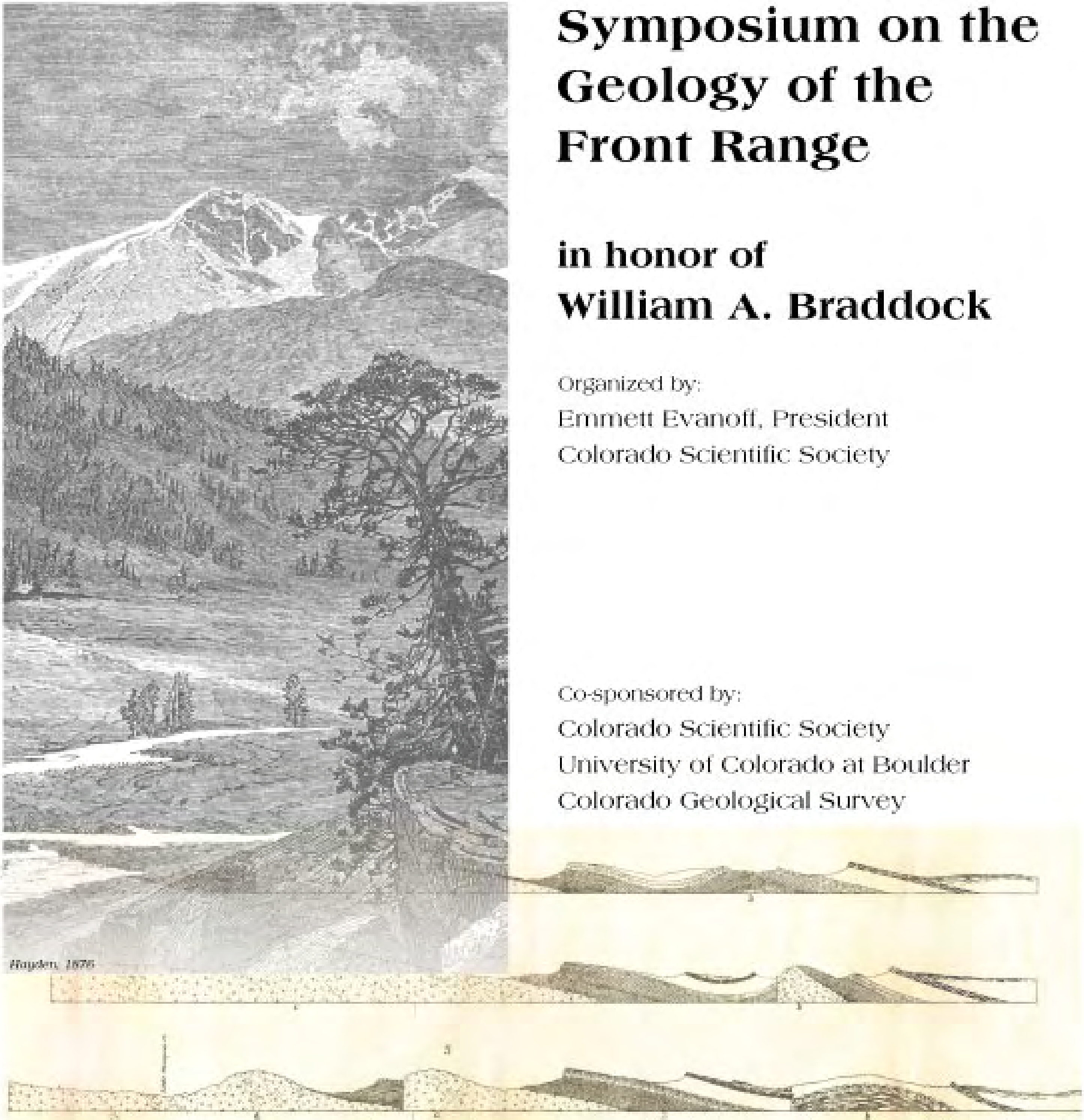
Symposium on the Geology of the Front Range

in honor of William A. Braddock

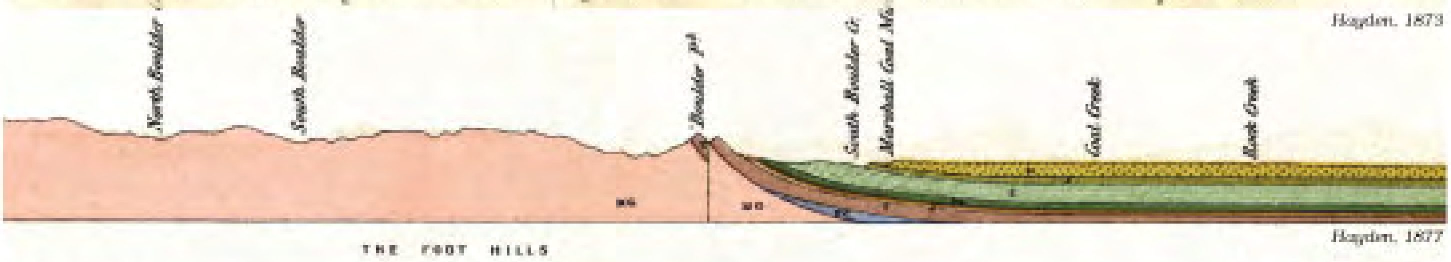
Organized by:
Emmett Evanoff, President
Colorado Scientific Society

Co-sponsored by:
Colorado Scientific Society
University of Colorado at Boulder
Colorado Geological Survey



Hayden, 1876

Hayden, 1873



Hayden, 1877

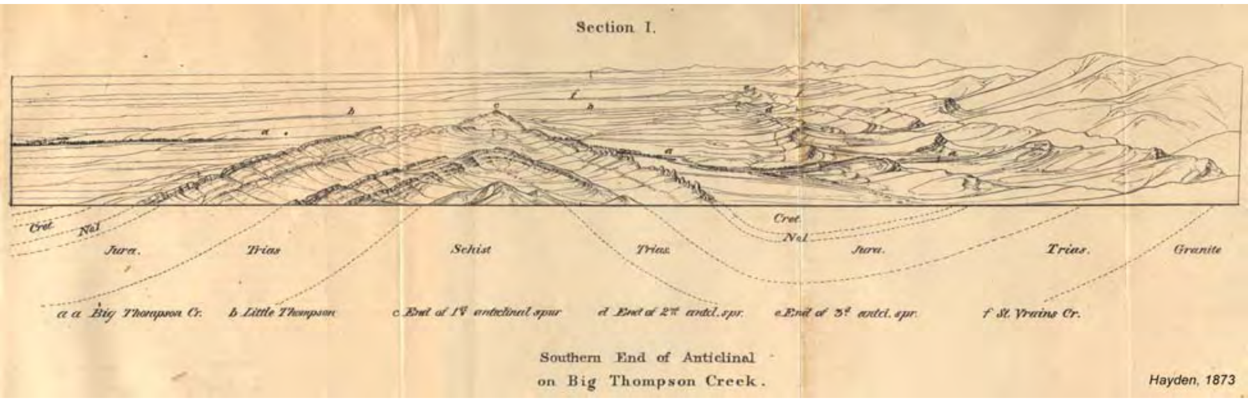
Edited by:
Mary-Margaret Coates, Emmett Evanoff & Matthew L. Morgan

April 3 and 4, 2004

Benson Earth Sciences Building, University of Colorado, Boulder

William A. Braddock
(1929-2003)

THE FRONT RANGE



Southern End of Anticlinal
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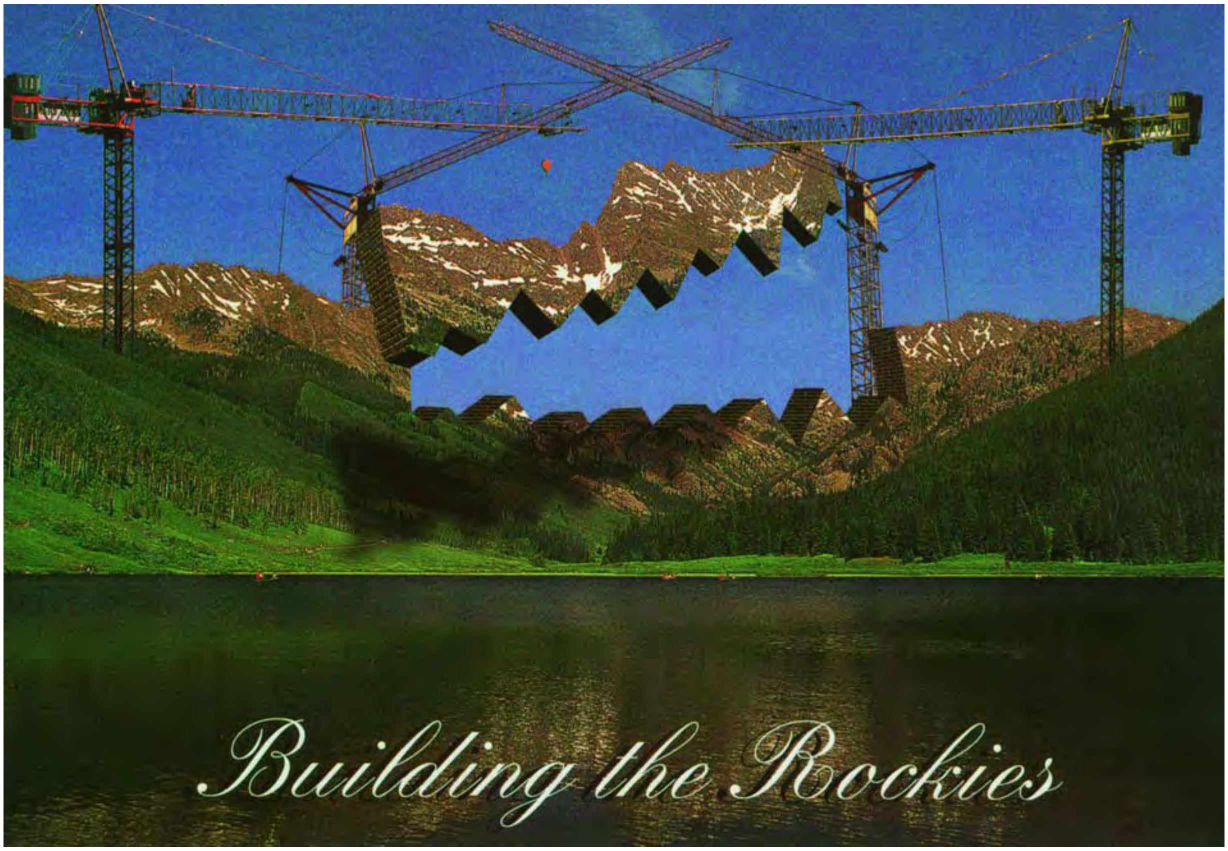
Hayden, 1873



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COLORADO SCIENTIFIC SOCIETY SYMPOSIUM ON THE GEOLOGY OF THE FRONT RANGE IN HONOR OF WILLIAM A. BRADDOCK

Saturday, April 3 2004 in Room 180, Benson Earth Sciences Building, University of Colorado at Boulder.

Schedule of Talks

8:30 AM – Introductory Remarks. **Emmett Evanoff**, University of Colorado at Boulder.
8:35 AM - Precambrian of the Front Range – From Marvine to Braddock. **John C. Reed**, U.S. Geological Survey.
8:55 AM - Proterozoic of the central Front Range – Central Colorado's beginnings as an island arc sequence. **Lisa R. Lytle**, Colorado School of Mines.
9:10 AM - Regional crustal conditions during emplacement of 1400 Ma granites – a tale told by three plutons. **James C. Cole**, U.S. Geological Survey.
9:25 AM - Front Range kimberlites: new dates, crustal xenoliths, and a view into mountain roots. **Alan Lester**, University of Colorado at Boulder.
9:40 AM - An old friend revisited: A new look at the stratigraphy of the Fountain Formation and implications for the Pennsylvanian Ancestral Frontrange Uplift. **Charles F. Kluth**, Colorado School of Mines.
10:00 AM – **Break**
10:20 AM - Precambrian through Miocene deformations along the west flank of the Front Range around Granby, Colorado. **David A. Schroeder**, University of Colorado Denver.
10:40 AM - Laramide Front Range Uplift and the Golden Fault. **Robert J. Weimer**, Colorado School of Mines.
11:00 AM - A tectonic model for the differing styles of deformation along the northeastern flank of the Front Range and adjacent Denver Basin. **Vincent Matthews**, Colorado Geological Survey.
11:20 AM - Limits on Laramide tectonic models of the Front Range based on detailed sequential cross sections of the Range. **William D. Nesse**, University of Northern Colorado.
11:40 AM - The Colorado Front Range: A wellspring of change in Laramide concepts: **Eric Erslev**, Colorado State University.

Noon – Break for Lunch

1:15 PM – Afternoon Introductory Remarks – **Neil Fishman,** U.S. Geological Survey.
1:20 PM - Timing of the uplift of the Front Range in Colorado as deduced from adjacent debris. **Robert G. Raynolds**, Denver Museum of Nature and Science.
1:40 PM - Kinematics of the Colorado Mineral Belt. **Eric P. Nelson**, Colorado School of Mines.
2:00 PM - Latest Cretaceous and Paleogene magmatism in the Front Range, Colorado**.** **Edwin E. Larson**, University of Colorado at Boulder.
2:20 PM - Laramide exhumation history and structural development of the Front Range based on apatite fission-track thermochronology. **Shari A. Kelley**, New Mexico Institute of Mining and Technology.

2:40 PM - **Break**
3:00 PM - The western Front Range margin near Dillon, Colorado--the interrelationship of thrusts, extensional faults, and large landslides. **Karl S. Kellogg**, U.S. Geological Survey.
3:20 PM - Incised meanders, geomorphic clues to neotectonism in the Colorado Front Range: **Tom Steven**, U.S. Geological Survey.

3:40 PM - Allochthonous diamictons on interfluves near the summit of the Front Range—Ancient till or valley-floor deposits elevated by late Cenozoic deformation? **Richard Madole**, U.S. Geological Survey.
4:00 PM – End of symposium.

