

Colorado Map of Potential Evaporite Dissolution and Evaporite Karst Subsidence Hazards

Map Discussion



John W. Hickenlooper, Governor
State of Colorado



Mike King, Executive Director
Department of Natural Resources



Vincent Matthews
State Geologist and Director
Colorado Geological Survey

by
Jonathan L. White

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
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FOREWORD

Large areas of Colorado are underlain by Mesozoic and/or Paleozoic evaporite deposits. The purpose of Colorado Geological Survey's (CGS) *Colorado Map of Potential Evaporite Dissolution and Evaporite Karst Subsidence Hazards* is to describe the geologic conditions where near-surface evaporite rocks occur in Colorado and the general description and hazard potential of ground subsidence that can occur from rock dissolution in evaporite terrain. CGS geologist Jonathan L. White was the principal researcher and author of this report. This publication benefited from a review by Daniel Doctor of the USGS and Peter Barkmann of the CGS. This map was created as part of CGS' ongoing mission to inform the public about potential geologic hazards in Colorado, as well as a guide for land-use planning and engineering staff in municipal and county governments whose boundaries lie within near-surface evaporite rock terrain.

This mapping project was funded by the CGS Critical Geologic Hazards Program. CGS funding comes from the Colorado Department of Natural Resources Severance Tax Operational Funds, from severance taxes paid on the production of natural gas, oil, coal, and metals in Colorado.

Vince Matthews
State Geologist and Director
Colorado Geological Survey

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MAP DISCUSSION

Introduction

Small but significant areas of Colorado are underlain by bedrock that is composed of evaporative minerals. Evaporative minerals are salts and sulfates that precipitate out of salt-concentrated surface waters. In the geologic past these minerals were deposited in shallow seas within closed or restricted basins where the seawater evaporation rate exceeds the replenishing supply. These minerals are predominantly anhydrite (CaSO_4) and halite (rock salt - NaCl) at depth, and gypsum ($\text{CaSO}_4 \cdot \text{H}_2\text{O}$) near the surface. Over geologic time, the evaporative minerals filled the sea basins and were subsequently buried beneath younger sediments. Through burial diagenesis, these deposits become evaporite bedrock. After the Rocky Mountains rose, millions of years of subsequent erosion and downcutting of rivers has now exposed some of these evaporite rocks at the surface.

From a geologic hazard standpoint, the most important characteristic of evaporite bedrock is that they dissolve in the presence of fresh water. The dissolution of evaporite rock alters ground and surface water flows, and creates subsurface voids such as caverns, open fissures, and solution pipes. Collapse of these subsurface voids manifests itself at the surface as subsidence, which can be a geologic hazard and risk for structures located thereon. Ground and surface water can be captured by the subsurface voids to create closed topographic basins and disappearing streams, subterranean rivers, and re-emergent springs. These landforms are described collectively as karst morphology. The term karst was first used in carbonate rock (limestone) areas of Slovenia where the landforms were first described and attributed to slow dissolution of rock. Evaporite karst comprises similar morphology that formed by dissolution in evaporite rock. Rock salt readily dissolves in fresh water while gypsum is up to 5 times more soluble than limestone (Brune, 1965). Dissolution of evaporite rocks may also create environmental concerns where elevated salinity, and total dissolved solid concentrations, can degrade surface and subsurface waters.

Another unique factor in evaporite rock, especially where massive deposits of rock salt occur underground, is that salt has the ability to deform plastically and “flow,” movements called salt tectonism. At times, this salt movement deforms overlying rock strata, actually piercing through them, forming what are called diapirs. Salt flowage and deformation is enhanced during times of tectonic activity (mountain building) and differential lithostatic loading caused by deposition of additional overburden, and/or subsequent erosion and relatively rapid downcutting of river valleys. The evaporite rocks are eventually exposed at the surface or at shallow depths where they are more influenced by surface weathering, exposure to fresh water, and increased solubility so that regional subsidence occurs. In surface exposures, evaporite rocks are chalky white to light gray, with streaks of yellow, tan, and gray-

black (**Figure 1**). Topography is generally subdued with low rounded hills that reflect the softness and easy erodibility of the rock. Rock strata where exposed can be highly contorted from salt-tectonic deformation, the dissolution of the actual rocksalt, and/or the volume expansion related to the near surface hydration of anhydrite to gypsum (Mallory, 1971).



Figure 1. Typical exposures of chalky, light-gray evaporite rock in Colorado. A) Evaporite (foreground) on floor of Paradox Valley. B) Eagle Evaporite hills southwest of town of Eagle. C) Diapiric uplift of Eagle Valley Evaporite emplaced against red Maroon Formation in the Roaring Fork River Valley. D) Typical contorted bedrock exposure with recumbent fold. E) Hills north of the town of Gypsum. American Gypsum Company wallboard plant is shown in right foreground. Note gypsum mine quarry (arrow) in center of photo.

As development occurs in areas of evaporite rocks, sinkholes and related ground-subsidence phenomena become potential geologic hazards, and the potential risks to structures increasingly become engineering and environmental concerns. Also, sediments derived from the erosion of

evaporite-rich rock sources in arid to semi-arid areas can be of low density, and create potentially collapsible soils that are prone to hydrocompactive settlement (White and Greenman, 2008).

