Structural Settings and Hypogenic Flow Paths for Three Colorado Caves

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Abstract

Colorado, a state with diverse geology and high topographic relief, contains several significant hypogene cave systems. Three are described here: the Orient Mine Cave System, Cave of the Winds, and Glenwood Caverns. All are located near present thermal springs, which help to determine the chemistry of the cave-forming water. The Orient Mine Caves were encountered during mining operations to extract limonite ore for the manufacture of steel. The ore follows the bedding, but hypogene cave galleries also cut across bedding and extend upward as domes. The galleries were formed by warm water rising along the San Luis fault and mixing with cool recharge from nearby mountains. Cave of the Winds follows the plunge of an anticline and probably formed when water with high CO_2 rose along faults and mixed with shallow meteoric water. At Glenwood Caverns, carbonic acid in rising thermal water is responsible for most speleogenetic dissolution, but some dry parts of the cave have a sulfuric acid overprint.

Keywords

Geologic structure • Thermal springs • CO_2 • Limonite • H_2S

1 Introduction

This paper concerns three of the many hypogenic caves of Colorado, which illustrate the influence of structure and stratigraphy on cave development: the Orient Mine Caves, Cave of the Winds, and Glenwood Caverns (Fig. 1). These show contrasting examples of deep flow, each located no more than 1.6 km (1 mile) from currently active thermal spring systems that are possible analogs for the water that formed the caves. The Orient Mine Caves are located on the west side of the Sangre de Cristo Range of the Rocky Mountains, adjacent to the San Luis Valley. Cave of the Winds is located near the Pikes Pike massif near the eastern margin of the Front Range. Glenwood Caverns is located on Colorado's Western Slope, near the border between the Rocky Mountains and the Colorado Plateau. They are all located in Mississippian (lower Carboniferous) and older carbonates (Fig. 2).

2 Caves of the Orient Mine

The Orient Mine and associated caves are located 15 km southeast of the town of Villa Grove in Saguache County. The mine is on the western edge of the Sangre de Cristo Mountains, in Mississippian Leadville Limestone, near the San Luis fault, which is the interface between the Sangre de Cristo Mountains and the San Luis Valley graben (Fig. 3). The limestone dips steeply to the east. Geologists first noted

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A. Klimchouk et al. (eds.), *Hypogene Karst Regions and Caves of the World*,
Cave and Karst Systems of the World, DOI 10.1007/978-3-319-53348-3_36

