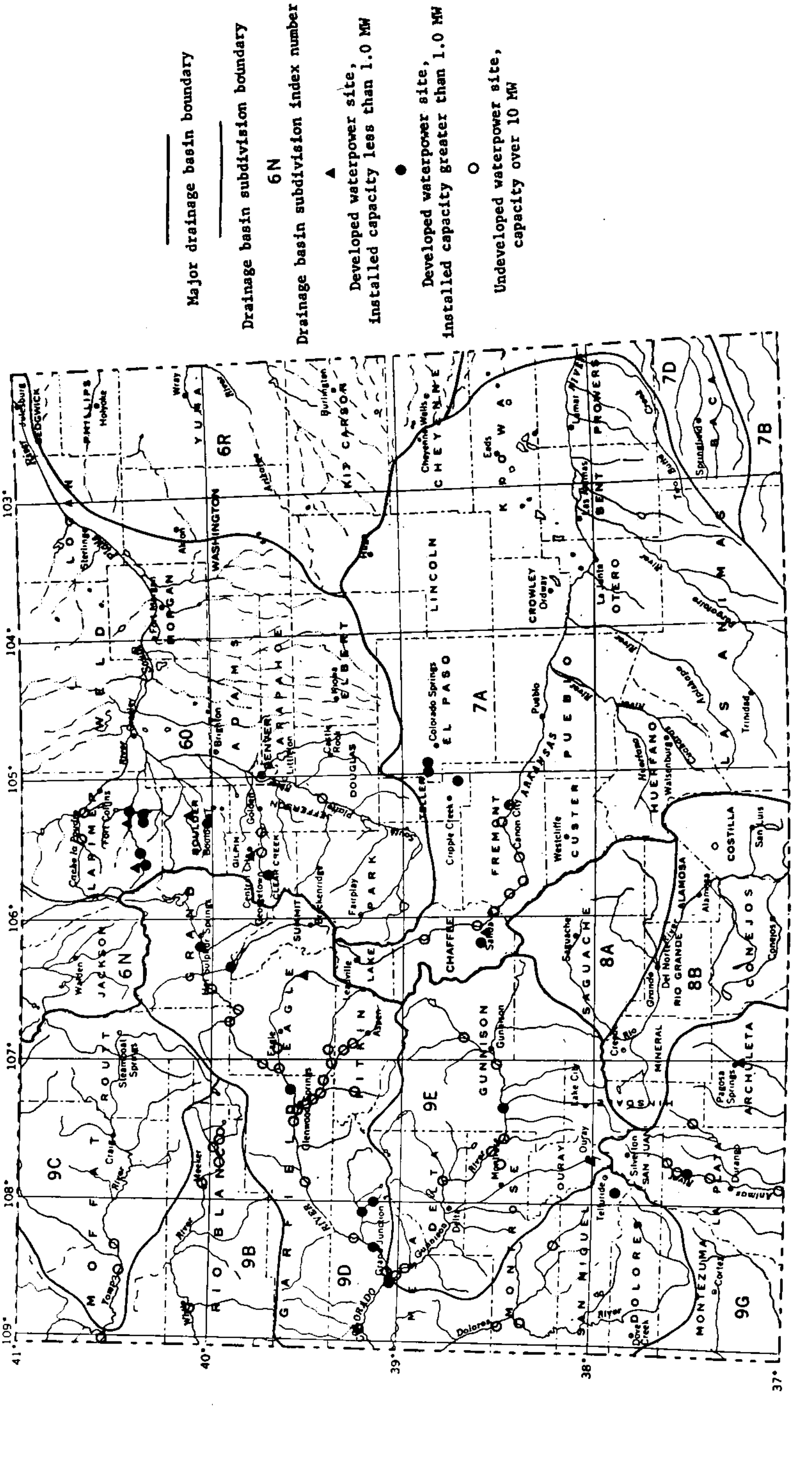

FIGURE 49.—Waterpower sites in Colorado, developed and undeveloped.

The potential power based on mean flow (Q mean) represents the maximum attainable. To realize this condition sufficient storage must be available to so regulate streamflow that all the water will be utilized through the turbines, a desirable but not always attainable condition on some streams.