In addition to localized karst features where evaporite rocks are near surface, regional collapse centers also occur in areas of Colorado. These areas have been deformed by salt tectonics and dissolution and a general lowering of the regional ground surface has occurred. From the map, it can be seen that most regional collapse centers are related to mapped near-surface evaporite bedrock and/or karst features (i.e., sinkholes or ground depressions).

Subsidence of the ground surface and sinkhole openings are a geologic hazard (**Figures 2 and 3**). Structure foundations and civil infrastructure generally cannot take the strain from slow differential movements that may occur near, or in subsidence features. Spontaneous sinkhole openings also occur in Colorado and can be dangerous and threaten public safety. Within regional collapse centers, it is presently not known whether their geologically slow, more regional, subsidence rates are a long-term risk for the typical lifetime of man-made structures.



Figure 2. Several sinkholes give Pothole Ranch its name where the Eagle Valley Evaporite is near surface along the North Fork White River valley about 4 miles east of Buford in Rio Blanco County.



Figure 3. Several sinkholes pockmark a mid-Pleistocene glacio-fluvial terrace in the Roaring Fork Valley near Carbondale in Garfield County.

About This Map and Its Uses for Land Planning

This digital map publication identifies locations of near-surface evaporite bedrock and locations of known sinkholes, depressions, and caverns attributed to dissolution of evaporite rocks in Colorado. The accompanying statewide map files are in both a 1:500,00-scale map plate in Adobe Acrobat Portable Document Format (pdf), and as Geographical Information Systems (GIS) data in ESRI's Shapefile format. The evaporite bedrock layer was created at a 1:24,000-scale and includes evaporite rocks at the surface and strata covered by relatively thin unconsolidated sediments. The mapped subsidence features include sinkholes, the centroid of larger ground depression features, open caverns and fissures in evaporite bedrock, and small lakes and springs attributed to evaporite karst. These features were digitized in ESRI ArcGIS from: 1) case histories generated for this study, 2) earlier inventories by Mock (2002) and White (2002), 3) available CGS and USGS geologic mapping in evaporite terrain, and 4) photo reconnaissance of 2006 and stereo 2009 National Agriculture Imagery Program (NAIP) 1-meter, color imagery. Most of the features selected from photo reconnaissance have not been field checked. Attribute fields in the GIS digital data includes the specific citation for each karst feature on the map.

This map is meant as a guide for landowners, planners, government land-use regulators, and the geotechnical and civil engineering community. Its limitations relate to the scale at which the mapping was conducted, geologic uncertainty, and unknown variability of surficial-soil thickness. The map should not be used to assign risk for a particular area and is not a substitute for professionally prepared, site-specific geologic hazard studies. Where new land-use proposals occur within or near the map boundaries, site-specific geologic and geotechnical studies should specifically address the evaporite karst hazard potential, as well as the overall condition of shallow or near-surface bedrock for adequate bearing capacities.

Evaporite Bedrock

In Colorado, potential land-use problems with karst environments are almost entirely associated with evaporite rocks instead of carbonate rocks. The climate of Colorado is predominantly semi-arid, so carbonate rocks such as limestone and dolomite are generally more resistant and form high ridges and cliffs, even if they may be karstic. Evaporite rocks weather more easily and generally become the topographic low-lying areas and valley bottoms. Those areas had available surface water or could be irrigated and were historically homesteaded, and so are now private property and available for future development, in contrast to the high areas commonly underlain by carbonates.

The depositional conditions for evaporite bedrock do not exist in present-day Colorado. However, 300 to 150 million years ago, much of Colorado was near sea level and restrictive sea basins in desert conditions occurred during the Pennsylvanian, Permian, Triassic, and Jurassic Periods. Colorado's evaporite minerals were deposited during the cyclic evaporation of shallow seas, near-shore desert estuaries and sabkas, and dry terrestrial ephemeral saline lake environments that existed in Colorado at various times in those geologic periods. As the water evaporates, the remaining solution became hyperconcentrated with salts and sulfates. The minerals precipitate out of solution and slowly accumulate, creating thick deposits within structural or depositional basins. Depending on the paleoenvironment, thinly interbedded fine-grained sandstone, mudstone, and black shales are associated with the evaporite beds.

In Colorado, there are four general areas where surface bedrock consists of evaporite-bearing formations and where karst landforms have developed: 1) west-central Colorado where the Pennsylvanian-Permian Eagle Valley Evaporite is exposed around the Colorado, Eagle, Roaring Fork, and White Rivers; 2) breached anticlinal valleys in the Salt Anticline Region of southwest Colorado where the Pennsylvanian Paradox evaporite member of the Hermosa Formation is exposed; 3) areas of central Colorado in South Park and along the Arkansas River valley between Coaldale and Salida where the evaporite facies of the Pennsylvanian Minturn Formation is present; and (4) the strike valley of the

Permo-Triassic Lykins Formation along the Front Range hogback, where thick gypsum beds up to 50 feet may occur. There are other minor areas where thin, discontinuous gypsum beds are exposed, mostly in the Jurassic Morrison and Ralston Creek Formations, but karst phenomena are not generally present other than minor vugs and small dissolution fissures. Gypsum has been historically mined in many of these areas (Withington, 1968), which are shown as small mine symbols on the map. Large-scale mining for gypsum continues today. Near the town of Gypsum, the American Gypsum Company mines gypsum for use in wallboard products that are produced in their Gypsum facility (Figure 1a). At its peak, over 500,000 tons of gypsum per year was quarried out of the Eagle Valley Evaporite (Carroll and others, 2001).