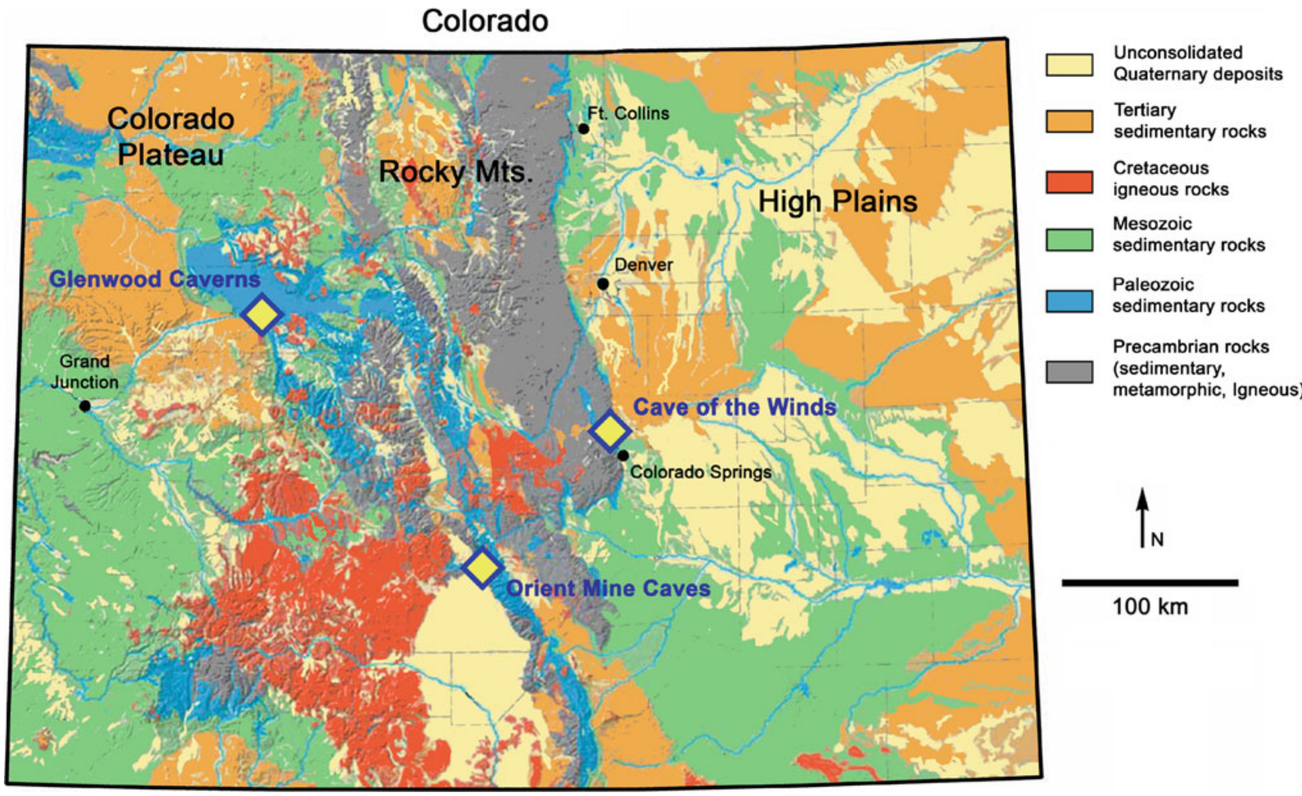

Fig. 1 Map of Colorado showing locations of caves discussed in this paper and their relationship to geologic provinces. Geologic map from the Colorado Geological Survey

limonite deposits in the area after the Hayden expedition of 1873. Mining began in 1880 and continued through 1932, supplying approximately 1,540,000 metric ton of limonite ore (Balleweg 1990) used for steel manufacturing. The caves were encountered during the mining operations.

There are three periods of solutional development represented, the first being Paleozoic. Unconformities in the Devonian Dyer Dolomite and the overlying Mississippian Leadville Limestone contain prominent paleokarst features including solution breccias and filled caves (Fig. 4). Maslyn (1976) documented similar features at the same stratigraphic levels in the Leadville in the area of Aspen, where they host base metal silver deposits. Paleozoic dissolution near the present Orient Mine produced a series of separate chambers up to 365 m long and 23 m wide that were later filled with sediment and breccia from the overlying Pennsylvanian Molas formation. Post-depositional thermal events altered the cave sediments to limonite, the principal ore in the Orient Mine. These ore bodies are generally parallel to the bedding and in places extend upward as domes (Fig. 4). The steep dip of the rock is apparent in the figure as well as the great width (55 m) of the excavated cave passage.

Open solution caves encountered during mining operations were described by Stone (1934), Dover (1981), Davis (1986), Fish (1986), and Balleweg (1990). Stone (1934) noted numerous solutional cavities in the Chaffee and Leadville formations that range in size up to caves 18–20 m wide that can be followed for “hundreds of feet.” Some caves terminate in the limonite-mineralized paleokarst fill (Fig. 5). Aardvark Caverns is the largest single cave within the mine, with an estimated passage length of 370–460 m and passage heights up to 30 m (Balleweg 1990; Dover 1981). Svetz (1984) further described the cave, noting “In one portion of the cave, there was a large amount of gypsum crystals covering the walls. Most of them were brown, having been covered by the dust from the mining operation. We finished taking pictures and went through the rest of the cave which consisted mostly of one long, large passageway with small offshoots.” Miners used the caves as access routes between mine levels and paleokarst-hosted limonite ore bodies.

Unlike the limonite-filled chambers, these caves are horizontal and crosscut the bedding. They, therefore, post-date Paleozoic anticlinal arching and the Miocene San