THE GEOLOGY OF THE FRONT RANGE, A SYMPOSIUM IN HONOR OF WILLIAM A. BRADDOCK

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James C. Cole, U.S. Geological Survey, Denver, Colorado

THE Front Range is the most striking geologic feature of the Denver region. Visitors to the metro area are always amazed how it rises abruptly above the plains and dominates the western skyline. It is along the margin of two major geologic provinces of North America. To the east is the stable platform of the North American Craton that underlies the Great Plains. The Front Range is the easternmost expression of the Cordillera, the series of mountain ranges that extend from Alaska to the southern tip of South America. The Front Range is one of the features that makes Colorado unique.

The geology of the Front Range was first studied in detail by members of the Hayden Survey in the 1870s, and has been the focus of some monumental studies, including the *Geology and Ore Deposits of the Front Range* by Lovering and Goddard (1950). However, since the publication of that report, one of the most influential researchers of Front Range geology was WILLIAM ALFRED BRADDOCK (1929-2003). Bill Braddock taught structural geology and petrology in the Department of Geological Sciences at the University of Colorado, Boulder. Bill was an expert in rock mechanics and metamorphic petrology, but his main area of research was in mapping the northern Front Range. In the 1960's through the 1980s, he and his students mapped in detail a total of 5,700 km^2 (2,200 mi^2) of the northern Front Range (Figure 1). This extensive area presented many challenging geologic problems that demanded mental toughness, critical observation, and persistent application of "multiple working hypotheses." The Front Range also demanded physical toughness owing to limited road access, more than 1,500 m relief (5,000 ft), dense forest cover, and widespread glacial deposits. Bill walked over essentially all of Rocky Mountain National Park, and knew all the best back-country fishing holes (see the frontispiece).

His students knew Bill to be a very perceptive and rigorous scientist, and he was the major advisor of over 40 masters and doctoral students. Of the participants at this symposium, James Cole, Karl Kellogg, William Nesse, David Schroeder, and our editor, Mary-Margaret Coates, were all students of Bill Braddock. His legacy is in the great number of geologists he trained and the most detailed set of geologic maps of the northern Front Range. This symposium is dedicated to Bill and his exceptional career.

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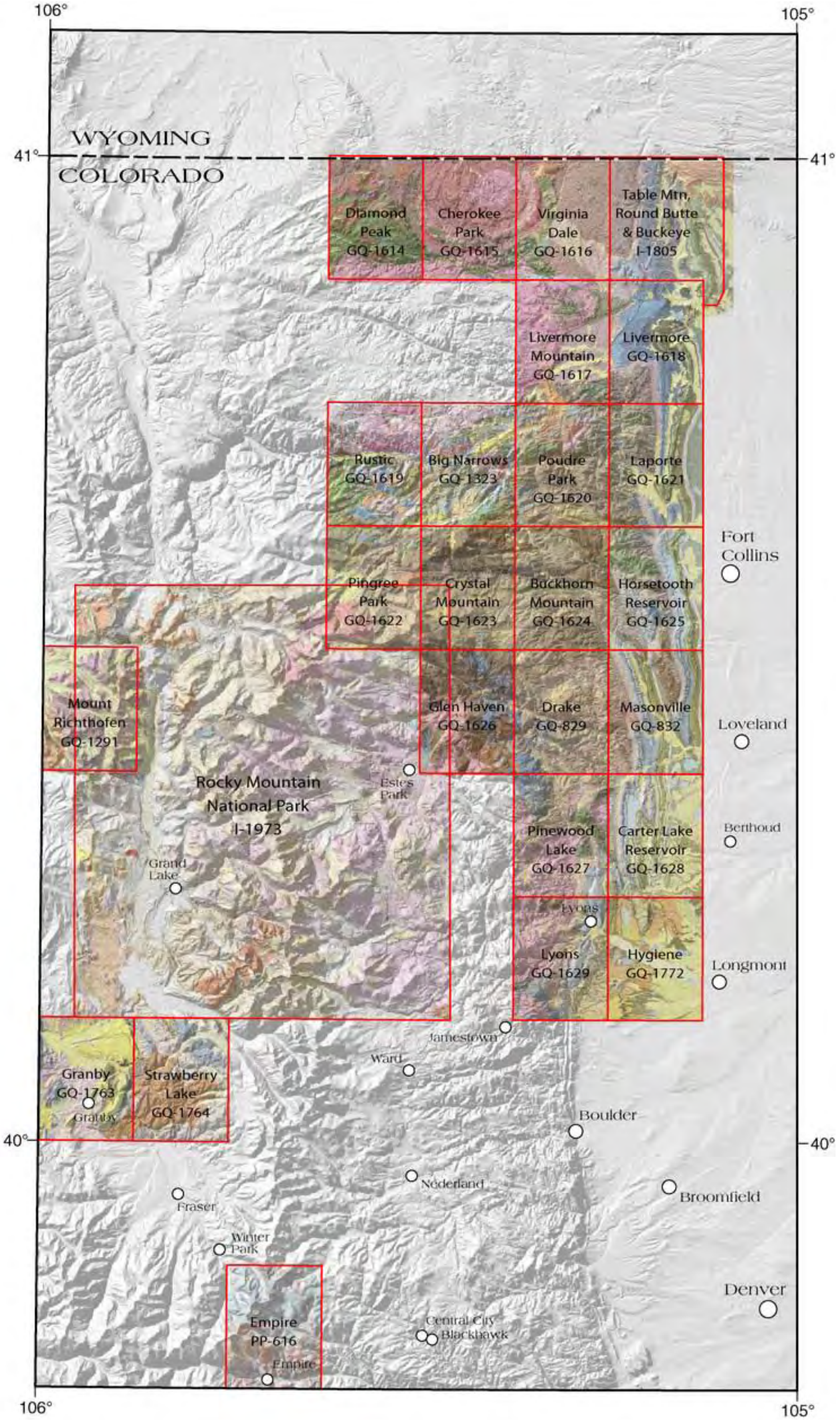

FIGURE 1. Quadrangles mapped in the northern Front Range by William A. Braddock and his students. Included are the maps by Abbott (1976), O'Neill (1981), and Schroeder (1995a,b) listed in the references.

REGIONAL CRUSTAL CONDITIONS DURING EMPLACEMENT OF 1400 MA GRANITES—A TALE TOLD BY THREE PLUTONS

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THE metasedimentary and metavolcanic rocks of the northern Front Range record sedimentation, folding, regional metamorphism, and syndeformational intrusion by intermediate calcalkaline magmas of the Routt plutonic suite. The thermal and deformation events were more or less contemporaneous at about 1725 ± 15 Ma and probably reflect processes of accretion to the older Wyoming craton to the north. Peak metamorphic conditions throughout the region produced sillimanite-K feldspar assemblages in metapelites (in general) and widespread partial melting that partially consumed biotite and produced cordierite or garnet (or both) in the restite assemblage. These observations are consistent with regional peak temperatures of about 650° ± 25°C and peak pressures of about 5 ± 0.5 kbars (water-undersaturated conditions).

Three plutons of Silver Plume Granite intruded the highest-grade metamorphic terranes in the northern Front Range at about 1400 Ma. None of these bodies produced contact-metamorphic effects. I infer that P-T conditions during emplacement resembled those of peak metamorphism 300 million years earlier, and that all three plutons were intruded at about 15 km depth. The geometry and style of each pluton is significantly different and informative about prevailing crustal conditions.

The Virginia Dale ring-dike complex intrudes steeply dipping schists and gneisses along sharp, near-vertical contacts. The complex is subcircular, about 14 × 12 km, and includes an early ring of hybridized diorite and granite (with enclaves of country rock), an outer ring of granite probably formed by cauldron collapse, and an inner, compositionally zoned core of granites that show inward-dipping trachytic foliation (Eggler, 1968). Late-stage granite-porphyry dikes cut all rock types and are radial and circumferential to the youngest core granite. Petrologic analysis and high concentrations of apatite, fluorite, and sphene indicate the granites had relatively high fluid contents (Eggler, 1968),

The Log Cabin pluton is a simple ovoid body, about 32 × 22 km, that is elongate in the general direction of foliation in the surrounding metamorphic rocks (Abbott, 1970, 1976; Braddock and Cole, 1979; Shaver, 1988). External contacts are sharp and steep, and the zoned granites within the pluton display steep trachytic foliation parallel to the margins. Abbott (1970, 1976) demonstrated that the pluton locally pushed outward against the wall rocks and caused preexisting folds to tighten. Late-stage pegmatite bodies form flat-lying sheets that discondantly cross-cut the surrounding schists and gneisses.

The Longs Peak-St. Vrain batholith is a large, irregular body, about 40 × 50 km in plan, that is characterized by generally flat-lying internal contacts and by numerous sheeted sill complexes intruded along foliation planes in the metamorphic country rock. Cole (1977) and Braddock and Cole (1979) demonstrated that emplacement of the Longs Peak-St. Vrain batholith involved major deformation, reorientation, and flattening of the country rock that attended buoyant rise of the viscous magma. Broad, open folds defined by granite foliation and compositional layering in the country rock formed during intrusion, not by compression but by differential buoyancy of magma and metamorphic rock.

The principal reason these three plutons intruded in such different forms and fashions can be related to water content of the magmas. Magma viscosity is strongly affected by volatile content (principally water) and phenocryst content. Viscosity contrast between country rocks and magma is the greatest determinant of the degree of effect that country rock structure will play on the form and progress of the intrusion. The most volatile-rich (and most fluid) magma was at Virginia Dale, and the cookie-cutter form of the pluton ignores all preexisting country-rock structure. The granite of the Longs Peak-St. Vrain batholith was relatively dry, about 50 percent crystallized when emplaced, and nearly as viscous as the country-rock schists and gneisses; thus, foliation in the metamorphic rocks was widely exploited by intruding sills, and the regionally steep country-rock foliation was rotated to flat attitudes as the granite rose through the crust (Cole, 1977). The Log Cabin magma had intermediate viscosity and was slightly influenced by preexisting structure.

These three plutons were intruded at about the same time and about the same depth in a mechanically similar metamorphosed terrane. The differences among them are due to differing degrees of magma-country rock interaction related to viscosity contrasts. Regional stress appears to have been relatively neutral. Andesitic dikes that cut the Virginia Dale complex imply mild ENE extension, but they are cut by the Log Cabin pluton and dismembered and reoriented by deformation around the Longs Peak-St. Vrain batholith. Mylonite zones developed in the granite in some areas are clearly related to late stages of consolidation and do not require postulated regional compressional stress fields.

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THE COLORADO FRONT RANGE: A WELLSPRING OF CHANGE IN LARAMIDE CONCEPTS

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DURING the last 50 years, the Front Range of Colorado has played a pivotal role in the development and testing of Laramide concepts, owing to its excellent exposures and proximity to the large and active Rocky Mountains geosciences community. The diverse Laramide features of the Front Range, which include low-angle thrusting on the west side of the range, high-angle thrusting on the east side of the range, and the enigmatic Colorado Mineral Belt, provide a fertile substrate for new Laramide concepts. Unfortunately, prior (e.g., Precambrian and Ancestral Rocky Mountain orogenies) and subsequent (mid-Tertiary and Rio Grande rift events) periods of deformation and magmatism can make it difficult to isolate Laramide features.

In the 1970s, the debate between advocates of horizontal shortening and vertical tectonics coalesced around seminars in Denver and field trips to the northeastern Front Range, which is so beautifully portrayed in the geologic maps published by Bill Braddock and his students. The western part of the range, which exposes low-angle Laramide thrust faults with substantial overhangs, was largely ignored because of the complications of pervasive Neogene magmatism and rifting. The vertical tectonics school correctly emphasized the important role of basement blocks in the northeastern Front Range, but they also reinterpreted earlier work that indicated reverse faulting in a vertical- or normal-fault context. More recent work in this area has showed that both the major and minor faults are strongly dominated by thrust, reverse, and strike-slip faults. Nearly vertical faults do exist, but they are almost exclusively strike-slip faults, not dip-slip faults as predicted by the vertical uplift school.

The large reverse faults in the northeastern Front Range provide an interesting dilemma in that they typically bring the basin side of the fault up and the range side of the fault down. This shows that they must be secondary structures and are not directly responsible for the uplift of the Front Range. Comparisons with less reworked and better-imaged Laramide arches in Wyoming show that analogous reverse faults form zones of stratal tightening on the sides of the arches opposite to the major basin-boundary thrusts. These backlimb-tightening structures can be explained by inner arc shortening during the bending of the hanging walls above low-angle, listric basin-boundary thrusts that sole into horizontal detachments near the Moho. Application of this model to the Front Range arch indicates that a triangle zone of thrusts breaches the surface on the western side of the arch and inserts a wedge of crust beneath the arch, causing crustal thickening and uplift.

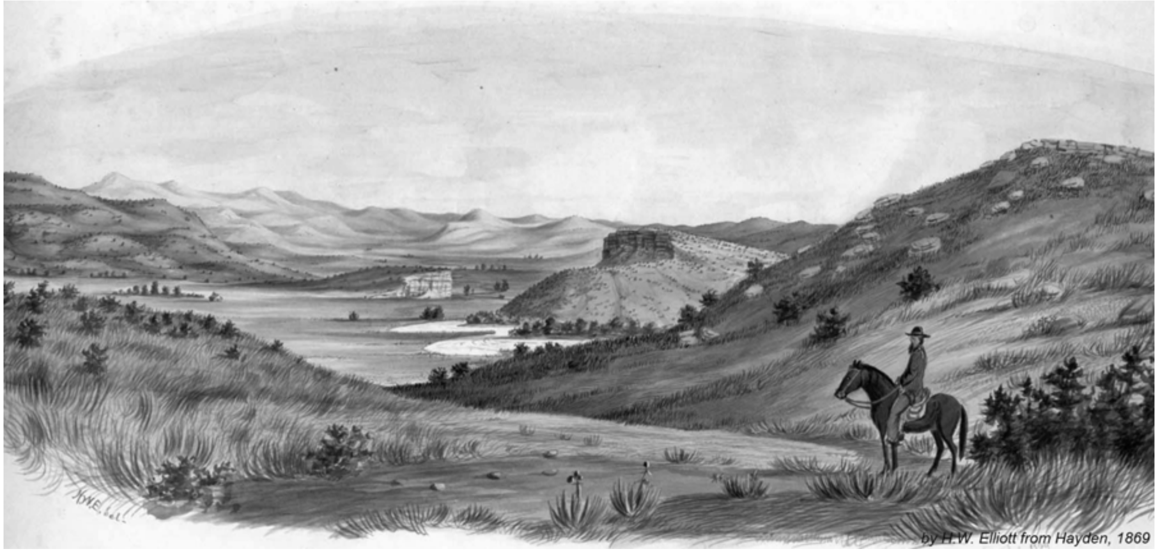
In the 1980s, a new concept of large, 100+ km northward displacements of the Colorado Plateau during the Laramide re-energized the geologic community. Evidence for large amounts of strike-slip movement is clearest in northern New Mexico, where the Picuris-Pecos fault system displays 38 km of right-lateral offset between distinctive Precambrian metamorphic belts. This displacement is clearly shown in aeromagnetic maps, which also reveal several parallel zones of equivalent right-lateral slip. Interpretations of apparent Phanerozoic stratigraphic separations have varied, and some investigators find abundant evidence for major right-lateral offsets whereas others find contrary evidence. This disagreement suggests that the basement offsets could be Precambrian in age as interpreted by early field investigators.