Engineering concerns with evaporite karst subsidence

Where evaporite is exposed at the surface or underlies unconsolidated surficial deposits, karst features occur and there is potential risk that other dissolution voids, currently hidden, could manifest themselves at the surface in the future. Dissolution of evaporite rock creates subsurface voids, caverns, pipes, fissures, dissolution and roof-fall breccia zones. Loosened chimney rubble is created as voids propagate upwards through surficial units to the surface. Caverns, open fissures, ground depressions, and sinkholes may occur at the surface; all of which can be of concern for development in an area of interest. The illustration in **Figure 4** represents typical types of ground openings that can result.

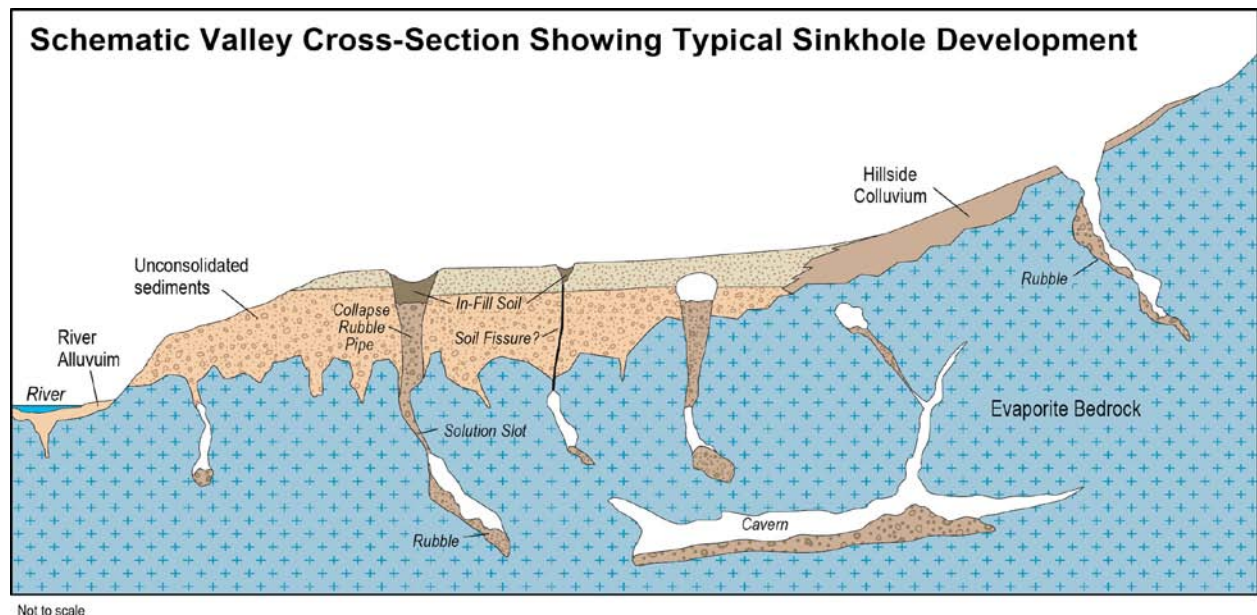


Figure 4. Illustration of typical karst and stages of sinkhole development. Sinkholes form by the upward progression of cavern roof collapse that reaches the surface. Small sinkholes can also occur by piping of fine grained sediments into solution slots.

While the subsidence hazard is a potential within the evaporite mapped area, the risk is probably greater in those areas with higher sinkhole densities. Spontaneous collapse and openings of subsurface voids can be dangerous and life threatening. Fortunately, such occurrences are relatively rare. They do occur, though, and not only in high-sinkhole density areas. In October 1999, a sinkhole opened on the shoulder of Highway 34 west of Loveland within the Lykins Formation in Larimer County. Others have recently opened in the Larimer County Red Mountain Open Space near Table Mountain (**Figure 5**) where thick gypsum beds (Blaine Gypsum) are present in the Lykins Formation redbeds. In 2005, a four-generation ranching family in the Paradox Valley of Montrose County had to rescue a calf that had fallen through a ground opening into a gypsum cavern (**Figure 6**). Such a ground condition would have been considered much more serious if a small child had disappeared in a similar hole.



Figure 5. One of many sinkholes in the Larimer County Red Mountain Open Space where the Lykins Formation contains thick beds of gypsum. Table Mountain is shown in background. View is to the southwest.

The Roaring Fork River valley in Garfield County has seen the most recent sinkhole activity where the underlying bedrock is the Eagle Valley Evaporite. This area between Aspen and Glenwood Springs has seen a marked change in land uses from ranching to residential. Voids have been uncovered during utility excavation (**Figure 7**) in the late 1990s where there was no sign of subsidence at the surface. In most cases, these types of openings discovered during residential development are quietly backfilled without further investigation. In 2003, two spontaneous sinkholes opened in the valley. A 25-foot wide and 20-foot deep sinkhole opened in February within the soccer field at the Colorado Mountain College Roaring Fork Campus (**Figure 8**). This area lies on collapse debris of the greater Carbondale Collapse Center, which will be discussed later in this report. After it was backfilled, the sinkhole reopened and further enlarged in 2004. Another sinkhole opened in August 2003 along the newly constructed



Figure 6. Recovery of a calf in 2005 that fell into a ground opening in a gypsum cave in the Paradox Valley. Photos courtesy of the Swain family.