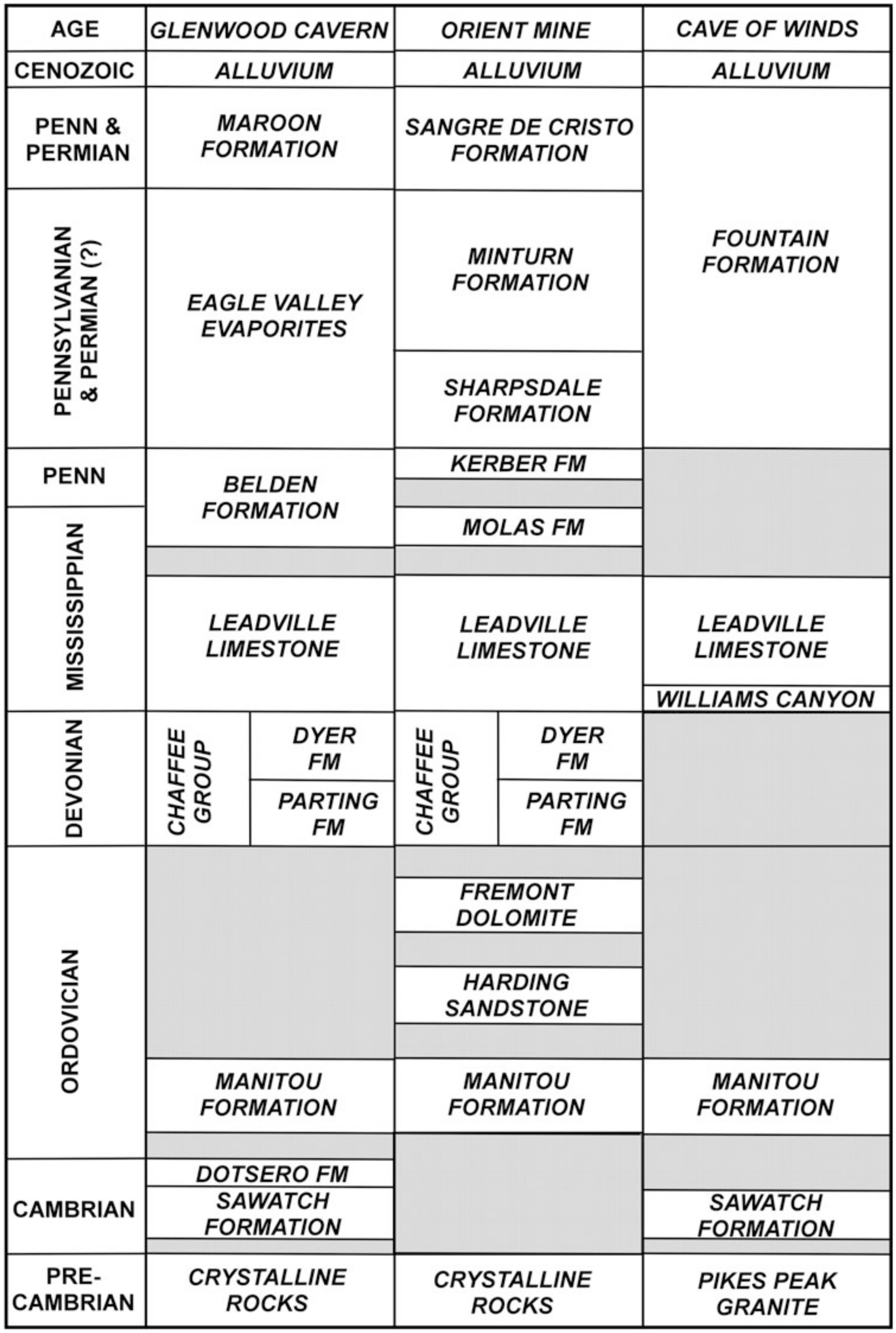

Fig. 2 Correlation of Paleozoic strata of Colorado. See text for the stratigraphic position of the caves. Ordovician, Devonian, and Mississippian strata are mainly carbonates and contain most of the caves in Colorado. Many unconformities along carbonate strata contain paleokarst features. The top of the Mississippian section is a pronounced unconformity in Colorado, as well as throughout much of the western United States. Strata overlying the unconformity are mostly arkoses, except in western Colorado where a thick section of Pennsylvanian evaporites and shales lies between the carbonates and the younger Pennsylvanian and Permian strata. (See Palmer, Chap. 38 for an example in South Dakota.)