The extrapolation of these hypothesized Laramide displacements northward is problematic. At the latitude of

Denver, the Front Range is the best place to accommodate lateral slip between the Colorado Plateau and the craton. To the west of the Front Range, the sinuosity of the Grand Hogback and the lack of major Laramide slip on the Gore fault system appear to rule out major strike-slip displacements. The lack of evidence for Laramide strike-slip along the margins of the Front Range suggests that the slip could be partitioned into the center of the range, making the arch a giant Laramide flower structure. But transverse Precambrian lithologic contacts like the Pikes Peak Batholith and the Iron Dike, which extends from Denver to North Park, show no evidence of major (>20 km) right-lateral displacements.

This lack of evidence has led us back to New Mexico to take another look at the Picuris-Pecos fault system. Seth Fankhauser, a M.S. student at CSU, found that the impressive, kilometer-thick breccias along the southern part of the Picuris-Pecos fault system are unusually well lithified, forming resistant knobs instead of the more usual zones of easily eroded Laramide gouge. The breccias' induration combined with their metamorphic biotite and lack of open-space fillings indicate that temperatures of deformation exceeded those seen by adjacent Paleozoic rocks. A Precambrian age for these breccias has been confirmed in Deer Creek Canyon (Santa Fe, NM) where Paleozoic limestones both unconformably overlie the breccias and inject them as clastic dikes. Local folding and faulting of adjoining Paleozoic strata indicate significant Phanerozoic reactivation of the zone, but if one correlates the 38 km of strike slip with the thick breccias, then the major strike-slip event was Precambrian in age.

In conclusion, the Front Range has and is continuing to play an important role in debates on the kinematics of Laramide basement-involved deformation. It has been both the basis for and a critical test against numerous models of Laramide deformation. New roles for the Front Range will emerge as we attempt to restore the Laramide foreland in three dimensions, determine the nature of Laramide lithospheric deformation, and unravel the cause of the enigmatic, early Laramide magmatism along the Colorado Mineral Belt. In the end, Front Range research will help elucidate the linkage between plate processes and basement-involved foreland deformation. But one note of caution needs to be stated. When proposing new models, pay careful attention to the interpretations of the earlier field geologists. While they may have been unaware of the plate dynamics that surely drive Laramide motions, their field observations have rarely been proven wrong.



by H.W. Elliott from Hayden, 1869

LARAMIDE EXHUMATION HISTORY AND STRUCTURAL DEVELOPMENT OF THE FRONT RANGE BASED ON APATITE FISSION-TRACK THERMOCHRONOLOGY

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THE base of an apatite fission-track partial annealing zone, which corresponds with a fossil ~110°C isotherm, formed across the Southern Rocky Mountain region during a period of relative tectonic quiescence in Late Cretaceous time. This paleoisotherm was subsequently faulted and folded during Laramide and post-Laramide deformation. Thus, the base of the partial annealing zone provides a valuable structural datum for studying Laramide and post-Laramide deformation and exhumation in the Southern Rocky Mountains.

The base of a fossil partial annealing zone, which separates apatite fission-track cooling ages of 45 to 70 Ma at low elevations from apatite fission-track ages >100 Ma at higher elevations, is exposed at several localities in the Front Range, including the south side of Pikes Peak, Mt. Evans, Mt. Logan, Waterton Canyon, Crow Hill, and Clarks Peak. The elevation of the base of the partial annealing zone ranges from ~3,500 m on Mt. Evans to ~1,700 m at the mouth of Waterton Canyon.

The base of the fossil partial annealing zone steps up and down across mapped faults in Waterton and Clear Creek canyons and is folded on Pikes Peak. The distribution of the apatite fission-track ages >100 Ma, which lie within the partial annealing zone, is used to document that the eastern and western margins of the southern Front Range were thrust laterally over the adjoining basins, while the center of the range was uplifted with respect to the margins.

An abrupt change in structural style along the eastern margin of the Front Range occurs between Golden Gate and Van Bibber canyons, just north of Golden, Colorado. To the south, east-verging thrusts and >100 Ma apatite fission-track ages characterize the margin. To the north, southwest-verging back thrusts and 50 to 80 Ma apatite fission-track ages prevail along the margin. The partial annealing zone is not present in the northeastern Front Range, even at elevations as high as the summit of Longs Peak (4,346 m). We interpret the difference in structural style and cooling history in the northern Front Range as compared with the southern Front Range to be in part related to the thermal effects of pluton emplacement along the Colorado Mineral belt during Laramide deformation and in part due to dramatic changes in the thickness in the Late Cretaceous Pierre Shale between Golden and Boulder.


by H.W. Elliott from Hayden, 1869

WESTERN FRONT RANGE MARGIN NEAR DILLON, COLORADO—INTERRELATIONSHIPS AMONG THRUSTS, EXTENSIONAL FAULTS, AND LARGE LANDSLIDES

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THE low-angle Williams Range thrust, of Laramide age (Late Cretaceous to early Eocene), and its probable southward continuation, the Elkhorn thrust, define the western structural margin of the Front Range. At most locations near Dillon, the Williams Range thrust places Proterozoic granite and granitic rocks above Late Cretaceous shale and sandstone. New and previous geologic mapping (Varnes and others, 1989; Kellogg, 2002) indicates that the hanging wall is extensively fractured and that most of the west side of the Williams Fork Mountains (a long, NW-trending ridge along the west side of the Front Range) is mantled by a large (tens of square kilometers) landslide complex. The crest of the Williams Fork Mountains is smooth and rounded, has a relatively constant altitude of about 3,700 m, and contains numerous landslide scarps and sackung structures (deep-rooted, commonly upslope-facing scarps or fractures). By comparison, similar Proterozoic rocks in the nearby Gore Range at comparable altitudes are relatively unfractured and form spectacular arêtes and cliff faces.

Why is the bedrock so fractured? One idea (Kellogg, 2001) is that during Laramide thrusting the relatively brittle hanging wall rocks were shattered by moving through a flexure in the surface of the Williams Range thrust. The attitude of the thrust, which has at least 9 km of structural overhang, may change from relatively steep at depth, where Proterozoic rocks make up both the footwall and hanging wall, to a flatter attitude where the footwall is mostly Cretaceous shale. Late Neogene and Quaternary downcutting by the Blue and Williams Fork Rivers led to gravitational spreading of the weakened, fractured bedrock underlying a large area, including the entire Williams Fork Mountains, and the creation of sackung and landslide features.

The Blue River valley occupies a half graben, the northernmost major expression of the Rio Grande rift, just west of the Williams Range thrust, down dropped on the west along the Blue River normal fault. The earliest basin fill in the half graben is 27 Ma (middle Oligocene), a time consistent with initial Rio Grande rifting elsewhere. Extensional faults in the Blue River valley are consistently east side down, suggesting a common detachment surface at depth (Kellogg, 1999). A possible detachment surface is the Gore fault, a high-angle, mostly east-dipping, reverse-fault system that forms the western structural boundary of the Gore Range. The Gore fault has a complicated history that includes both Laramide and late Paleozoic movement.

Apatite fission-track ages as young as late Miocene (Naeser and others, 2002) along both flanks of the Blue River half graben are considerably younger than ages farther to the east in the central Front Range or farther to the west in the White River uplift. These young ages result from a combination of uplift, erosion, and elevated heat flow along the axis of the Rio Grande rift during Neogene time.

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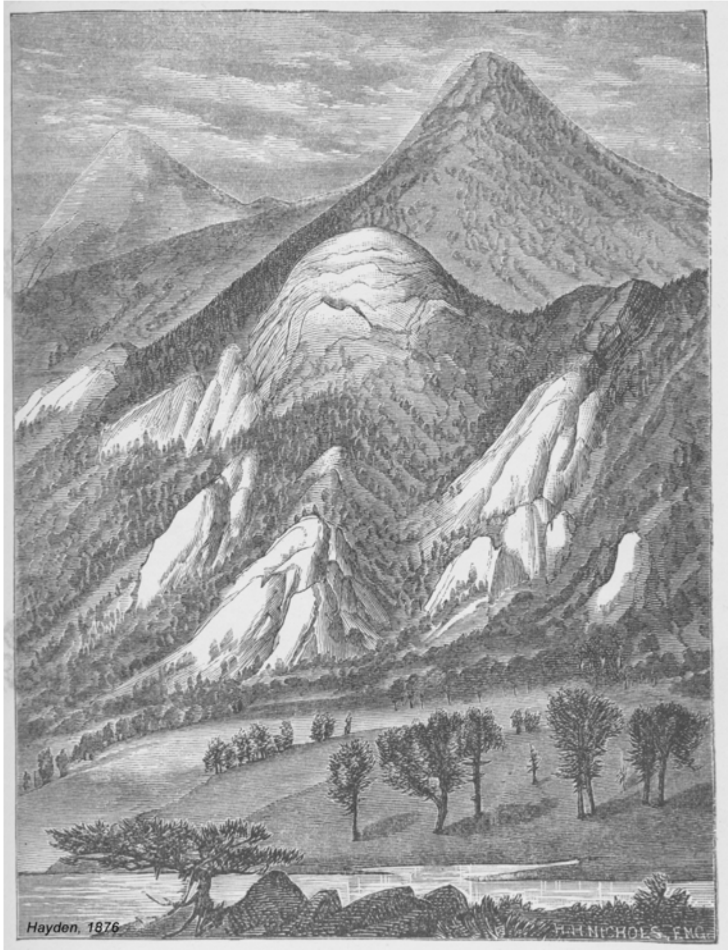
Hayden, 1876

AN OLD FRIEND REVISITED: A NEW LOOK AT THE STRATIGRAPHY OF THE FOUNTAIN FORMATION AND IMPLICATIONS FOR THE PENNSYLVANIAN ANCESTRAL FRONTRANGE UPLIFT

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LATE Paleozoic tectonics of the Frontrange (traditionally spelled as one word to distinguish it from the Late Cretaceous-early Cenozoic Front Range uplift) are part of a widespread intraplate deformation of western Pangea. This intraplate deformation has been interpreted to relate to suturing of South America and North America in the assembly of Pangea.

The Fountain Formation has been widely considered to have been deposited in alluvial fans, and its internal stratigraphic changes have generally not been incorporated into the paleogeography. Work just beginning suggests that deposition in a braided stream is more consistent with the characteristics in outcrop and that important stratigraphic changes exist along the north-south outcrop belt. The thickest part (approximately 1,800 m) of the Fountain is in the Colorado Springs area and includes a course alluvial fan related to movements on the Ute Pass fault, grading into marine sandstones and carbonates. In the vicinity of Perry Park and Roxborough Park a lower, recessive unit of arkosic fluvial sandstones is nearly 300 m thick. This lower unit appears to gradually pinch out northward against the NW-SE oriented core of the Frontrange. An upper unit of more resistant, amalgamated, arkosic, braided channel sandstones that is prominent from Roxborough Park northward sits on the basement core of the Frontrange at Red Rocks Park and Boulder. This resistant unit makes up the total (decreased) thickness of the Fountain Formation west of Denver. The arkosic fluvial sandstones appear to change northward to less resistant facies. Marine carbonates interfinger with the less resistant lower unit at Perry Park and eastward into the basin. It appears that there is considerable paleogeographic data in the details of the stratigraphy of the Fountain Formation.

The paleogeography of the Frontrange has often been depicted in terms of present-day north-south geography. Interpretation of the pattern of units that subcrop below the Pennsylvanian Fountain Formation, the age of formations that unconfomably overlie the Frontrange, and the preliminary interpretation offered here, suggest that the late Paleozoic feature was aligned more southeast-northwest and extended beyond the present physiographic features, which are more related to the Laramide deformation of the region.

The eastern side of the Frontrange appears to have had a gentle eastward dip slope with no significant mountain-front faulting. Interpretation of the thickness changes from Boulder and Golden westward to the deep well on the Rocky Mountain Arsenal may or may not require minor (tens of meters) Pennsylvanian faulting. The structural relief on the western side was on the order of kilometers and separates the uplift from the deep Central Colorado Trough, into which a complex array of sedimentary facies were deposited. Included in this array are deep water turbidites, fan delta sandstones, and evaporites. The western side of the present Front Range in North Park cuts north-south, obliquely across the more northwesterly trend of the Pennsylvanian uplift. The new interpretation of the Frontrange paleogeography is different than that of the later Laramide uplift and different than it has generally been depicted in the literature.

LATEST CRETACEOUS AND PALEOGENE MAGMATISM IN THE FRONT RANGE, COLORADO

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DURING the last 70 m.y., Colorado has been the site of three different magmatic episodes. Only the earliest two occurred in the Front Range, that from ~70 to 45 Ma, the Laramide pulse, and that from ~40 to 26 Ma, the Paleogene pulse (Figure 2).

The Laramide magmatic interval, which occurred during compressive tectonism, was areally restricted to a relatively narrow zone that extended from the southwest corner of Colorado northeastward to the eastern edge of the Front Range. This magmatic zone has been termed the Colorado Mineral Belt. Most of the activity, which began essentially contemporaneously along the entire length of the Colorado Mineral Belt, occurred from ~70 to 60 Ma. Compositionally, the magmas were of two distinct types—mafic alkaline and calc-alkaline. Most intrusions emplaced during this interval comprised small stocks, sills, and dikes; batholiths were entirely lacking. Some of these intrusive bodies fed volcanic activity, the traces of which have been almost entirely removed by subsequent erosion.