Midland Avenue bypass near a large retail development under construction in Glenwood Springs (**Figure 9**). In the Roaring Fork River valley, a large sinkhole damaged the golf course facilities at the Ironbridge Development in early 2005 (**Figure 10**). In a nearby field in one of the few working ranches on the valley floor, another sinkhole opened in the summer of 2008. Even without spontaneous openings of sinkholes, differential-settlement subsidence can occur by removal of fine-grained soils via piping into subsurface voids or fissures. The resulting differential stress and strain to rigid structures can cause damage to facilities that are unknowingly constructed over or near ground depressions, subsidence troughs, or near-surface but unknown underground voids. There are also a few small gypsum cave openings in the Roaring Fork River valley that have been investigated by local caving societies (Davis, 1999; Medville, written commun.).

Avoidance of known subsidence features is the preferred mitigation alternative, but this is not always possible. Many areas having karst and potential sinkhole and subsidence



Figure 7. Subsurface void encountered during excavation for utilities in the Roaring Fork Valley. Photo courtesy of Steve Pawlak (HP Geotech).



Figure 8. West view of Colorado Mountain College 2003 sinkhole showing proximity to Roaring Fork Campus buildings. Sunlight Ski Area is shown by black arrow in left background. Roaring Fork river valley is in left middle background below ski area and first row of ridges. Inset photo of sinkhole wall exposing fine-grained loess. CMC maintenance staff is using road-pavement waste as fill.

risks lie within areas of Colorado experiencing heavy development pressure. Because of the high exploratory cost, most home locations have not had investigations to determine the condition of the evaporite rock below the surficial deposits. The typical geotechnical drilling method is by auger, either solid or hollow flight, which cannot easily advance through bouldery outwash gravels that typically terrace most valley bottoms of rivers that flow from the mountains. Wireline coring, though much more costly, and not typically done for residential investigations; can advance through these alluvial deposits and provide cores of the evaporite rocks to better assess their condition, rock type, and whether dissolution voids exist.

Many older sinkholes have been covered with recent soil in-filling, or historically filled and forgotten, and are now completely concealed at the surface. Near-surface voids that have not broken through to the surface would also be similarly concealed. Subsurface inspections, either by investigative trenching, a series of investigative borings, or observations made during overlot grading or utility installation, can ascertain whether filled sinkholes, near-surface voids, or subsidence depressions exist within a development area. Low-altitude stereo and oblique aerial photography, eyewitness reports,



Figure 9. Sinkhole opening in 2003 along new bypass of Midland Avenue in West Glenwood Springs. View is to the east towards downtown Glenwood Springs and Lookout Mountain. Chalky white slopes exposed along valley wall is the Eagle Valley Evaporite. Photo courtesy of Larry Thompson, City of Glenwood Springs.



Figure 10. Large sinkhole opened in 2005 at golf course club grounds at Ironbridge Development. Two golf carts inside the structure were lost down the throat of the sinkhole. View is to the northwest, down the Roaring Fork River valley towards Glenwood Springs. Red cliffs are the Maroon Formation. For scale, note person in white hardhat standing in the snow.

and historical records may also be helpful to identify filled sinkhole locations. At times, vegetation changes in aerial photography can delineate the boundaries of an ancient sinkhole that may now be completely infilled and not be easily noticed in the field. There are also geophysical investigation methods that may be able to detect shallow-subsurface voids and soil/rock property changes, such as ground penetration radar, electric resistivity imaging surveys, downhole tomography, magnetic surveys, and seismic surveys.

Where sinkholes, near-surface voids, or filled sinkholes are detected nearby, an experienced geotechnical firm should be retained to evaluate the hazard and risk potential for future subsidence on the property. On a number of occasions, evaporite bedrock voids have been encountered during excavation of grading and foundation footprints (Figure 7). **Figure 11** shows another such occurrence where a clay and silt-filled cavern was discovered during excavation. If this feature had not been fortunately uncovered during excavation a foundation could have been placed upon it. The thin bridge of gypsum would likely have failed over time and adverse differential settlement could result as the bridged material, upon loading and long term wetting, began to settle into the unconsolidated in-filled sediments within the cavern. In the Beaver Creek Ski Resort in central Colorado, dissolution caverns in Eagle Valley gypsum bedrock, up to 13 feet wide and up to 80 feet deep, were discovered while drilling the investigative borings for foundation designs of a condominium complex (Koechlein and Irish, 2007).



Figure 11. Residential foundation excavation in Eagle County has exposed a near-surface cavern in gypsum that is almost completely infilled with fine-grained sediment. Topsoil is at top of photo and original ground surface shown in upper right corner. Field notebook is shown for scale. Photo courtesy of Steve Pawlak (HP Geotech).

There are ground modification and structural solutions to mitigate the threat of subsidence if avoidance is not an option. Owners and developers in evaporite terrain should consult with knowledgeable geotechnical and structural engineering firms and ground modification specialty contractors. At the Beaver Creek condominiums mentioned above, deep drilled-pier foundations were designed. Pier holes were drilled out to below the subsurface voids. The caverns were then cased off and isolated prior to pouring the concrete into the drill shaft. (Koechlein and Irish, 2007). In other circumstances in Colorado, subsurface grouting techniques are used to plug or seal the throat of active sinkholes to prevent the continued downward movement of soil into the evaporite bedrock voids. Another option for small sinkholes where the bedrock can be exposed is the reverse-graded filter approach. The throat is exposed to bedrock and larger boulders and rocks are placed at the bottom. Followed with cobble, then gravel, then sand. Reinforcement and filter geotextiles can also be used to construct structural fill mats to bridge small depressions and prevent piping of fine-grained soils.