Luis Valley rifting. They apparently formed in the late Neogene when thermal water was forced upward from the San Luis Basin along the San Luis fault, converging with cool surface waters flowing down-gradient from the adjacent Sangre de Cristo Mountains. Dissolution took place where the two waters mixed, as suggested by present evidence for groundwater mixing at the Valley View Hot Springs ~1.5 km south of the mine (see Table 1). The springs yield thermal water of 35–36 °C in a structural setting similar to the Orient Mine Caves and are considered to be a modern

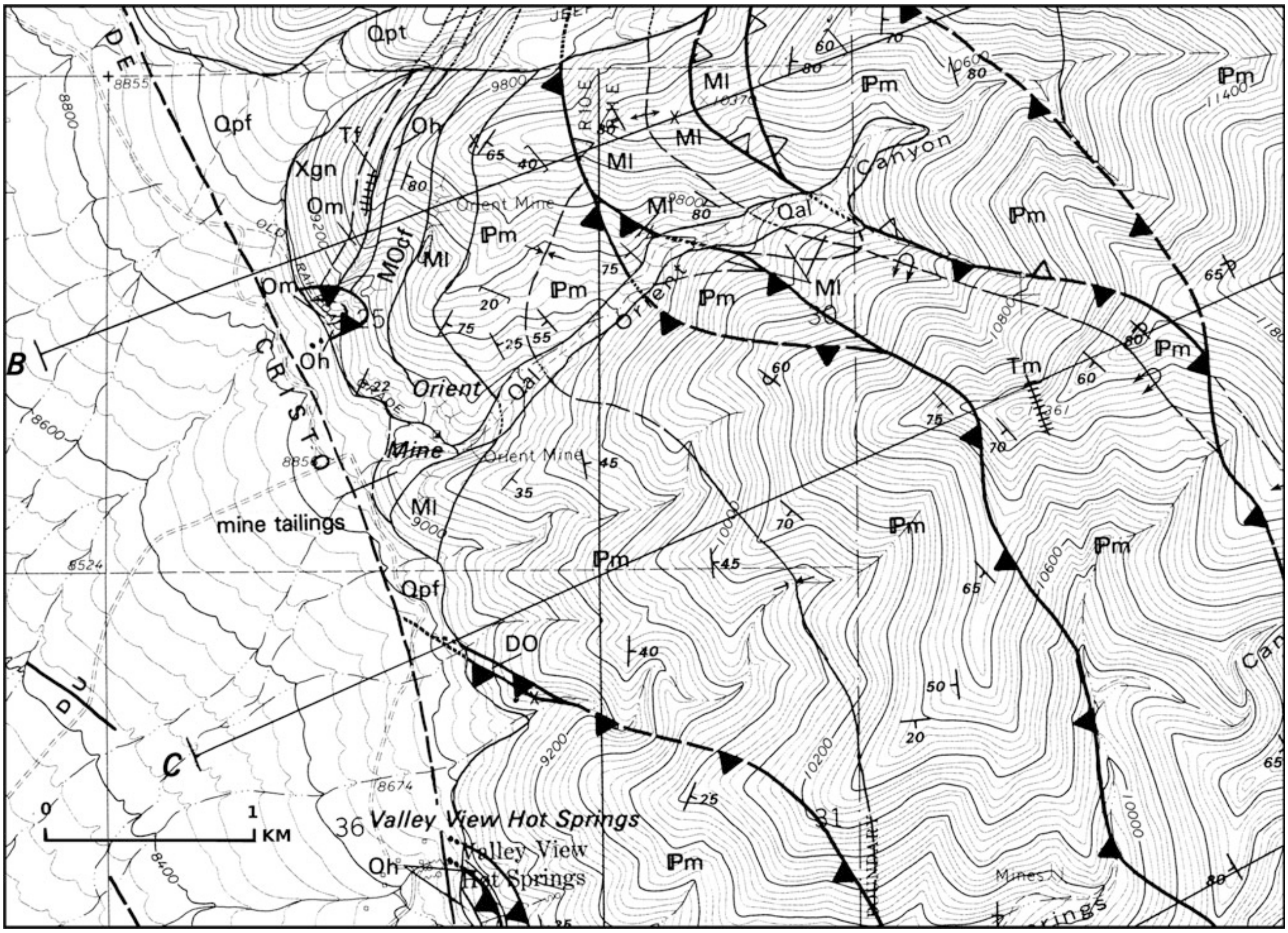

Fig. 3 Geologic map of the Orient Mine area from Lindsey and Soulliere (1987) showing its relation to the San Luis fault zone. The mine is located near the center of the map. Valley View Hot Springs is located at the bottom-center of the map. *Map legend* Precambrian Gneiss; *Om* Ordovician Manitou; *DO* Devonian-Ordovician undifferentiated; *Ml* Mississippian Leadville; *Pm* Pennsylvanian Minturn (including Sharpsdale); *Tm, Tf* Tertiary Intrusives; *Qaf* Quaternary Alluvial Fan; *Qal* Quaternary Alluvium

analog of the hydrologic conditions that were active during cave origin. More recently, vadose processes have modified the hypogene caves.