In the Front Range, one of the most southwestern of the plutons is the Empire stock, described by W.A. Braddock (1969). To the east, north, and northeast are a group of smaller and larger plutons. Among the latter are the Bryan Mountain, Caribou, and Mount Audubon stocks. Along the eastern range margin, Laramide bodies include sills, dikes and flows, nearly all of which formed from ~66 to 64 Ma. Mafic alkalic (shoshonitic) rocks make up the E-W Valmont dike, close to Boulder, as well as the sill and dike at Ralston Reservoir and the lava flows on North and South Table Mountains. Calc-alkaline felsic sills were discontinuously emplaced into mountain-front sediments from Boulder, northward to Lyons.

The Paleogene magmatic episode was a widespread noncompressional event that affected not only Colorado but also large areas in the Basin-Range region, New Mexico, Utah, Arizona, and west Texas. In Colorado, the activity began in and north of the Central Colorado Volcanic Field ~40 Ma, spread SSW to the San Juan region by ~35 Ma, and continued moving north and south of the Colorado Mineral Belt from ~35 to 25 Ma. The magmas were predominantly calc-alkaline except for some alkaline types along the eastern edge of the activity.

Front Range activity included the 39-Ma Montezuma stock as well as several other nearby smaller plutons. At 36.7 Ma, a large pyroclastic flow (Wall Mountain Tuff) erupted from the south end of the Sawatch Range, flowed eastward across South Park and the southern portion of the Front Range, and out onto the Great Plains near Castle Rock. In South Park, mafic and intermediate lavas lapped onto the western edge of the Front Range ~36 to 35 Ma. One laharic unit dammed a stream valley, resulting in the formation of Lake Florissant. Westward, activity in the area of Cripple Creek 32.5 to 31 Ma produced breccia pipes and diatremes(?). Farther north, the set of nested small felsic stocks in the Urad-Henderson area was emplaced from ~29 to 27 Ma. And, at Apiatan Mountain, near Grand Lake, magmatic activity produced a stock ~28 Ma. By far the greates pulse of Paleogene activity occurred in the Never Summer Range. This area, near Mt. Richtofen, was mapped by C.U. personnel over many years, particularly by W.A. Braddock and two of his students. It is conjectured that volcanism began ~32 Ma and continued over an extended period, producing at least 1.5 km of interlayered basalt flows, andesite flows and lahars, and rhyolitic flows and ashes. Near the end of activity, explosive volcanism at ~29 Ma produced a thick pyroclastic flow that now caps Specimen

Mountain. The related Mt. Richtofen granodiorite stock and the smaller Mt. Cumulus granite stock to the south were emplaced at ~29 and ~28 Ma, respectively.

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by H.W. Elliott from Hayden, 1869

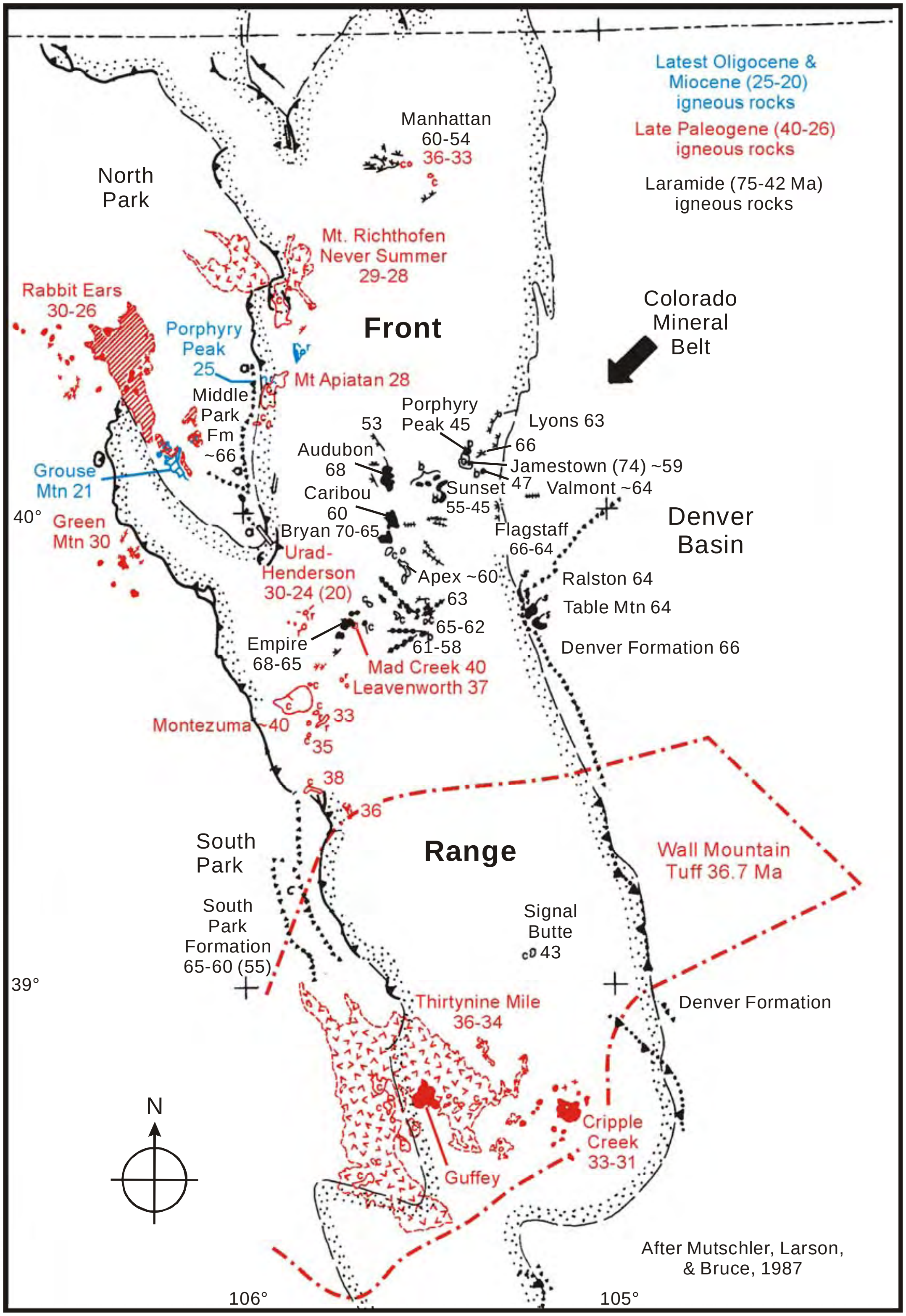

FIGURE 2. Distribution of Late Cretaceous and Cenozoic igneous rocks in the Front Range. After Mutschler et al., 1987, and McIntosh and Chapin, 2004.

FRONT RANGE KIMBERLITES: NEW DATES, CRUSTAL XENOLITHS, AND A VIEW INTO MOUNTAIN ROOTS

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ALTHOUGH more than 100 kimberlitic diatremes and sills have been identified within the Colorado-Wyoming kimberlite province, very few isotopic dates exist with which to constrain the timing of emplacement. Since their discovery in the early 1960s, a limited number of Rb-Sr dates, yielding Early to Late Devonian ages (e.g., Smith, 1979), fostered the notion of a single emplacement episode. New isotopic dates for two kimberlite bodies, one at Chicken Park (30 km northwest of Fort Collins, Colo) and one on Green Mountain (near Boulder, Colorado), indicate Neoproterozoic emplacement and imply that the Colorado-Wyoming province, similar to other kimberlite provinces worldwide, underwent multiple intervals kimberlitic magmatism.

Preliminary calculations of initial ^{143}Nd/^{144}Nd values for three discrete periods of kimberlite magmatism, 620-640 Ma (Chicken Park), 570 Ma (Green Mountain), and 350 Ma (State Line District), are commensurate with the uniform isotopic evolution of a kimberlitic mantle source region that underwent an enrichment episode at approximately 1.4 Ga.

It has long been recognized that kimberlites in the State Line District, located south of the Cheyenne Belt Archean-Proterozoic suture, contain mafic lower crustal xenoliths, including opx+/-cpx+/-garnet (hornblende absent) granulites (Bradley and McCallum, 1984). Recent studies have further demonstrated that these xenoliths represent Paleoproterozoic lower crust, portions of which underwent partial melting at ~1.4 Ga (Farmer et al., 2004). In contrast, mafic lower crustal xenoliths entrained in Quaternary ultrapotassic lavas at Leucite Hills (southern Wyoming), located north of the Cheyenne Belt, are Archean age hornblende granulites that lack garnet, despite estimates of peak metamorphism (~1.1 GPa, 800°C to 1000°C) that overlap the metamorphic conditions recorded in the State Line garnet granulites. We speculate that Archean lower crust north of the Cheyenne Belt, unlike the Proterozoic lower crust to the south, has remained hydrous and largely unperturbed thermally since the Late Archean, possibly due to thermal shielding by thick, buoyant Archean lithospheric mantle.

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PROTEROZOIC OF THE CENTRAL FRONT RANGE—CENTRAL COLORADO'S BEGINNINGS AS AN ISLAND ARC SEQUENCE

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Tectonics and Geology

PROTEROZOIC rocks of Colorado represent addition of the Colorado Province to the Wyoming craton in a 1.8 to 1.7 Ga accretionary event (Condie, 1986). Current studies (e.g., CD-ROM Project) are endeavoring to determine how and when the individual components of the terrane were formed and the location of boundaries of accreted arc sequences and thus to gain a better understanding of the tectonic processes involved. The metamorphosed volcanic and sedimentary arc sequence of the central Front Range is one component of the accreted terrane in the Colorado Province.

The boundaries of the central Front Range arc sequence are currently undefined. The eastern and western extents are terminated by Laramide-age faulting. To the south, a boundary separating the sequence from that of the Wet Mountains must exist, but it has yet to be established. The Pikes Peak Batholith may obscure this boundary. The northern boundary is also difficult to determine as geologists have not yet recognized any clear lithological, geochemical, or structural breaks.

The arc sequence of the central Front Range has characteristics in common with others of the Colorado Province but still differs in some respects. Metamorphic grade of the central Front Range is upper amphibolite. This grade is higher than that of many other Colorado sequences, such as the Gunnison Greenstone Belt at greenschist grade. The protolith of metasedimentary rocks in the central Front Range was pelitic shale, and quartzitic sandstones and conglomerates. Elsewhere in Colorado these may be greywackes, the more common sediment type found in similar sequences in the Gunnison area.

Central Front Range Arc Sequence

The main units present in the central Front Range arc sequence are metamorphosed volcanic and sedimentary units consisting of mica schists and gneisses, iron formations, calc-silicate gneisses, hornblende gneisses, amphibolite gneisses, felsic gneisses and quartzites (all part of a package unofficially called the "Idaho Springs Formation"), with plutons of Boulder Creek (~1700 Ma), Silver Plume (~1400 Ma), and Pikes Peak (~1000 Ma) ages. Isotopic data restrict the age of the gneisses to between 1700-1900 Ma. The units are interpreted as follows (Finiol, 1992):

Interlayered Gneiss: Interlayered metamorphosed intermediate felsic and mafic volcanics, volcaniclastics, and related intrusives, representing a low-K tholeiitic, immature, bimodal, volcanic arc assemblage related to subduction occurring south of the Wyoming craton.

Hornblende Gneiss: Metamorphosed submarine volcanic sequence with related carbonates and cherts, representing backarc generation of submarine tholeiitic basalt flows, with interlayered carbonates, cherts, greywackes, and other minor sediments that accumulated during periods of volcanic quiescence.

Transition Zone: Metamorphosed laterally variable package of chert, sediment, stratabound sulfides, and iron formations, representing exhalative-related deposits related to declining volcanic activity. The cherts and iron formations represent the more distal or lower temperature portions of hydrothermal vent deposits; the sulfides were deposited nearer to the higher temperature vents.

Mica Schist: Metamorphosed pelitic shales containing sandy channels and cherty carbonate pods, representing basin sedimentation in a continental margin arc.

Coal Creek Quartzite: Metamorphosed sandstone with intercalated conglomerate and shale layers.

This arc sequence then collided with the growing Wyoming craton to the north, resulting in the deformation and metamorphism of the package. Syntectonic emplacement of the Boulder Creek plutons occurred as the area became part of the magmatic arc.

Metamorphism

The metamorphic rocks of the central Front Range are of upper amphibolite grade: a high T–low P metamorphism, where anatectic melting reactions were reached. This high grade indicates that heat added to the crust from intrusive bodies, rather than deep burial, was more important to the regional metamorphism.

One small area in the vicinity of White Ranch Park, Jefferson County, is of slightly lower metamorphic grade. PT conditions for anatectic melting were not reached, and sillimanite-muscovite and/or andalusite-muscovite were stable. Indicated pressures and temperatures of metamorphism are 525° - 625°C at 3 to 3.75 kbars (approximately 10–12 km depth: Finiol, 1992).

Outside of the White Ranch Park area, anatectic migmatites are commonly developed and appear to be compositionally controlled. In the mafic and calc-silicate units, P-T conditions for anatectic melting were not reached, and the migmatites present were produced by injection, metasomatism, or subsolidus processes, not of anatectic origin. However, P-T conditions for anatectic melting are lower for rocks of pelitic and felsic compositions, and anatectic migmatites are common in the pelitic and felsic volcanic units. The degree of migmatization changes across the area. Although not a simple relationship, there is a general increase of metamorphic grade towards the Mt. Evans pluton.

Future Work

We have learned much over the last 20 years about the how the Colorado Province was formed, but we still have much to discover. There is a need to define strategies for determination of arc sequence boundaries, more accurately date the sequences, and determine more about the tectonic processes that formed the Colorado Province.

Through continued study of the central Front Range, we can work to define and understand the role this sequence plays in the larger picture. New work is underway to re-examine the Coal Creek Quartzite (Fisher & Lytle, 2004), looking past the metamorphic overprint with attention to sedimentologic and stratigraphic detail. This new assessment may help to characterize basin extent, depositional environment, tectonic environment, etc., and may aid in defining arc sequence boundaries.

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ALLOCHTHONOUS DIAMICTONS ON INTERFLUVES NEAR THE SUMMIT OF THE FRONT RANGE—ANCIENT TILL OR VALLEY-FLOOR DEPOSITS ELEVATED BY LATE CENOZOIC DEFORMATION?