There can be other geotechnical engineering concerns with evaporite rock terrain. Deformation and contortion of the bedrock can result in folded, steeply dipping bedrock zones (See **Figure 12** and 1(d)). In such circumstance, engineering properties of the rock can significantly change laterally and typical subsurface borings for foundation design may not necessarily encounter the weakest zones with the lowest load-bearing capacity.



Figure 12. Diapiric fold in Eagle Valley Evaporite bedrock has caused steeply dipping bedrock at the ground surface near Eagle, Colorado.

Drainage issues and proper water management are important in evaporite karst terrain. Because the bedrock and gypsiferous soils derived from them are soluble, changed hydrologic conditions and increases in fresh water may destabilize certain subsidence areas, rejuvenate older sinkhole locations, or cause new dissolution to occur. Several re-activations of sinkholes have been the result of proximity to irrigation or irrigation ditches. Another important factor with water management is that erosion of evaporite rock in the semi-arid climates of Colorado forms deposits of low-density soils. Alluvial fan and colluvial sheetwash deposits from soft evaporite rocks have been shown to be highly susceptible to hydrocompaction and are prone to collapse-type settlement when they get wetted. More detailed discussion on gypsiferous soils and hydrocompactive soils, as well as drainage and water management concepts are in White and Greenman (2008).

Environmental concerns of evaporite karst

In Colorado, the major environmental concerns of evaporite karst, and evaporite rocks in general, are salt loading of the rivers that pass through the evaporite terrain, and unfavorable water quality in water wells. Almost every area where evaporite rocks occur have names such as Salt Creek, Gypsum River, Alkali Creek, Salt Spring, Salt Ranch, Big Gypsum Valley, etc. Several cold and thermal springs with high total dissolved solids exist within evaporite terrain, and flow directly into rivers, contributing to salt loading (**Figure 13**). The highest point loading of the Upper Colorado River Basin is at the Yampah Hot Springs in Glenwood Springs. From this one source, 265 tons (240 metric tons) of dissolved halite and gypsum flow into the Colorado River each day (Barrett and Pearl, 1976). Using an average unit weight of 140 pounds per cubic foot, the amount of daily dissolved salts is equivalent to a 141-yd³ volume of evaporite material. That would be a new 15x16x16-foot void every day. At current concentration rates, this spring alone could account for a cubic mile of evaporite dissolved and washed down the river in 100,000 years.

Subsurface seepage of saline ground waters also can occur into alluvial aquifers that flow into adjacent river streams. Definite rises in salinity and changes in water chemistry are observed where major tributary rivers of the Upper Colorado basin pass through evaporite terrain. The most notable are the actual Colorado River (Chafin and Butler, 2002), the Roaring Fork River (Kirkham and others, 2003), the Dolores River (U.S. Bureau of Reclamation), and the White River (R. Tobin, ret. USGS, person. commun.). Saline seepage affects the water quality of the upper Colorado River basin and may preclude the completion of potable water wells in certain locations (Warner and others, 1984). The U.S. Department of Interior Bureau of Reclamation (USBR) has a Colorado River Basin Salinity Control Program (CRBSCP) that is tasked to monitor and mitigate salt introduction into the Upper Colorado River Basin. Two of their projects directly address salinity from evaporite rocks. The Paradox Valley Unit in

the Paradox Valley intercepts saline groundwater from Paradox Formation evaporite rocks from flowing into the Dolores River. The Meeker Dome Unit along the White River was a project to plug abandoned oil and gas wells that were leaking high salinity water from evaporite formations. Increases in salinity levels have also been measured in the South Platte River basin across evaporite terrain in Park County (Kimbrough, 2001) and is a big concern for Arkansas River basin water that leaves Colorado.



Figure 13. Brackish spring emerging onto South Platte River outwash plain in South Park, Park County. The spring-fed creek flows to Antero Reservoir, shown in upper right of photo.

Regional Collapse Centers

Shown on the publication map are regions of Colorado underlain by evaporite where strong evidence suggesting salt tectonics, dissolution, and subsidence has caused regional ground deformations. These locations can have active karst landforms where evaporite rocks are near surface but also show evidence of regional subsidence and geologic deformation where thick deposits of evaporite rocks are buried by hundreds of feet of younger rock strata. The modern subsidence rate of regional evaporite collapse areas and the hazard of related ground movements are presently unknown. The risk of damage is also unknown, but likely very low for current or planned developments for the design life of normal residential structures. Movement over geologic time, ranging from hundreds to thousands of years, could still be significant. For the planning and construction of long-term or critical facilities, more in-depth study of the collapse regions should be considered.