2.1 Stratigraphy

The oldest rock in the Sangre de Cristo Mountains is Precambrian gneiss cut by pegmatitic and mafic intrusions of Precambrian age. These rocks were exposed in the Ordovician during a major erosional event. Overlying the unconformity is a sequence of carbonate and clastic formations composed of Ordovician Manitou Dolomite, Harding Sandstone, and Fremont Dolomite. The Devonian Chaffee Group rests on the Fremont Dolomite and comprises the Parting Sandstone and the overlying Dyer Formation. Unconformably, overlying the Dyer is the Mississippian Leadville Limestone, one of the most important cave-bearing units in Colorado. Major erosion followed deposition of the Leadville and resulted in regional karstification of the Mississippian carbonate strata. Overlying the Leadville Limestone are Pennsylvanian arkoses more than 3 km thick. Arkosic strata include the Minturn Formation and the overlying Sangre de Cristo formation, which are exposed above the Orient Mine in the adjacent Sangre de Cristo Mountains (Fig. 2).

Paleokarst breccias and cave fills are present in the Dyer Formation and Leadville Limestone (Fig. 6). Limonite deposits are restricted to paleokarst in the Leadville, but hypogenic caves are present in both the Dyer and Leadville formations. The Leadville Limestone varies greatly in total thickness as a result of the karst unconformities at the top of each of the three members. The stratigraphic column of Balleweg (1990, Fig. 6) shows a total formation thickness of 73–102 m. Some of the caves filled with paleokarst sediment can be relatively large. For example, Fig. 4 shows the

Fig. 4 Downward view into a Mississippian-age paleokarst cave conduit after removal of the limonite ore filling the passage. Distance from the near cave wall to the encircled adit on the far wall is 55 m. Photo by K.J. Balleweg

Fig. 5 Paleokarst fill intersected by a hypogenic cave passage in the orient mine. Note the rounded solutional bedrock surfaces of the cave walls. Photo by K.J. Balleweg

outline of a formerly filled paleokarst cave after removal of the limonite ore. The cave is concordant with the bedding and slopes steeply downward.

Tertiary intrusive events in the area are generally minor, with the exception of the Oligocene Rio Alto Stock, 6.4 km northeast of the Orient Mine. Balleweg (1990) speculated that alteration of the paleokarst cave fill breccias to limonite ore was related to Tertiary intrusive events.

2.2 Geologic Structure

One of the major factors contributing to the occurrence of mineral springs at Valley View Hot Springs and the Orient Mine caves is the complex geologic structure of the area. During the Paleogene Laramide orogeny, Paleozoic sediments in the Sangre de Cristo Range were strongly deformed, resulting in a broad north–south trending, doubly plunging anticline with steeply dipping limbs. Remnants of this fold are present in a band that crosses the Sangre de Cristo Range and on the west side of the San Luis Valley. Thrust faults that accompanied development of the dome are present at the Orient Mine, at Valley View Hot Springs, and as north-trending features in the Pennsylvanian–Permian sedimentary section in the nearby mountains. At the Orient Mine, cavernous strata dip an average of 75° east (Fig. 4).

In the Oligocene to early Miocene, extensional faulting related to the opening of the Rio Grande rift caused the San Luis Valley to subside along large-scale normal faults. The dome that formed during Laramide compression was broken and the western part down-faulted into the San Luis Valley where it was covered with synorogenic sediments derived from the uplifts on the margins of the rift. (See Fig. 7, and Tweto 1979).