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BOULDERY till-like deposits blanket interfluves and cols in places near the summit of the Front Range and also are present in similar locations in other north-central Colorado ranges. Some of these deposits have been mistaken for till. Consequently, several journal articles and geologic maps state or infer that (1) the region was glaciated prior to the cutting of deep canyons and (2) precanyon glaciation was much more extensive than later (postcanyon) glaciations. The notion of a precanyon ice-cap glaciation was well entrenched in the geologic literature of the Southern and Middle Rocky Mountains long before the marine oxygen-isotope record revealed that ice volume during late Pliocene and early Pleistocene glaciations was less than during most glaciations since 800 ka.

Wahlstrom (1940, 1947) believed that bouldery deposits on summits near the Continental Divide in western Boulder County (Niwot Ridge, for example) were till and that this till was equivalent in age and origin to bouldery deposits on interfluves at lower elevations (Tungsten Mountain and Winiger Ridge) well beyond both middle and late Pleistocene terminal moraines. Jones and Quam (1944) also concluded that the deposits on Tungsten Mountain and Winiger Ridge were glacial, although others (Van Tuyl and Lovering, 1935, for example) believed that they were pre-Pleistocene gravel.

In high mountains, glacial, alluvial, and mass-wasting processes all can produce bouldery, matrix-supported, unstratified deposits. However, a glacial origin is least likely for diamictons like the one on Niwot Ridge. Glacier geometry and mass balance, specifically the relationship between glacier accumulation and ablation areas and the location of the equilibrium-line altitude rule out a glacial origin for these diamictons. In addition, most bouldery diamictons are much thicker (typically 10–40 m) than till in ground moraine, and they are much more voluminous than comparable areas of end- and lateral-moraine systems constructed by middle and late Pleistocene valley glaciers. In the Front Range, ground moraine of any age is thin (typically 2–8 m), and few till deposits older than Bull Lake are as much as 2 m thick. In contrast, the diamicton on Niwot Ridge, which is about 0.7 km wide by 2.2 km long, is as much as 36 m thick, and a similar deposit on a ridge in the Tenmile Range, which is at least 1 km wide and nearly 4.5 km long, is estimated to be 30 to 40 m thick (Madole, 1982, and unpub. data, 2003).

I believe that the ridge-capping and col-filling bouldery diamictons described here are inverted relics of paleovalleys that were elevated by late Cenozoic deformation. These ancient valley-floor deposits were segmented and isolated when uplift redirected some drainage and caused many streams to cut deep canyons.

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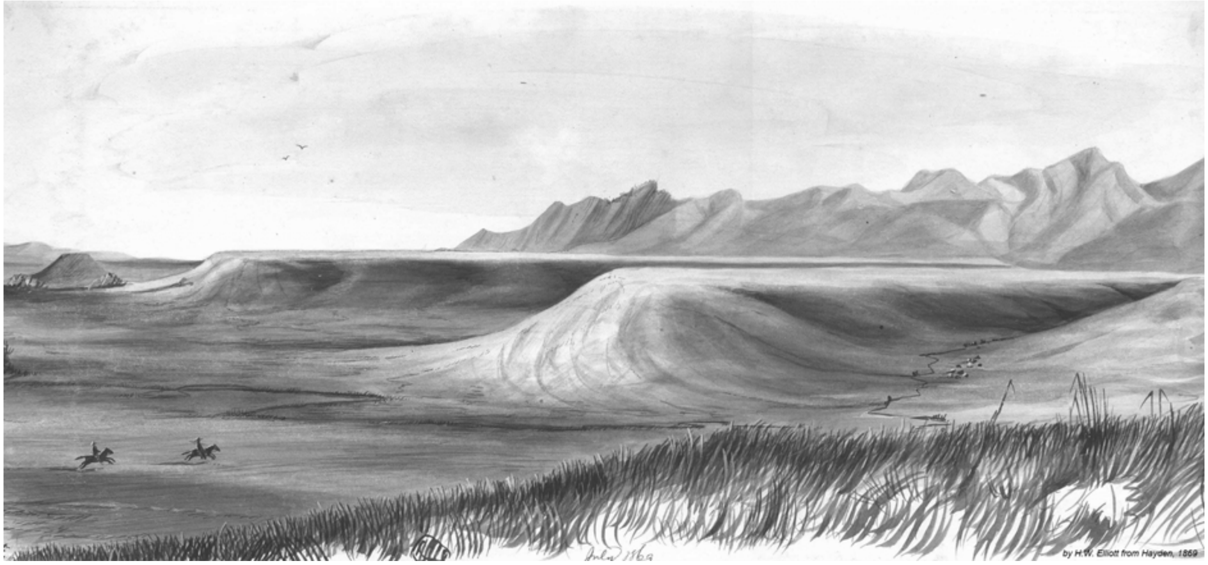

by H.W. Elliott from Hayden, 1869

A TECTONIC MODEL FOR THE DIFFERING STYLES OF DEFORMATION ALONG THE NORTHEASTERN FLANK OF THE FRONT RANGE AND ADJACENT DENVER BASIN

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THE northeastern flank of the Front Range uplift is characterized by three distinct styles of Laramide deformation: a northern area characterized by differential uplift of basement blocks with associated monoclinal folding in the overlying sedimentary strata; a central area characterized by differential uplift *and rotation* of basement blocks with asymmetrical anticlines and synclines developed in the overlying sedimentary strata; and a southern area characterized by major, high-angle frontal faults.

The upper crust underlying the northern Front Range and Denver Basin appears to be broken into three major blocks separated by two northeast-striking lineaments that are interpreted as scissor faults (Figure 3). The lineaments cross the Front Range and extend to the axis of the Denver Basin. Modern earthquakes possibly occurred along the lineaments. The lineaments may also have Precambrian ancestry, in part.

The differences in style of the second-order structural features along the flank of the uplift are caused by differences in vertical rotation of the three first-order blocks. The amount of rotation is reflected in the structural gradient between the Front Range uplift and the Denver Basin. The structural gradient on the northern block is low (50 m/km), the gradient on the central block is moderate (90 m/km), and the gradient on the southern block is steep (415 m/km). These different gradients probably reflect differences at the brittle/ductile transition.

Structural traps for hydrocarbons in the Denver Basin are located only on the two northern blocks. These blocks are reflected in the geologic, topographic, gravity, magnetics, and heat flow data. Movement occurred during both the Laramide and Neogene mountain building episodes. The brittle upper crust broke into at least four size domains of differing area ~17,300 km^2, ~6,700 km^2, ~50 km^2, and ~10 km^2.

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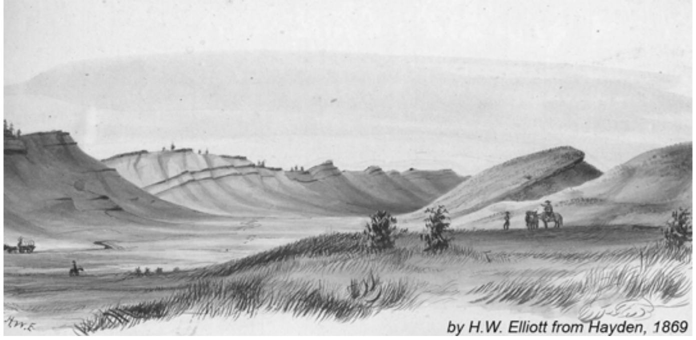

by H.W. Elliott from Hayden, 1869

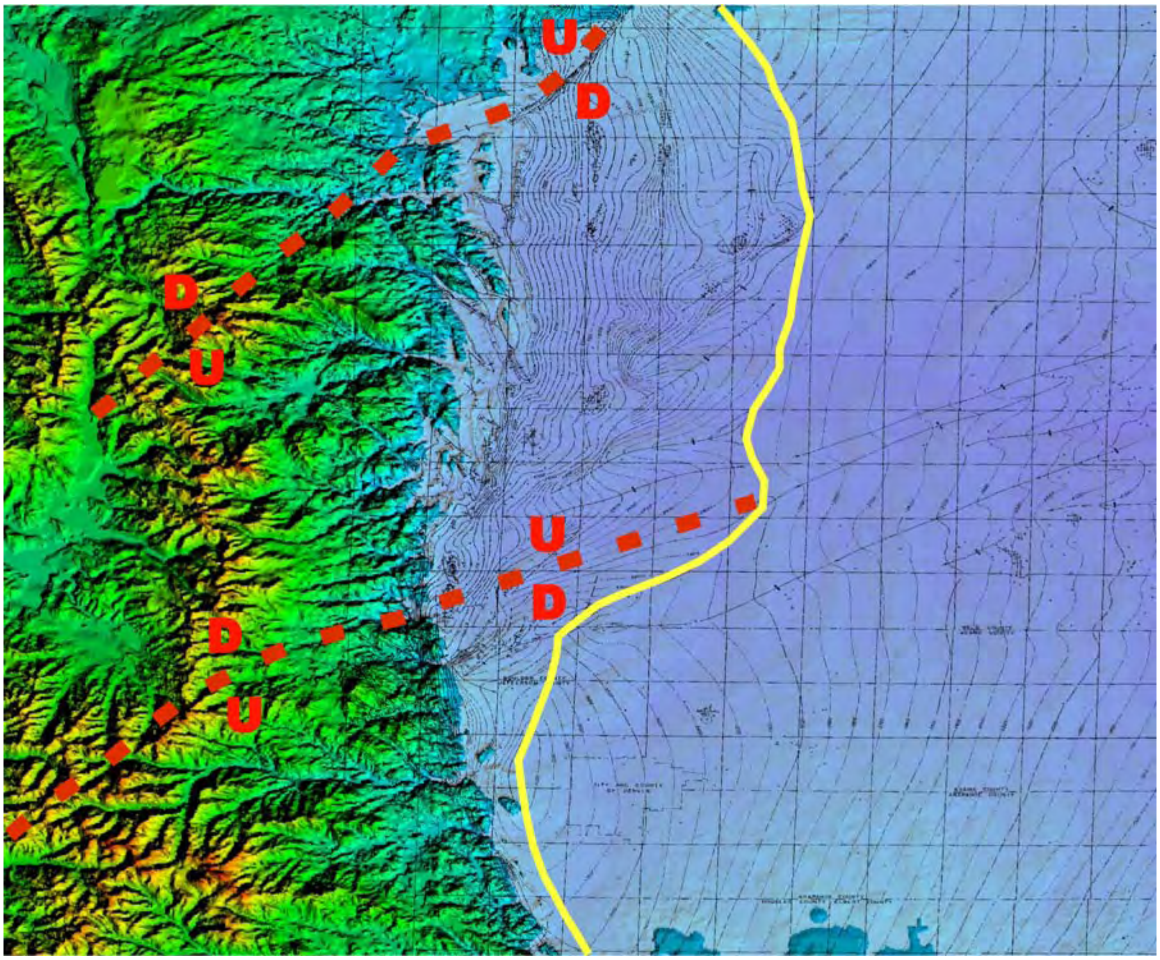

FIGURE 3. Digital elevation model of the northern Front Range merged with Dakota (Muddy J) structural contour map from Haun (1968). Red dashed lines are regional lineaments interpreted as scissor faults. These lineaments separate the northern Front Range and Denver Basin into the large blocks. Yellow line is axis of Denver Basin. Note that the axis between the two lineaments is ~40 km from the mountain front (~6,500 foot elevation contour), whereas it is only ~5 km from the same elevation on the mountain front in the southern part.

THE LAKE MORAINE GLACIAL SYSTEM, MANITOU SPRINGS QUADRANGLE, COLORADO

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LAKE Moraine is located on the southeastern margin of the Pikes Peak Massif and approximately 5 miles southwest of the town of Manitou Springs (Figure 4). The lake is situated within a northeast trending U-shaped drainage basin that was connected to Boehmer Creek sometime before the late Pleistocene. However, the drainage has since been blocked by younger glacial till. An obvious well-defined cirque is not apparent in the valley. Previous studies and geologic maps of the area show a single, Pinedale-age end moraine, a lateral moraine, and ablation till within the valley (Wobus and others, 1976; Trimble and Machette, 1979; Huber and Grogger, 1985). These previous workers suggested these deposits were Pinedale age on the basis of weathering rinds, soil development, and moraine character and preservation. Currently, the Pinedale end moraine and a small human-made concrete barrier dam the lake.

Recent geologic mapping of the 1:24,000-scale Manitou Springs quadrangle (Keller and others, 2003) by the Colorado Geological Survey revealed additional glacial deposits that may be of Bull Lake age (Figure 5). Soil profiles, weathering rinds, and moraine morphology was examined for the Bull Lake deposits and the younger Pinedale till to determine the relative glacial history of the Lake Moraine basin. Aerial photography was used to map the extent glacial landforms.

Two or possibly three different tills of Pinedale age are recognized near Lake Moraine. The most prominent of these was mapped by Wobus and others (1976). It forms a topographically distinct and well-formed lateral and end moraine 0.6 miles up-valley from the outer edge of the Bull Lake terminal moraine; moraine crests rise approximately 85 feet above the valley floor. Closed depressions with organic-rich sediments are common. A soil profile examined on the crest of this moraine consists of a 6-in.-thick A horizon and a 15-in.-thick Cox horizon overlying glacial till. Munsell colors range from 7.5 YR 5/4 for the Cox horizon to 7.5 YR 6/2 for the A horizon. Cumulative soil thickness is approximately 21 in. Thickness of weathering rinds on granitic clasts range from 0.06 in. to 0.1 in., and less than 10 percent of the granitic clasts show signs of decomposition. Numerous clasts are visible on the surface of the moraine. Maximum thickness of the deposit locally exceeds 60 ft. Younger tills of Pinedale age occur up-valley from this deposit and exhibit similar soil and clast weathering characteristics.

The previously unmapped Bull Lake terminal moraine is approximately 0.5 miles down valley from the Pinedale end moraine and is topographically more subdued and discontinuous compared with the Pinedale moraine. Soil profiles examined on the Bull Lake terminal moraine generally consist of a 9-in.-thick A horizon, a 22-in.-thick Bt horizon, and a 10-in.-thick Cox horizon overlying till. Munsell colors range from 5 YR 4/6 for the Bt horizon, to 5YR 7/2 for the A horizon. Cumulative soil thickness is approximately 3.5 ft. Roughly 20 percent of contained clasts are weathered to grüs and fewer clasts are visible on the surface compared to till of Pinedale age. Maximum thickness of deposit is approximately 50 ft.