If one were to look at paleogeographic maps of the western US from 320 million years ago, there were shallow sea basins on all sides of two major mountain ranges in Colorado: the Ancestral Uncompahgre Mountains and Ancestral Front Range. Thick beds of evaporite minerals were deposited in the Pennsylvanian-age (approximately 315 million years ago) Central Colorado Trough (Eagle Basin) and the Paradox Basin in the four-corners region of southeast Colorado. East of these ancient mountains in present-day eastern Colorado and Western Kansas were shallow seas within another Permian to Pennsylvanian (315 to 280 million years ago) basin called the Hugoton Embayment. Beneath the plains of Colorado and Kansas are evaporite rocks at considerable depth, from 1,000 to 5,000 feet. Salt tectonics in the Paradox Basin west of the Ancestral Uncompahgre Mountains created the salt anticline valleys in southwest Colorado (Cater, 1970), and have been identified and described in detail in Kirkham and others (2002) forming regional collapse centers in west-central Colorado. Regional collapse from dissolution also occurs near Buford in Rio Blanco County along the North Fork White River (Trask, 1956; White, 2003) and is suspected in South Park (Park County) based on recent CGS geologic mapping (Kirkham and other, 2007; Kirkham and others, in prep.).

There are also strong indications that ground subsidence from dissolution of evaporite at depth also extends from a mapped dissolution front in southwest Kansas at the boundary with Prowers County in southeast Colorado. While this is not specifically an area of surface exposure of evaporite bedrock, it is believed that the evidence of dissolution was compelling enough to include data on the map and discuss further in this report.

West-central Colorado Collapse Centers

The Pennsylvanian Eagle Basin of central Colorado has been tectonically deformed by later mountain building (called the Laramide Orogeny) that formed the present-day Southern Rocky Mountains of Colorado. Eagle Valley Evaporite rocks occur around the circumference of the Laramide White River Uplift. The map shows thick evaporite rocks exposed in west-central Colorado in the areas of the Upper White River valley east of Meeker, and the Roaring Fork River valley, the Eagle River Valley, and their confluences with the Colorado River. Regional collapse is evident in each of these areas.

Regional collapse centers were identified by a number of lines of evidence. In the vicinity of the Eagle and Roaring Fork River Valleys, research papers compiled in Kirkham and Scott (2002) mention several in their study of the Carbondale and Eagle Collapsible Centers: 1) diapiric uplift (See figure 1(c)); 2) salt bedrock at shallow depths verified by oil and gas exploration well logs; 3) age-dating of subsided, faulted, and tilted volcanic flows; 4) salt loading in hot springs; 5) downwarping of strata and structural sags; and 6) large landslides and collapse debris that imply a more vertical component of ground movement versus lateral movement. The evidence of subsidence is best preserved in a regional topographic low at the Carbondale Collapse Center where the land surface has been calculated to have been lowered 4,000 feet by underground dissolution and lateral flowage of salt (Kirkham and others,

2003). Between Glenwood Springs and Carbondale the Roaring Fork River valley approximates the trend of the Cattle Creek Anticline. This river-centered, salt-tectonic fold was formed in response to evaporite diapirism as the salt plastically flowed toward the incised valley where lithostatic overburden pressures were lower. Pleistocene-aged terraces in the valley, which were originally deposited as flat surfaces along the longitudinal profile of the river, have been tilted away from the river because of continued uplift of the Cattle Creek Anticline (**Figure 14**). Dissolution of evaporite rocks continues and sinkholes continue to form, so deformation rates related to regional collapse may present undefined long-term risk for development at structural margins where deformation may be highest. This includes areas located near Quaternary and Neogene faults and hinge zones of structural basins, flexural edges, near or within depressions and sinkholes, and areas underlain by collapse debris (Kirkham and others, 2003). Those structural features are accurately shown on 1:24,000-scale geologic maps that were completed of the Roaring Fork River valley between Glenwood Springs and Basalt. Those geologic maps were produced and available from the Colorado Geological Survey (CGS). For more information on the Carbondale and Eagle Collapse Centers, see GSA Special Paper No. 266, *Late Cenozoic Evaporite Tectonism and Volcanism in West-central Colorado*, edited by Kirkham and others (2002).

Similar collapse morphology can be seen near Buford in Rio Blanco County where the Eagle Valley Evaporite is exposed on the north margin of the White River Uplift. River-centered anticlines occur at actively upwelling evaporite karst areas such as Pothole Valley, named for the many sinkholes that occur in the valley (figure 2). Trask (1956) mentioned examples of contorted bedrock and mapped structural sags and folds in his geologic mapping of the Buford area. The review of Trask's work, and further photoreconnaissance review and mapping of sinkholes and subsidence features, with the understanding gained in Kirkham and others (2002), provides compelling evidence of collapse there. Furthermore, water chemistry reflecting sulfate and sodium chloride loading of the North Fork White River through evaporite terrain compared to the South Fork has also been documented (Bob Tobin, pers. communication). There is other evidence of deep subsurface evaporite in the immediate area. Oil and Gas exploration wells have encountered thick deposits of salt nearby called the Meeker Halite Basin (Dodge and Bartleson, 1986). Near that basin at the Meeker Dome structure, briny waters migrated from deep formations and leaked from deep oil and gas exploration wells into the White River. These wells were capped by the USBR CRBSCP at their Meeker Dome Unit (U.S. Bureau of Reclamation).

Another area with evaporite bedrock near surface that are also suspected of exhibiting regional collapse are in the southeastern portion of South Park near Antero Reservoir (Kirkham, pers. communication). Recent CGS geologic mapping of several quadrangles in the area revealed salt springs, sinkholes, and warping of surface rock units where the evaporite facies of the Minturn Formation is at or near surface (Kirkham and others, 2007; Kirkham and others, in prep.)