2.3 Hypogenic Flow Paths

Davis (1986) and Balleweg (1990) speculated on the origin of the Orient Mine caves. Both suggest that the water originated in the Sangre de Cristo Mountains. Although there are

Table 1 Chemistry of Mineral Hot Springs and Valley View Hot Springs (Barrett and Pearl 1976; discussion in Hinkle and Erdman 1995)

Chemical variable	Mineral Hot Springs	Valley View Hot Springs
As (μg/L)	30	1
B (μg/L)	372	30
Cd (μg/L)	0.5	1
Ca (mg/L)	58	48
Cl (mg/L)	40	1.8
F (mg/L)	4	0.4
Fe (μg/L)	60	20
Li (μg/L)	322	8
Mg (mg/L)	13	14
Mn (μg/L)	20	7
Hg (μg/L)	Not detected	Not detected
N (mg/L)	2.1	0.21
Phosphate as P (mg/L) (mg/L)	0.03	0.01
Phosphate as ortho-PO_4 (mg/L)	0.08	0.03
K (mg/L)	14	2.4
Se (μg/L)	Not detected	Not detected
SiO_2 (mg/L)	48	19
Na (mg/L)	140	3.6
So_4 (mg/L)	180	85
Zn (μg/L)	7	5
Alkalinity as $CaCO_3$ (mg/L)	283	103
Alkalinity as HCO_3 (mg/L)	345	125
Non-CO_3 hardness (mg/L)	not detected	76
Total hardness (mg/L)	200	176
Specific conductance	1014	366
Total dissolved solids (mg/L)	680	237
pH field	6.7	6.8
Discharge (L/s)	6.8	4.7
Temperature (°C)	60	34

Note Dilution of concentrations at Valley View Hot Springs as the result of mixing with water from the Sangre de Cristo Mountains

vadose features such as slot canyons, allogenic sediment, stream channels, and waterfall undercuts in the uppermost caves (Davis 1986), we believe that these are overprints resulting from recent influx of surface water, and that most of the cave passages and galleries resulted from dissolution by hypogene waters. Balleweg (1990) noted that several of the caves adjacent to the limonite zones exhibit "rounded surfaces, solution corrosion, and local caves," that appear more characteristic of phreatic dissolution (Fig. 5).

McCalpin (2013) observed that thermal water at Valley View Hot Springs likely originated in the adjacent San Luis basin and is forced to the surface by hydrostatic pressure. He also noted that at least part of the water issuing from the springs is cool, with its most likely source in the Sangre de Cristo uplands to the east. The warm and cool waters mix near Valley View Hot Springs, resulting in cooling of the hot spring water. The spring temperatures fluctuate from year to year. In dry years, when there is less runoff from the mountains, there is less cool water available to dilute the upwelling basinal hot water, and the spring water is warmer. During years of high precipitation, when more runoff is available, the temperature of the springs is cooler. This suggests a mixing zone located at or near the springs (McCalpin 2013; see Fig. 7).

Another indication of the mixing of two waters is provided by the chemical analysis at Valley View Hot Springs at the eastern edge of the San Luis Valley near the Orient Mine Caves, compared to that of the Mineral Hot Springs waters near the center of the San Luis Valley (Table 1). It is clear that ionic concentrations at Valley View Hot Springs