Moraine morphology and preservation, soil characteristics, and weathering rinds are evidence that the Lake Moraine valley was glaciated during Bull Lake time. Furthermore, Bull Lake equivalent deposits were mapped in other valleys around Pikes Peak by Wobus and others (1976). Subsequent glaciation during Pinedale time resulted in the deposition of two or three additional tills. Damming of Lake Moraine occurred at least during the early Pinedale.

Lake sediments may provide an excellent opportunity for obtaining radiometric ages, thus providing an absolute glacial chronology for the Lake Moraine valley.

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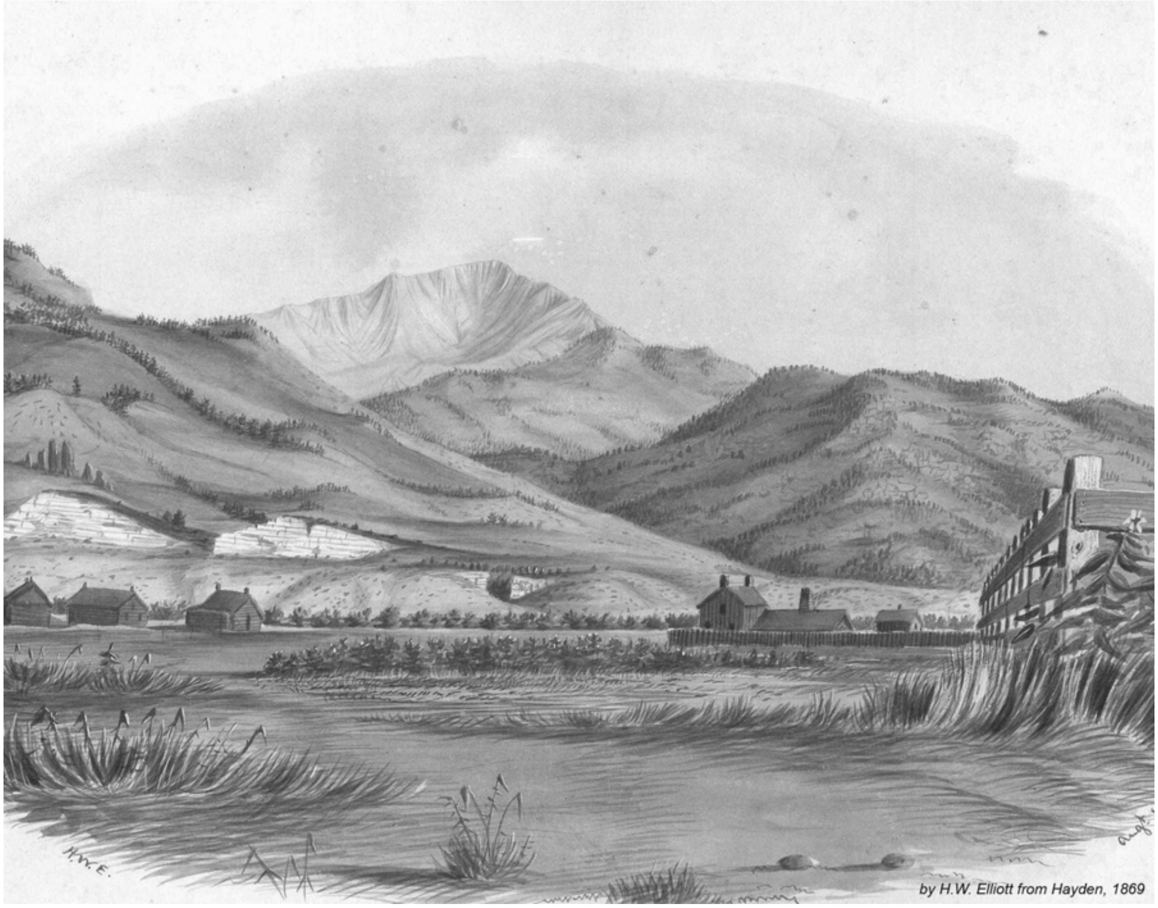

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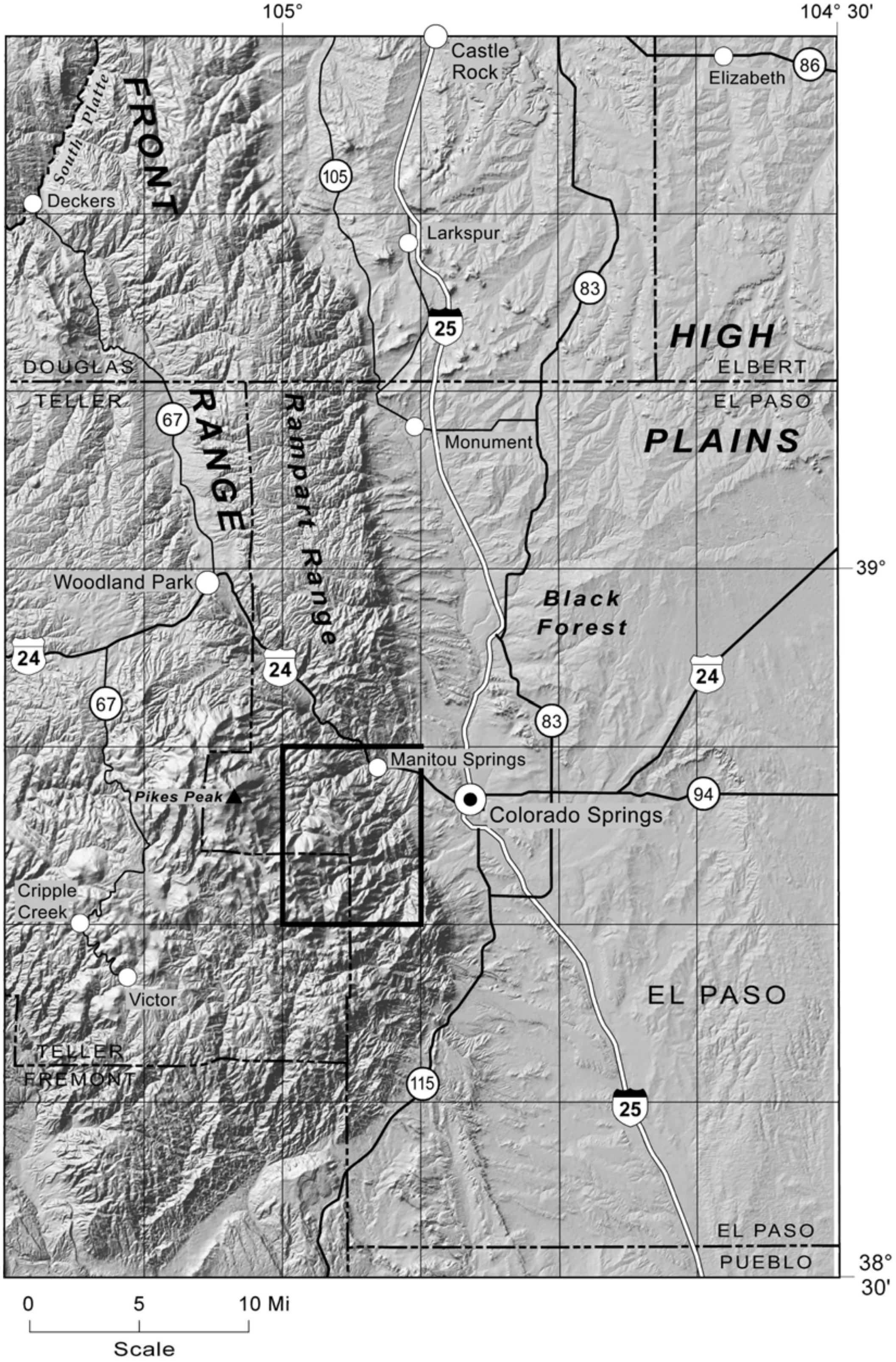

FIGURE 4. Location of the Manitou Springs quadrangle (heavy black rectangle) in relation to the southern Front Range, High Plains, and the City of Colorado Springs.

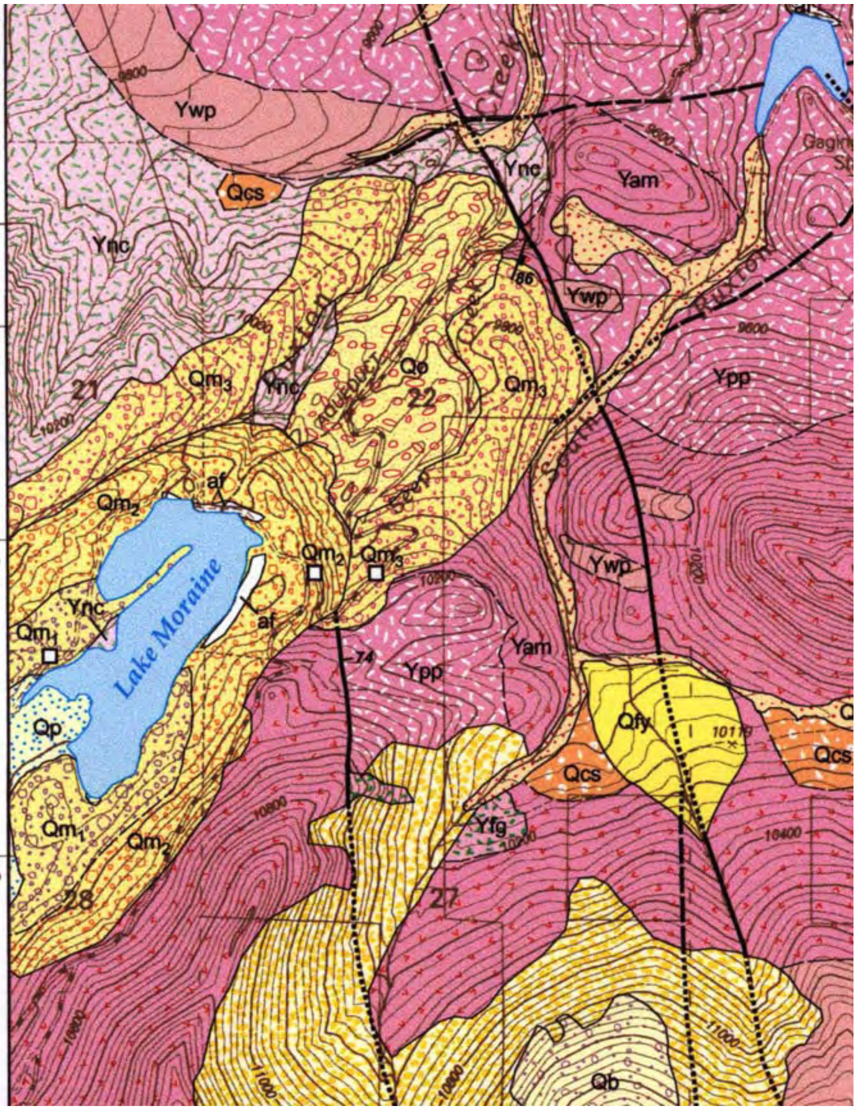

FIGURE 5. Eastern portion of the Mantiou Springs quadrangle 1:24,000-scale geologic map showing the surficial deposits and bedrock units near Lake Moraine. Pinedale-age glacial till is labeled Qm1 and Qm2; Pinedale-age outwash is labeled Qo; Bull Lake-age glacial till is labeled Qm3. Geologic mapping before Keller and others (2003) did not show the Bull Lake deposits. Excerpted from Keller and others (2003).

KINEMATICS OF THE COLORADO MINERAL BELT

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THE Colorado mineral belt trends northeast across the Colorado Rocky Mountains and hosts a large array of mineral deposits of varying ages and types. Mineralization ages range from Laramide (Late Cretaceous-early Tertiary) through late Tertiary, and thus mineralization events spanned the transition from shortening tectonics (Laramide orogeny) through a transition phase, to extensional tectonics (Rio Grande rift).

Many of these ore deposits are structurally controlled and consist of mineralized fault and/or vein systems. Through a combination of field work and literature review, the kinematics of faults and veins were analyzed in two districts (Idaho Springs and Alma), and the stress field during mineralization was modeled. Veins in the Idaho Springs district formed during the Laramide between 67 and 62 Ma, whereas veins in the Alma district formed just before or during early Rio Grande rift formation between 31 and 28 Ma.

The Idaho Springs mining district forms the central portion of a structurally controlled hydrothermal base and precious metal vein system in the Front Range portion of the northeast-trending Colorado mineral belt. Approximately 1 Moz of gold and 55 Moz of silver were mined from 1860 through 1914. Mineralization is mostly in quartz-sulfide veins in faults and extension fractures. The extent and orientation of mineralized veins is strongly controlled by Precambrian structures. The mineralized vein system is mostly within the 2-mile-wide northeast-trending Precambrian Idaho Springs-Ralston shear zone (IRSZ).

Although veins formed mostly in conjugate strike-slip faults, right lateral veins dominate (average strike 061°) and formed parallel to Precambrian foliation in the IRSZ (average orientation 060° 74NW). Veins widen where they strike across the host rock foliation and approach the maximum compressive stress orientation. Southeast of the southeast boundary of the IRSZ the regional strike of Precambrian large-scale folds and foliation is northwest, or nearly perpendicular to similar structures to the northwest, and economic veins are not present.

Kinematic indicators (slickenlines, fault offsets, en echelon vein patterns and vein thickness variations with strike change) were compiled from interpretations of published mine maps and from underground mapping in the Bald Eagle mine. Fault-slip analysis was applied to all applicable veins to model the orientation of σ_1 at the time of their formation (average trend is 076° ± 12°).

This orientation is nearly parallel to proposed σ_1 orientations of the Laramide orogeny from previous workers in the Front Range, particularly Erslev and Selvig (1997; $\sigma_1 = 072°$), who conducted fault slip analysis in Mesozoic sedimentary rocks near the projection of the IRSZ shear zone to the northeast. That the orientations are nearly identical suggests that the Laramide stress was consistently oriented in the northern Front Range. Also, this orientation indicates that the IRSZ was properly oriented for dextral reactivation at this time.