Figure 14. Diapiric uplift of the Cattle Creek Anticline (white dashed line) has prominently tilted a middle-Pleistocene terrace (~620,000 years before present) in the Roaring Fork River valley (shown by red arrow). The late-Pleistocene (~16,000 years before present) lower terrace on the east side (right side) of the river also has a perceptible tilt but the angle is flatter (shown by black dotted line). Red rocks on the right (northeast limb of the anticline) is the Maroon Formation, which tilts away from the axis much more steeply than the terrace surface. Photo view is northwest along the trend of the anticline axis towards the confluence with the Colorado River at Glenwood Springs. The White River Uplift is in the background. Photo by R. Kirkham.

Salt Anticline Valleys of the Paradox Basin

Paradox basin evaporite deformation and diapiric upwelling is well documented in the formation of the parallel valleys of the Salt Anticline Region (See figure 1(a)). Cater (1970) mapped the breached anticlines in this arid area and discussed the valley-centered salt diapiric movements there, as well as mapping the exposed evaporite on the valley floors and describing sinkholes that occur there. Figure 6 shows the potential hazards that ground openings pose to the ranching community of Paradox. The Paradox Valley Unit of the USBR CRBSCP is tasked with preventing high-salinity, ground water from entering the Dolores River.

Possible Eastern Plains Subsidence

Permian-age salt and anhydrite beds occur at 3,000- to 6,000-foot depths in northeastern Colorado. Late Cretaceous to early Tertiary dissolution and collapse has deformed the overlying Niobrara Chalk formation and formed structural traps for oil and gas that have been actively explored and developed

(Oldham, 1996; Watney, 2005). In southeastern Colorado, Permian-age evaporite strata are thinner, but shallower, approximately 1,300 feet deep near the Arkansas River valley. Dissolution of evaporite rocks and surface subsidence has been well documented in southwestern Kansas, extending to the Colorado border, and large sinkholes have opened along the Colorado/Kansas border. There are also subsidence features in Prowers and Kiowa Counties in southeastern Colorado and strong evidence to suggest that dissolution of these Permian evaporite rocks also is the cause of this subsidence.

Poorly understood at this time, there are many natural ground depressions with tens of feet of topographic closure in eastern Colorado. Many of these subsidence features have been used as irrigation storage reservoirs so the original morphology is somewhat obscured. Many in Prowers and Kiowa counties of southeast Colorado appear to be structurally controlled along a northwest to southeast trend with depression depths that can exceed 70 feet of topographic closure. They do not exhibit the morphology that is typical of shallow wind-scour depressions in eolian deposits, or the typically shallow playas of the Great Plains, and are too geographically restricted and low in latitude to be considered thermokarstic in origin. Their shapes can be irregular and considerably deeper, and also much older; several have developed extensive drainage networks that radiate from them. Several in close proximity, known as the Great Plains Reservoirs (approximately 17 miles north of Lamar) are used as agriculture reservoirs. These natural ground-depression locations are shown as points on the statewide map called *anomalous eastern plains ground depressions*.

The reason for inclusion of these points and collapse perimeter on this map is that this northwest to southeast trend of depression is bounded by late Tertiary and Quaternary faulting and downwarping of Cretaceous strata shown in the Prowers County, Colorado, geologic map by Voegeli and Hershey (1965). This bedrock deformation in Prowers County extends southeastward to become the Bear Creek fault zone in Hamilton County, Kansas (Johnson 2003a, 2003b). This fault is recognized as an evaporite dissolution subsidence zone in Kansas (McLaughlin, 1943; Gutentag and others, 1984; Young and others, 2000) and can be best visually shown in a 2009 figure of the subsurface depth to Cretaceous bedrock prepared by the Kansas Department of Agriculture (2009) that is reproduced in **Figure 15**.

Voegeli and Hershey (1965) did not specifically address the cause of their mapped ground depression, deformation of surface bedrock, and the tectonics of “post-Cretaceous” faults in Prowers County, Colorado. Fortunately, the mapping is of suitable scale and detail to suggest evaporite subsidence as: 1) the cause of deformation in the Cretaceous bedrock, and 2) having influenced the bounding faults along the subsidence trend that is a continuation of the trend described in Kansas (Figure 15). The river profile sections (Plate 4 in Voegeli and Hershey, 1965) within this deformation zone also show highly irregular karst-type bedrock surfaces on the valley floor below the alluvium, atypical for a mature river valley profile. Also, their valley profiles show a rapid thickening of valley fill

deposits where the subsidence zone crosses the Arkansas River valley. Over 250 feet of Quaternary and possibly Tertiary sediments were measured from water well logs.