Evaluations of potential power based on the flow and fall of a stream tend to give higher values than generally can be realized, either because of the absence of feasible damsites, lack of adequate storage capacity, or the use of water for industrial or agricultural purposes. As previously stated, the estimates are based on 100 percent efficiency in accordance with World Power Conference recommendations. Experience has shown that overall efficiency for a power project will vary between 75 and 85 percent.

The gross theoretical power by drainage basin subdivisions is shown in table 44. The location of all the developed sites, and the undeveloped sites with a potential of over 10 MW based on mean flow is shown on figure 49.

There are 30 developed sites, distributed according to size as follows:

Size	Number of plants	Installed capacity (MW)	Percent of total
Less than 10 MW	23	68	21
10 to 25 MW	3	56	17
25 to 50 MW	2	78	24
50 to 100 MW	2	123	38
Total	30	325	100

Two plants account for over one-third of the total and seven plants account for four-fifths of the total installed capacity.

The early waterpower installations were, for the most part, small and many of them have been abandoned. As of January 1, 1937, there were 58 waterpower plants in the State with a total installed capacity of 76.5 MW. As stated above, at present there are 30 plants with an installed capacity of 325.6 MW. In other words, since 1937 the number of operating plants has been reduced about one-half whereas the installed capacity has increased more than four times. This illustrates the trend toward larger installations.

Table 44 lists 100 undeveloped or prospective waterpower sites with a total potential of 2159 MW, based on mean flow. According to size these are grouped as follows:

Size	Number of sites	Gross theoretical power (MW)	Percent of total
Less than 10 MW	43	282	13
10 to 25 MW	36	525	24
25 to 50 MW	11	366	17
50 to 100 MW	6	399	19
Over 100 MW	4	587	27
Total	100	2,159	100

The foregoing indicates that four sites account for over one-fourth of the undeveloped power. Two of these sites are on the Colorado River and one each on the Gunnison and Green Rivers. There are 21 sites with a potential of over 25 MW and these account for 63 percent of the State total. In other words, two-thirds of the undeveloped power is concentrated at one-fifth of the prospective sites.

Information on the early development of hydroelectric power in Colorado is not too definite. It appears from a State Engineers Report (1913) that the first development of hydroelectric power in Colorado was in 1888. Two plants were built that year, one on North Boulder Creek and one on the Arkansas River. Data is incomplete for the former. The latter had an installed capacity of 80 kilowatts. By 1900 nine plants had been built. Apparently the largest, built in 1892 in the Colorado River basin, used the flow from Maroon Creek, Castle Creek, and Hunter Creek in a single plant with an installed capacity of 1,200 kw.

A summary prepared by the State Engineer in 1912 showed 33 powerplants in existence with an aggregate installation of 71,575 horsepower (51 MW), distributed as follows:

	Number of plants	Installed capacity (horsepower)
South Platte River basin	14	22,571
Arkansas River basin	3	5,525
Colorado River basin	12	29,021
San Miguel River	2	6,433
Animas River	1	8,000
Yampa River	1	25
Total	33	71,575

The growth of waterpower development in the State is shown by the following figures, taken from Department of Interior press releases:

Year	Number of plants	Installed capacity (megawatts)
1889		1.3
1902		19.2
1912		72.3
1921	57	68.3
1930	58	73.2
1937	58	76.2
1962	30	325.5

The foregoing indicates that during the 25-year period 1912–37 the total installed capacity remained much the same whereas during the 25-year period since 1937 the installed capacity has increased fourfold.

A present trend in waterpower development is the use of pumped storage to supply power for peakloads. This is well exemplified by the Cabin Creek Pumped Storage Hydroelectric Project for which a license was issued by the Federal Power Commission on March 23, 1964. The project is located on South Clear Creek and its tributary, Cabin Creek, in Clear Creek County. The difference in elevation between the upper and lower reservoir is 1,125 feet. An installation of three reversible pump-turbine units is planned with a generating capacity of 225 MW.

According to the Federal Power Commission, there were, at the end of 1962, 75 electric generating plants in Colorado with a total capacity of 1,491 MW. Of this total 266 MW, or 18 percent, were supplied by 28 waterpower plants; 1,168 MW, or 78 percent, by 24 steam-plants; and 57 MW, or 4 percent, by internal combustion plants. Waterpower plants are thus supplying about one-fifth of the electric energy used in the State.

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