The Sweet Home mine in the Alma district has been mined for silver and, more recently, is currently being mined for museum-quality rhodochrosite crystals. Preliminary kinematic analysis of faults and fault-veins indicates that σ_1 during mineralization was roughly vertical resulting in an extensional strain field. This corresponds to the stress field expected during rifting.

However, other stress orientations were also modeled for various veins, suggesting that the stress field may have been fluctuating in a transitional phase between shortening and extension. Both mineral districts formed in the Colorado mineral belt yet under very different stress fields, suggesting that some deep crustal (or mantle?) lineament controlled their emplacement over a long period of time.

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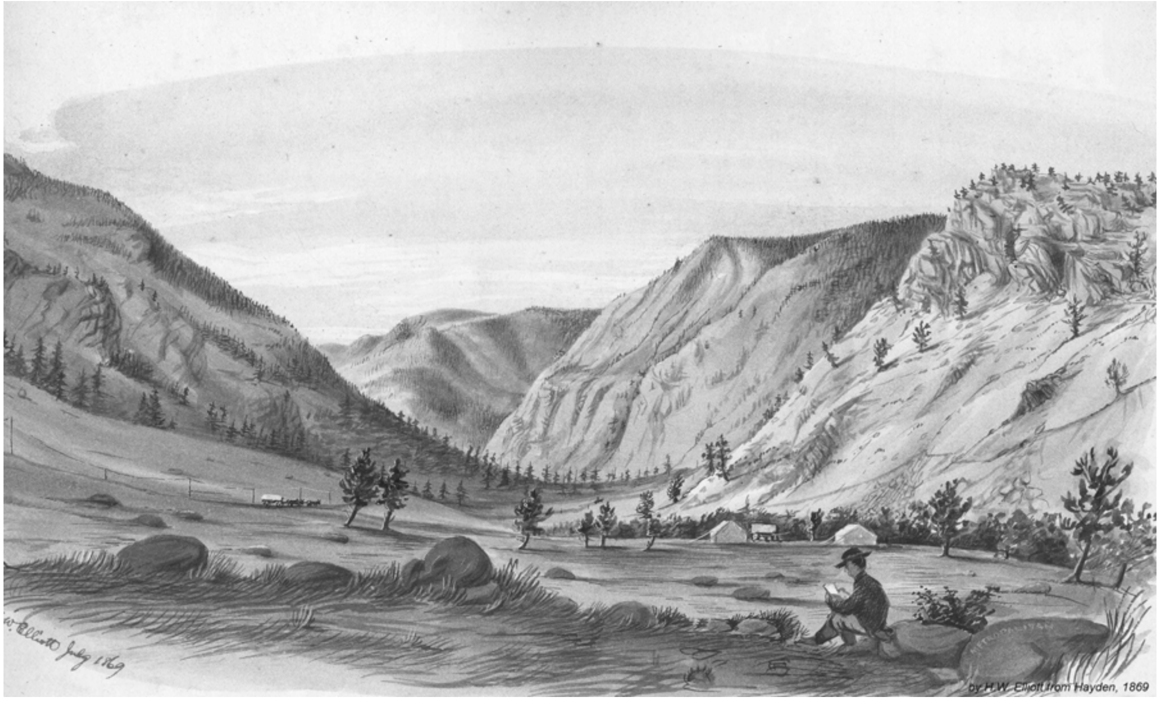

by H.W. Elliott from Hayden, 1869

LIMITS ON LARAMIDE TECTONIC MODELS OF THE FRONT RANGE BASED ON DETAILED SEQUENTIAL CROSS SECTIONS OF THE RANGE

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DETAILED east-west structural cross sections based on published geologic maps and on oil well and related data extending across the Front Range of Colorado between 39° 15' and 41° 00' N latitude. Two of the 15 sections are shown as Figure 6. These sections show the following:

- The east flank of the Front Range is an east-dipping homocline cut at intervals by relatively small E- to NE-dipping, high-angle reverse faults and fault-propagation folds. South of ~40^o N latitude (near Boulder) the homocline is locally modified by the east-directed Boulder, Golden, Jarre Canyon, Perry Park, and Rampart Range thrusts whose net slips are less than 1 to 2 km. These faults are not continuous along the mountain front and are located where the dip of the homocline exceeds roughly 60° to the east.
- The west flank of the Front Range is bounded by a series of west-directed thrusts. The thrust faults include, from north to south, Green Ridge thrust, thrust of Canadian River, Cameron Pass thrust, Never Summer thrust, thrust of Ninemile Mountain, thrust of Bottle Pass, Mount Bross thrust, Williams Range thrust, and Elkhorn thrust. They are associated with large-scale, usually overturned folds that apparently developed prior to propagation of discrete thrust faults. The net slip on the west-directed thrusts is10 to15 km, based on exposures in the Never Summer Mountains and in the Roberts Tunnel adjacent to the Montezuma Stock. The cross sections based on these exposures are shown in Figure 1.

These observations suggest that the Laramide Front Range in Colorado was produced by dominantly west-directed thrusting associated with net shortening of the crust beneath the range (Figure 7a, b). The net tectonic uplift is ~6 km. The thrusts along the east flank of the range are interpreted as backthrusts. Contemporaneous shortening produced east-directed thrusting in the

Laramie Range to the north, suggesting that whether thrusting broke to the east or west in response to crustal shortening was largely a matter of chance. Tectonic models that involve vertical uplift on faults whose dip increases with depth on both flanks of the Front Range are not compatible with the geologic data. Tectonic models that involve a deep-seated, blind, east-directed thrust derived from the Sevier thrust belt to the west and extending beneath the Front Range are geometrically compatible with the cross sections but seem improbable given that the preponderant mode of thrusting is in the opposite direction.

If the Front Range is basically a large thrust, the amount of tectonic transport (slip) must be related to dip of the fault and the amount of tectonic uplift (TU) (Figure 7c). Given ~6 km of tectonic uplift and assuming a dip on the thrusts of 35°, about 10.5 km of tectonic transport is indicated, similar to the actual movement on the Never Summer and William Range thrusts. Further, for a range width of ~60 to 70 km, the depth at which the thrust must flatten to produce the homocline on the east flank of the Front Range is ~40 to 45 km, which is approximately the depth to the Moho.

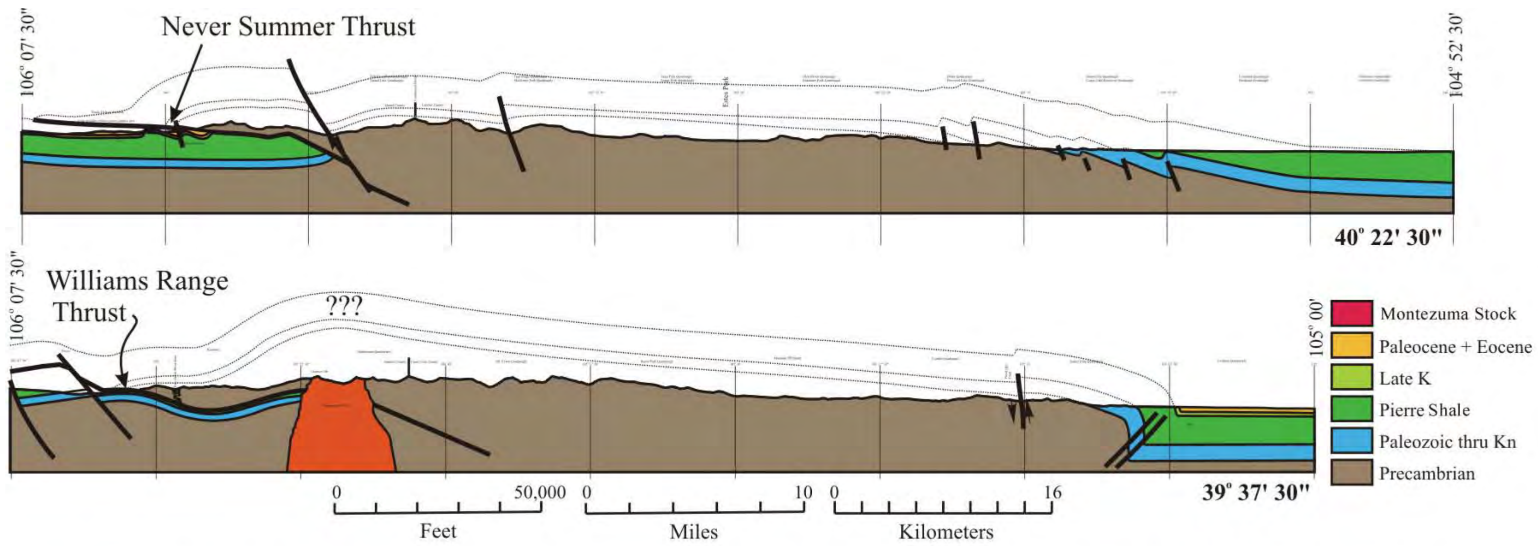

Figure 6. Cross sections at 40° 22' 30" and 39° 37' 22" across the Front Range showing typical geometries. The position of the sedimentary contacts over the top of the range is schematic. The vertical lines are boundaries between 7.5' quadrangles. No vertical exaggeration.

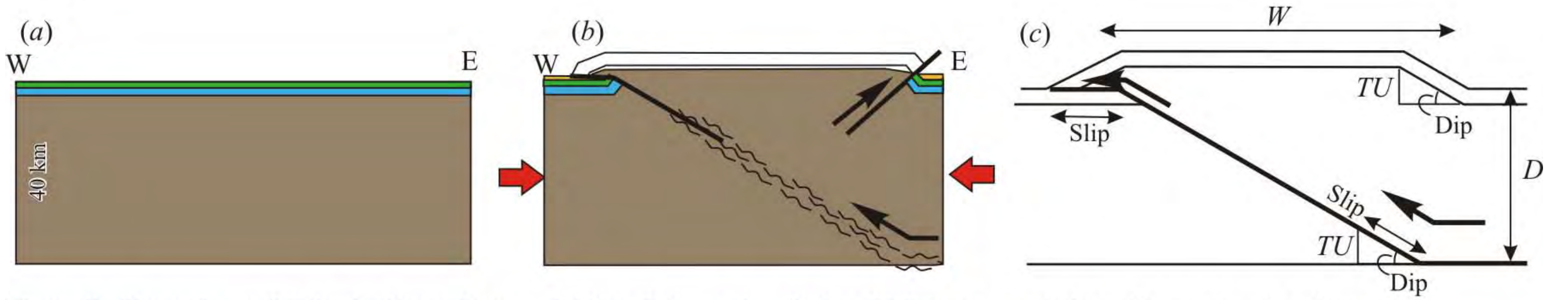

Figure 7. Tectonic model for the Front Range. (*a*) Pre-deformation 40 km thick crust consisting of a veneer of sediment on Precambrian basement. (*b*) Net shortening of the crust produces a west-directed thrust with ~10-15km of movement. Backthrusts develops locally along the east flank. (*c*) Geometric model. The tectonic uplift (*TU*) depends on the amount of slip and the dip of the thrust. The depth (*D*) at which the thrust must flatten to produce the east flank homocline depends on the width of the range(*W*) and the dip of the fault.

TIMING OF THE UPLIFT OF THE FRONT RANGE IN COLORADO AS DEDUCED FROM ADJACENT DEBRIS

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MOUNTAIN uplift is a signature that is challenging to recover from the rock record; we use surrogates and inferences to deduce the timing of orogenesis. Inferences of orogeny derived from the stratigraphic record are based primarily on sand grain and clast provenance (composition and flow polarity), sediment isopach patterns, and facies distribution patterns. Fission track thermochronometric data and paleo-orographic data can also be used to constrain uplift models.

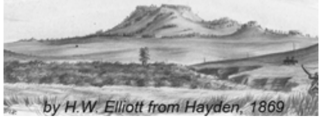
The rigorously time-calibrated rock record preserved in the Denver basin and in the somewhat less temporally well-constrained South Park basin both contain stratigraphic data sets preserving evidence of the development of topographic relief on the Laramide Front Range.

Based on the published map patterns showing relatively linear and gently curved Fox Hills shorelines, regression of the Interior Seaway appears to have been due to a regional fall in base level rather than displacement away from localized uplifts. This conclusion is noted with the caveat that shoreline orientation data is absent from the eroded ranges and the story is pieced together from the record preserved in the basins and along mountain flanks.

The 69 to 68 Ma Laramie Formation displays changes in lateral facies patterns and sandstone bed thickness in the Denver basin that are interpreted to have been caused by early deformation patterns. Both the aggregate thickness and the thickness of individual channel sandstone beds increase towards the western side of the basin suggesting an early sag phase that may have been a precursor to mountain uplift.

The onset of clearly developed Laramide synorogenic strata is associated with inception of D1 sequence sedimentation at about 68 Ma (the Arapahoe conglomerate) in the Denver basin, and with the onset of South Park Formation sedimentation at about 66 Ma in the South Park basin. These strata reveal by their arkosic and plutonic pebble composition that granitic basement rocks were exposed within the core of the Front Range. In both the D1 sequence and the South Park Formation we discern evidence for the uplift of the Front Range and document sediment preservation in the flanking basins. We infer differential motion on the basin-bounding thrust faults.

The unconformity that represents a 9 m.y. gap between the D1 and D2 sequences in the Denver basin does not yet have a recognized equivalent in the South Park basin. It is not known if the Laramide uplift was active during this time span. It is hypothesized that the absence of accommodation in the Denver basin at this time was associated with an absence of active faulting along the thrust faults defining the eastern range front. Renewed subsidence and sediment accumulation at the onset of the Eocene led to the development of the D2 sequence in the Denver basin and to the inference that the Laramide deformation was episodic along the east side of the Front Range.



by H.W. Elliott from Hayden, 1869

PRECAMBRIAN OF THE FRONT RANGE—FROM MARVINE TO BRADDOCK

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IN the 1873 report of the Hayden Survey, A.R. Marvine described the "Archean" rocks that core of the Front Range and remarked: "…when sufficient time is expended in their examination I conceive that some exceedingly interesting and clear results will follow." In the 130 years since Marvine wrote, hundreds of geologists have devoted their efforts to the Precambrian rocks of the Front Range and their results have amply borne out Marvine's speculation, although we are still a bit longer on interesting results than clear ones!