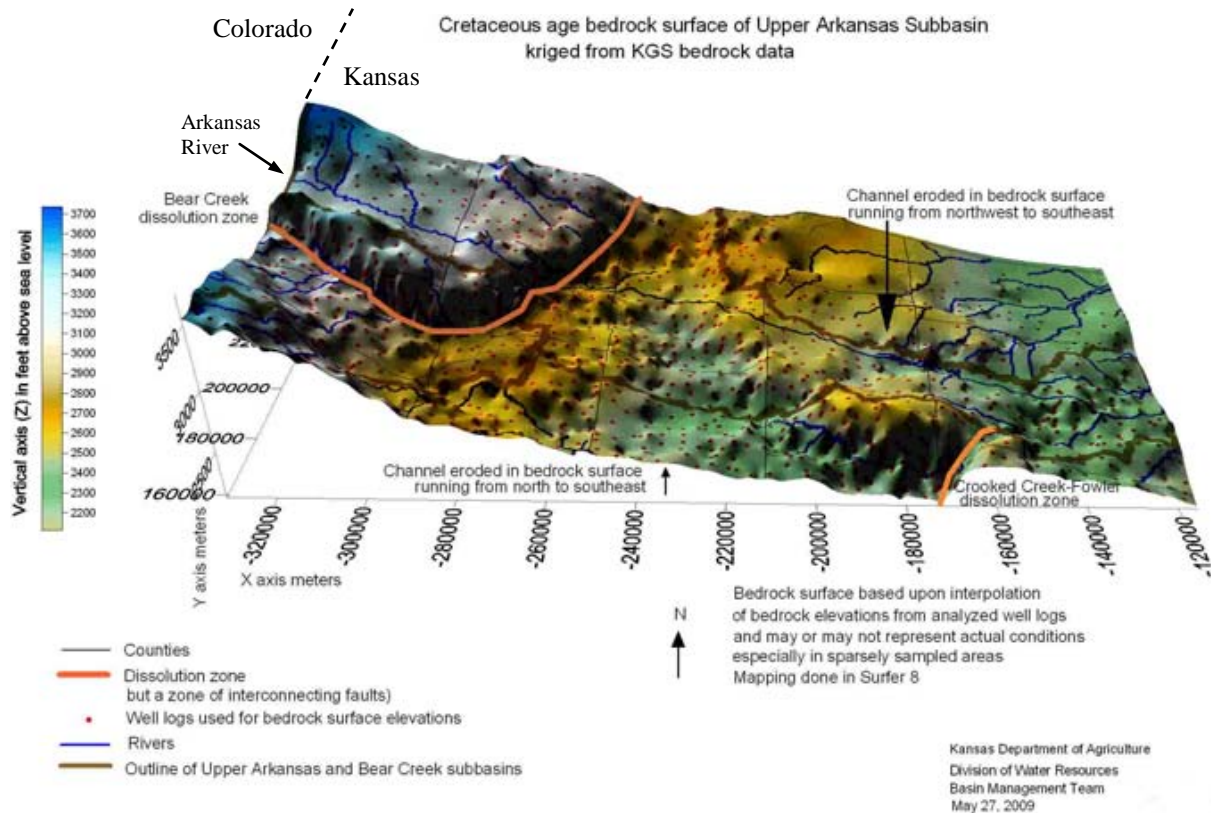


Figure 15. Block diagram of bedrock surface by the Kansas Department of Agriculture, Division of Water Resources that shows the Bear Creek dissolution zone where it crosses into Colorado near the Arkansas River.

At this general southeast to northwest trend there are also documented ancient sinkholes, structural deformation, and surface subsidence features in eastern Colorado and west Kansas near the Colorado border. In Kansas, a historic sinkhole opened in Hamilton County south of Coolidge (Bass, 1931). It occurred along the Bear Creek fault trend only 1½ miles from the Colorado border. Based on the stratigraphy exposed along the walls of the fresh sinkhole, Landes (1931) attributes the Hamilton County sinkhole to dissolution of pre-Dakota Sandstone strata within the Permian salt and gypsum some 1000 feet below the ground surface. This depth to evaporite bedrock is similar to the subsurface conditions where Wink Sink and the Borger Sinks collapsed in Texas (Johnson and others, 2003). The Wink sinkhole was attributed to dissolution of evaporite, accelerated by oil field activity, and successive roof failure in the overlying strata, thereby producing a collapse chimney filled with brecciated rock that migrated upward to the surface. There is a Colorado report in the literature about a fossil sinkhole site where remnants of Niobrara Formation have subsided into the underlying Carlile Shale that is

exposed at the surface (Dane and Pierce, 1934). This sinkhole, 13 miles northeast of Lamar, is geologically old, because the overlying Niobrara Formation has been subsequently stripped away by erosion.

The Cretaceous limestone of the area, such as the Niobrara and Greenhorn, are thinly bedded, very shaly, and contain bentonite beds (Voegeli and Hershey, 1965). They are relatively impervious and don't easily produce water in wells. Few springs exist, and so the units are not amenable to the formation of caverns. There have been no reports of significant voids or caverns in either the Niobrara Formation (Smoky Hill or Fort Hays) or the Greenhorn Limestone in southeast Colorado. Another line of evidence that the subsidence source occurs below the Cretaceous rocks can be seen in regional geologic maps. Structural contours of the Lower Cretaceous Dakota Sandstone in the 1:250,000-scale geologic map of the area (Sharps, 1976 and Scott, 1968) show localized deflections and depressional lows along this same northwestern trend.

The area of the eastern plains of Colorado along the northwest to southeast structural trend into Kansas is shown on this map, as is the Bear Creek fault as mapped by Voegeli and Hershey (1965). While sinkholes attributed to evaporite dissolution have occurred in Kansas very near the Colorado border, and in Oklahoma and Texas, this author could find no record of sinkholes historically opening in eastern Colorado. From an environmental viewpoint, the abovementioned evidence also presents a compelling possibility that salinity levels in the Arkansas River in southeast Colorado may, in part, be from natural causes where the river crosses this suspected dissolution and subsidence zone before entering Kansas.

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