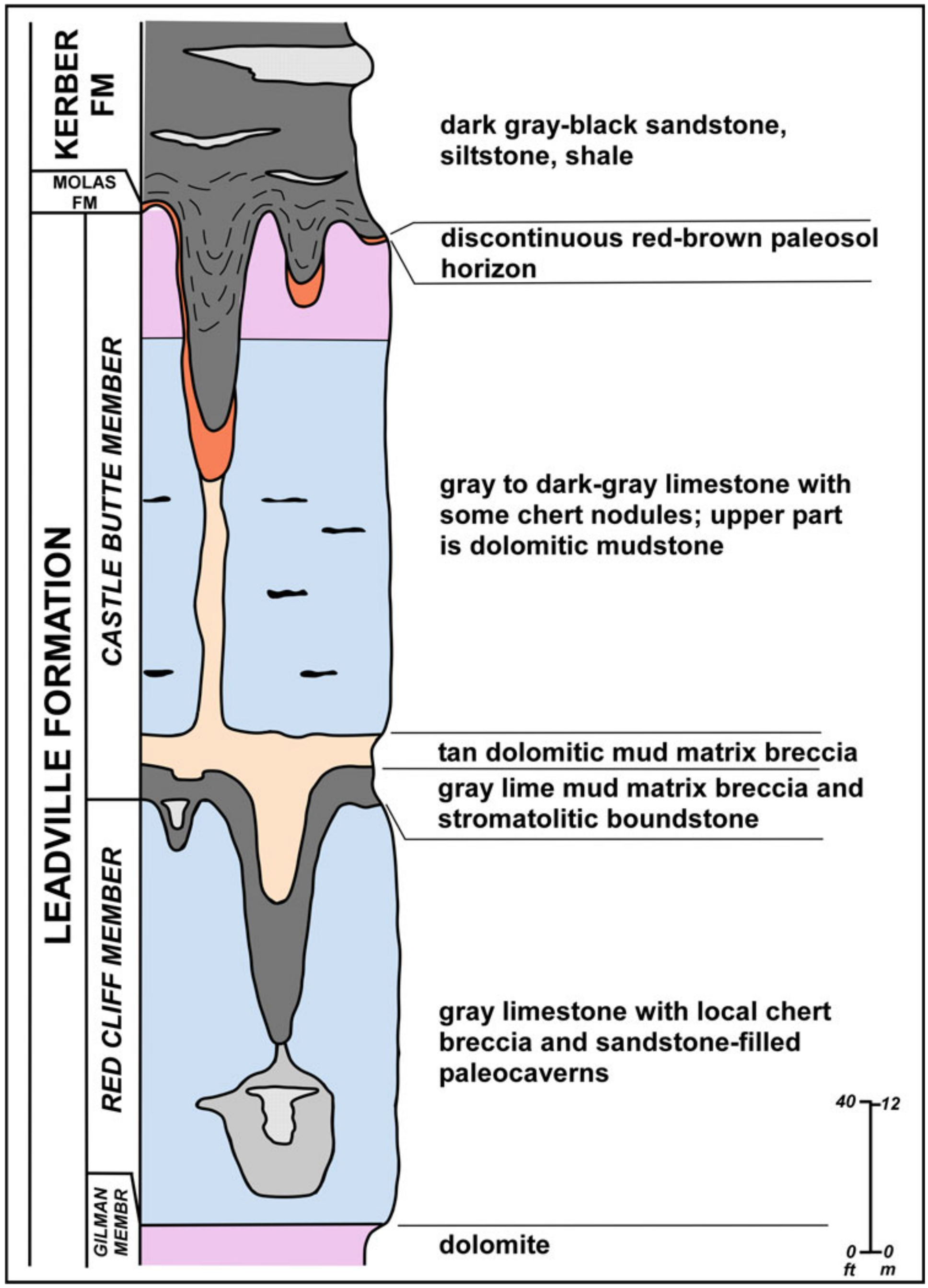

Fig. 6 Composite stratigraphic column for the Leadville Formation in the orient mine area. From Balleweg (1990)

are generally diluted in comparison to those of the Mineral Hot Springs.

Figure 7 is a cross section through the Orient Mine area showing the various faults that directed both the downward and upward water flows. Note that the sedimentary section near the Orient Mine is steeply dipping, and that thrust faults cut Pennsylvanian and Permian strata topographically above and east of the mine. These faults and associated fractures are believed to collect and channel water downward from the Sangre de Cristo Range. According to the favored speleogenetic model, water travels from the crest of the Sangre de Cristo Range through fractures and along thrust-fault surfaces and rises to the surface within the more permeable carbonate rocks of the Leadville and Dyer Formations. Simultaneously, warm water is forced from Tertiary-age basin aquifers into the fractured rocks along the San Luis fault. The fault zone acts as a conduit, channeling water upward where it mixes with cool, mountain-derived water.