The Precambrian rocks in the Front Range include multiply deformed and polymetamorphic volcanic and sedimentary rocks extensively invaded by granitic plutons of several ages (Figure 8). Two broad groups of supracrustal rocks are widespread in most of the range: (1) complexly interlayered feldspathic gneiss, amphibole gneiss, and amphibolite interpreted as representing a bimodal volcanic and volcaniclastic sequence, and (2) interlayered mica schist (commonly migmatitic) and mica gneiss interpreted, interpreted as being largely metasedimentary. The supracrustal rocks have not been directly dated but are probably between 1790 and 1715 Ma based on dates from less metamorphosed volcanic sequences elsewhere in the Colorado Province. Isoclinal folding and ductile deformation has largely destroyed stratigraphic continuity within the supracrustal rocks and obliterated any evidence of the stratigraphic relations within and between the broad lithologic units. The intrusive rocks include a diverse group of calc-alkaline plutons emplaced between about 1750 and 1720 Ma, plutons of granite and quartz monzonite emplaced between 1440 and 1390 Ma; and the Pikes Peak Granite, emplaced at about 1100 Ma. Except for a few detrital zicons, not trace of Archean basement has been recognized in the Front Range or elsewhere in the Colorado Province.

The supracrustal rocks were regionally metamorphosed and isoclinally folded during emplacement of the ~1700 Ma plutons. In most places the early regional metamorphism was at sillimanite grade, but in several areas the rocks escaped high-grade metamorphism. The ~1400 Ma plutons have traditionally been described as "anorogenic," but several recent studies have shown that their emplacement was accompanied by widespread retrogressive metamorphism of earlier high-grade rocks, resetting of Ar^{40}/Ar^{39} systematics, deformation of wall rocks, and movement along a several of the large NE-SW trending shear zones that cut across the range. The Pikes Peak batholith post-dates regional metamorphism and deformation, although aeromagnetic surveys suggest it may have had some contact metamorphic effects.

The Early Proterozoic rocks of the Front Range are interpreted as products of magmatism and related sedimentation in magmatic arcs and inter-arc basins that were accreted to the Archean rocks of the Wyoming craton beginning at about 1760 Ma. However, the extent and interrelationship of component tectonic units in the accretionary complex are not yet well enough established to recognize individual terranes in the modern tectonic sense, but some boundaries have been suggested in the Front Range and elsewhere in Colorado.

Recent studies in the northeastern Front Range indicate that the early metamorphism was directly related to closure along the Cheyenne Belt (the suture separates the accreted terranes from the

Archean Wyoming craton). At the peak of metamorphism the rocks now at the surface probably lay at depths of ~35-24 km at temperatures of 550˚ to 600˚ C. Oblique subduction along the Cheyenne belt at this time may have been responsible for the initial development of the ENE-trending shear zones. Uplift and unroofing during the next 100 million years or so brought the rocks to depths of 10 to 15 km, and the crust into isostatic equilibrium. Retrograde metamorphism accompanying the cooling and decompression destroyed any high-PT mineral assemblages formed during subduction. A short but widespread thermal episode at ~1400 Ma resulted in the emplacement of the widespread granite and quartz monzonite plutons and in reheating of the supracrustal rocks over broad areas, producing high-PT mineral assemblages. The late dip-slip movement along the ENE shear zones apparently took place at this time. Some ~1,400 Ma plutons have been cataclastically deformed along shear zones, while others seem to have been emplaced concurrently with movement, as indicated by flow foliation that parallels cataclastic foliation in the shear zones. During or shortly after the ~1,400 Ma heating episode an extensive swarm of NNW-trending mafic dikes was emplaced, possibly due to NNW compression during high angle reverse movement along the ENE trending shear zones

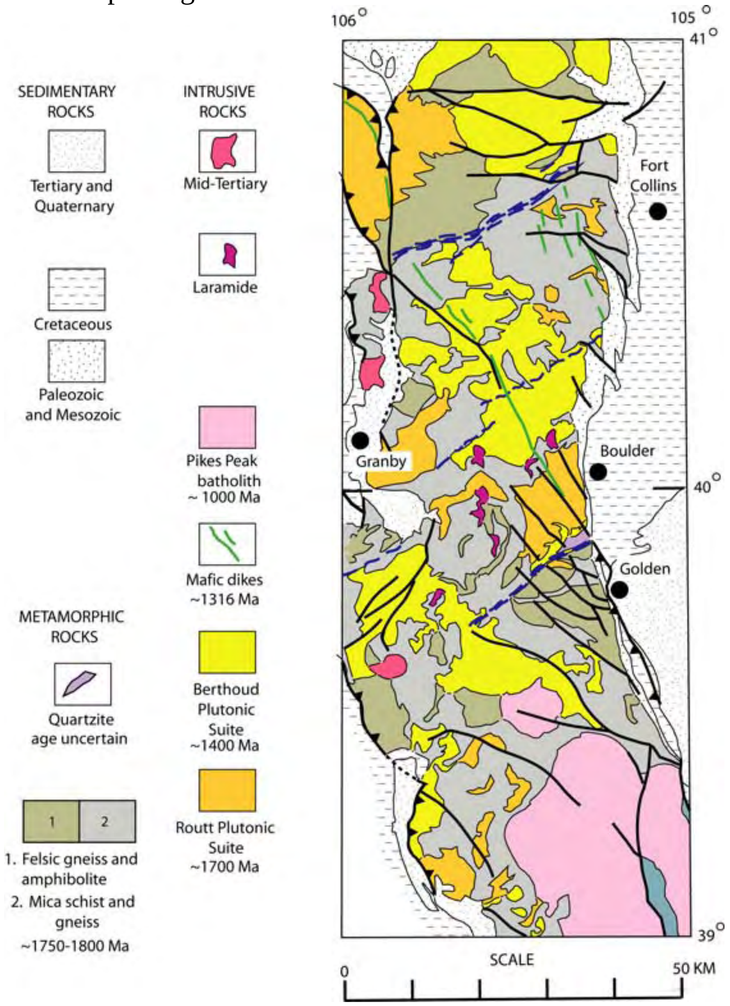

Figure 8. Generalized geologic map of the Front Range.

PRECAMBRIAN THROUGH MIOCENE DEFORMATIONS ALONG THE WEST FLANK OF THE FRONT RANGE AROUND GRANBY, COLORADO

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THE west flank of the Front Range straddles the complex boundary between the Laramide Middle Park basin and Front Range uplift. The Front Range is stripped to Proterozoic rocks whereas Middle Park retains rocks deposited after erosion of the Ancestral Front Range (Triassic Chugwater Formation through Cretaceous Pierre Shale). Early Laramide deformation created an angular unconformity overlain by Cretaceous(?)-Paleocene Middle Park Formation. Late Laramide deformation created an angular unconformity overlain by Miocene-Oligocene (previously strictly Miocene) Troublesome Formation and interlayered basalts that encroach upon the Laramide Front Range. Subsequent deformation created an angular unconformity beneath a partial cover of Quaternary deposits that include till, terrace gravel, loess, colluvium, talus, landslides, debris flows, and alluvium.

Proterozoic rocks consist of metamorphic rocks, a 1.7 b.y. Boulder Creek Granodiorite pluton, and a 1.4 b.y. Silver Plume Granite pluton. The metamorphic rocks are dominantly migmatitic biotite schist with minor granitic and granodioritic gneiss, amphibolite, and interlayered gneiss including calc-silicate gneisses, quartzite, and marble. Multiple deformation and metamorphism to upper amphibolite facies (630°–720°C, 4–6.4 kbars), about 1.7 b.y. ago, produced dominant steep dipping, northeast-striking foliation; two domains of steep-dipping, northwest-striking foliation; and minor folds with variable trends. A mineral assemblage zonation (east to west) in biotite schist shows sequential absence of cordierite, almandite, and sillimanite and microcline, with appearance and progressive increase of muscovite across the same area. The zonation is due, at least in part, to increased retrograde metamorphism westward.

Zircons similar to those in Boulder Creek Granodiorite occur in metasedimentary rocks and suggest an igneous (volcanic[?]) component in the parent material, ranging from very sparse (biotite schist) through abundant (granitic gneiss) to dominant (granodioritic gneiss). Silver Plume granite zircon morphology overlaps that of the Boulder Creek Granodiorite, necessitating statistical treatment for discrimination.

A date on a clinopyroxene latite porphyry sill (66 ± 4 m.y.; Cretaceous) supports a Cretaceous(?) age for the basal Middle Park Formation, which contains clinopyroxene latite porphyry clasts. Paleomagnetic data indicate emplacement of the sill during normal polarity near the date given above.

by H.W. Elliott from Hayden, 1869

INCISED MEANDERS, GEOMORPHIC CLUES TO NEOTECTONISM IN THE COLORADO FRONT RANGE

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DEEPLY entrenched meanders occur at one place or another along every major and moderate-sized stream that drains the Front Range. Judged from modern streams such as the South Platte River, these meanders originally formed at gradients of 5 to 10 feet per mile, yet the streams with incised meanders have clearly anomalous gradients of tens to hundreds of feet per mile. We infer that the intrenchment and steepening gradients indicate penecontemporaneous differential uplift and related erosion.

Meanders were initiated along low-gradient streams during rejuvenated erosion resulting from irregular uplift of the Front Range beginning in the middle Miocene. This rejuvenation followed development of a hilly to low-relief paleotopography when most of the irregular cover of Oligocene volcanic rocks was being removed. Early stages of rejuvenation were relatively slow, and broad valleys with hilly interfluves formed; meanders developed along the larger streams in these valleys. The broad valley-hilly interfluve stage aggregated into an irregular bench all along the east flank of the Front Range that Lee in 1923 called the Rocky Mountain peneplain. The meanders developed at the same time as middle-upper Miocene Ogallala Formation of the Great Plains was deposited to the east, and gravel deposited in some broad mountain valleys and now surviving in scattered patches may be correlative with the Ogallala.

Later phases of incised erosion progressively developed flaring-walled canyons that pass downstream into steep-walled canyons toward the mountain front. Early into canyon development, uplift expanded east into the plains, terminating deposition of the Ogallala, causing excavation along the main streams and intrenchment of the inherited meanders within the mountains.

Meanders along the Cache la Poudre and Big Thompson River systems near the north end of the Front Range developed early during uplift of a broad composite dome capped by the summit of Longs Peak, and the meanders were progressively incised during subsequent uplift. Modern gradients along meandering segments that extend as much as 25 miles into the dome exceed 100 feet per mile; the upper ends of the meandering courses have been obliterated by Pleistocene glaciers. Major uplift of the dome was thus post-Ogallala Formation in age and took place during the Pliocene and into the Pleistocene.

At the south end of the Front Range a structural platform, more than 20 miles across and surmounted by the prominent Pikes Peak protrusion, also developed during formation of the incised terrain. Ancestral South Platte River flowed south from the vicinity of Florissant to the Arkansas River near Canyon City. It was a meandering stream that occupied a low-gradient valley. It became antecedently entrenched along the flank of a rising topographic and structural ramp that offset upper Oligocene volcanic units at the west margin of the Pikes Peak platform.

The depth and character of middle and late Miocene erosional incision indicate the position and relative uplift of the various structural blocks that make up the composite Front Range. Previously proposed evolutionary models that suggest simple epeirogenic uplift of the Front Range in late Cenozoic time seem greatly oversimplified. Whether changing climates influenced geomorphic form, tectonic uplift was the dominant factor.

LARAMIDE FRONT RANGE UPLIFT AND THE GOLDEN FAULT

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THE history of the Front Range Uplift is recorded in 5,000 ft of Late Cretaceous and early Tertiary strata in the west-central Denver Basin. In the Golden-Green Mountain area, the unroofing and flank deformation of the uplift occurred as two main events during the approximate interval of 71 to 63 Ma. First, the central core of the range was uplifted out of the Cretaceous seaway and eroded to the Precambrian. Sediment was deposited in the adjacent subsiding Denver Basin as the upper Pierre Shale (marine), Fox Hills Sandstone (shoreline) and Laramie Formation (delta plain). Braided streams then deposited conglomerates of the Arapahoe Formation with chert and igneous pebbles, followed by volcanic-derived sediment and flows in the Denver Formation. Angular unconformities with up to 10° of discordance are present at the base and top of the Arapahoe Formation.

During the second main event, the above formations were deformed to nearly vertical dip on east flank of the Front Range anticline and broken by the Golden fault zone. Large boulders in the Green Mountain Conglomerate, possibly indicating maximum stream gradients, were deposited in early Paleocene.

In the type locality at Golden, Colorado, the Golden fault has been debated for more than a century. Through the use of structural, stratigraphic, and geophysical observations, the Golden fault geometry is now largely known. Of significance is the documentation that the originally defined Golden fault plane is accompanied by an east branch (imbrication) mapped as the Basin Margin fault. Between the two fault planes is a narrow zone of nearly vertical deformed strata that represents the limb of the Front Range fold.

Factors related to the geometry of the Golden fault zone are as follows:

- The Golden fault has been mapped for about 18 miles where surface exposures of the Pierre Shale in the footwall of the reverse fault are in contact with the Pierre or older rocks in the hanging wall.
- Although the dip of the fault plane is controversial, two trenches across the fault trace, 1.5 miles south of Clear Creek, indicate a west dip. Where the fault trace crosses the Clear Creek valley at Golden, a contour map on the fault plane indicates an approximate 35° W dip. One half mile west of the mountain front, the dip increases to 45° or more, where the fault plane passes beneath an 1,854-ft-deep well drilled in the Precambrian near an oil seep.
- Modeling of a 4.5-mile seismic line in Golden Gate Canyon and of gravity data suggest a 50° to 60° W dip from 2 to 3 miles west of the mountain front where Precambrian rocks are faulted over the sedimentary rocks in the footwall.
- Maximum throw along the Golden Fault is estimated to be 10,000 ft in the area between I-70 and U.S. 6, from 1 to 4 miles south of Clear Creek.
- The Basin Margin branch places strata with 50° to 70° dip on the west side of the fault trace in contact with strata dipping 5° or less on the east side. The throw of the fault is generally less than a few hundred feet.

Documentation of the geometry and zone of flank deformation in the Golden area is important to understanding the geological history of the area, the structural style of deformation, and the economic resources in the area.


by H.W. Elliott from Hayden, 1869