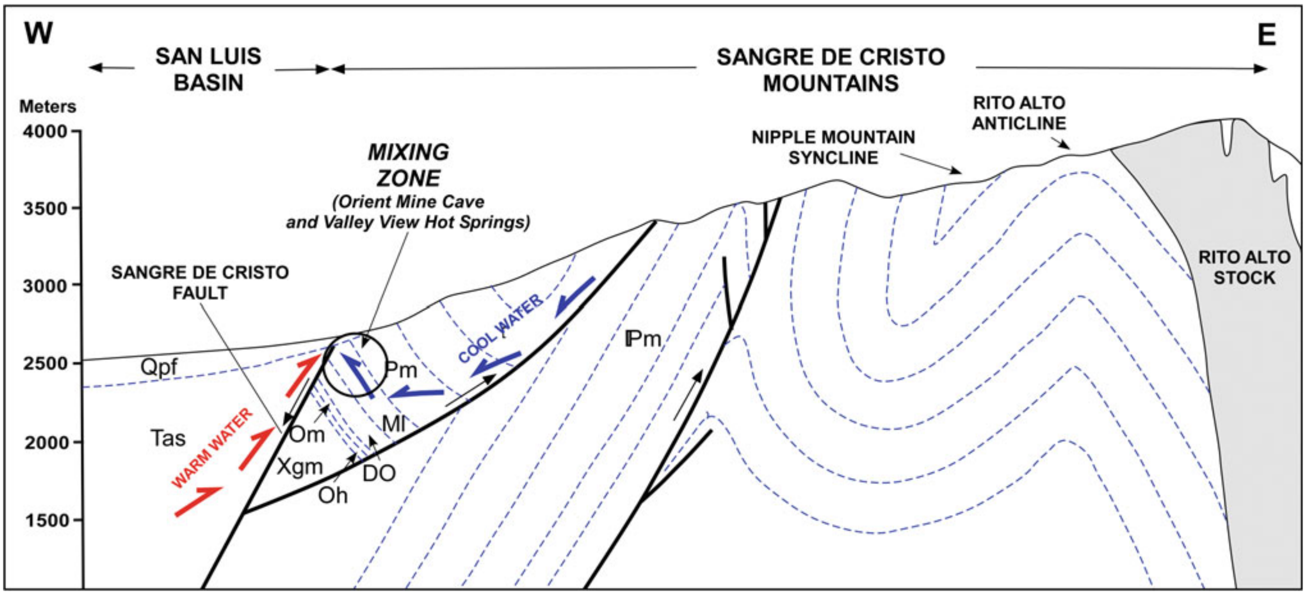

Fig. 7 Geologic cross section showing hypothetical flow paths for warm and cool water. The diagram represents the paleo-flow at the time of the formation of the Orient Mine Caves and the present-day flow at Valley View Hot Springs, which are located in the mixing zone. Base cross section adapted from Lindsey and Soulliere (1987) and corresponds to Section C on Fig. 3. *Formation symbols Xgm* Precambrian Gneiss; *Om* Ordovician Manitou; *DO* Devonian-Ordovician undifferentiated; *Ml* Mississippian Leadville; *Pm* Pennsylvanian Minturn (including Sharpsdale); *Tm, Tf* Tertiary Intrusives; *Qaf* Quaternary Alluvial Fan; *Qal* Quaternary Alluvium

At depth, the thrust faults are cut by the basin-bounding Sangre de Cristo normal fault at the edge of the San Luis Valley. Sufficient hydraulic head is generated by the 1220 m elevation difference between the crest of the range and the caves to force underlying meteoric water to rise to the present surface elevation of the Orient Mine. Thus, in the past, it is likely that water flowed upward through porous and fractured Paleozoic carbonates to the elevation of the Orient Mine, where it mixed with hypogenic water from the San Luis valley and formed open cave galleries. The Valley View Hot Springs, 1.6 km south of the Orient Mine Caves, is a present-day analog to the hydrologic flow paths and conditions that existed during the formation of the Orient Mine Caves.

3 Cave of the Winds

Cave of the Winds is a show cave with 3.2 km of surveyed passages located 1.5 km north of the resort community of Manitou Springs, Colorado (Figs. 1, 8, 9). Manitou Springs is known for its mineral water from natural springs and wells. The temperature of spring and well water is slightly warmer than that of shallow groundwater, putting them in the category of warm springs (Luiszer 1997).

3.1 Geologic Setting

Principal cave development is in the Ordovician Manitou Limestone, with lesser development in the overlying Williams Canyon formation and Leadville Limestone, both of Mississippian (early Carboniferous) age. The cave is developed in a south-plunging anticline composed of Cambrian through Pennsylvanian (late Carboniferous) strata (Fig. 9). Overlying the carbonates are the Pennsylvanian arkosic Glen Eyrie Formation and the Fountain Formation. Both of these units are aquicludes that prevent water from flowing upward from the carbonates and are treated hydrologically as a single unit. Paleozoic strata extend northwest–southeast in the footwall of the Ute Pass high-angle reverse fault. Water enters fractures in the granite, travels downward to the fault, then rises where the fault overlies south-dipping Paleozoic strata (Fig. 10).

The cave is located near the crest of a northwest–southeast-trending anticline (Fig. 8) and is one of several similar ones in the area. The anticline parallels a northwest–southeast-trending syncline to the south. The east limb of the syncline is truncated and partly overlain by Pikes Peak Granite along the Ute Pass high-angle reverse fault. The faults formed as a result of the regional compressional event that caused the Ute Pass fault. Figure 8 shows the structural

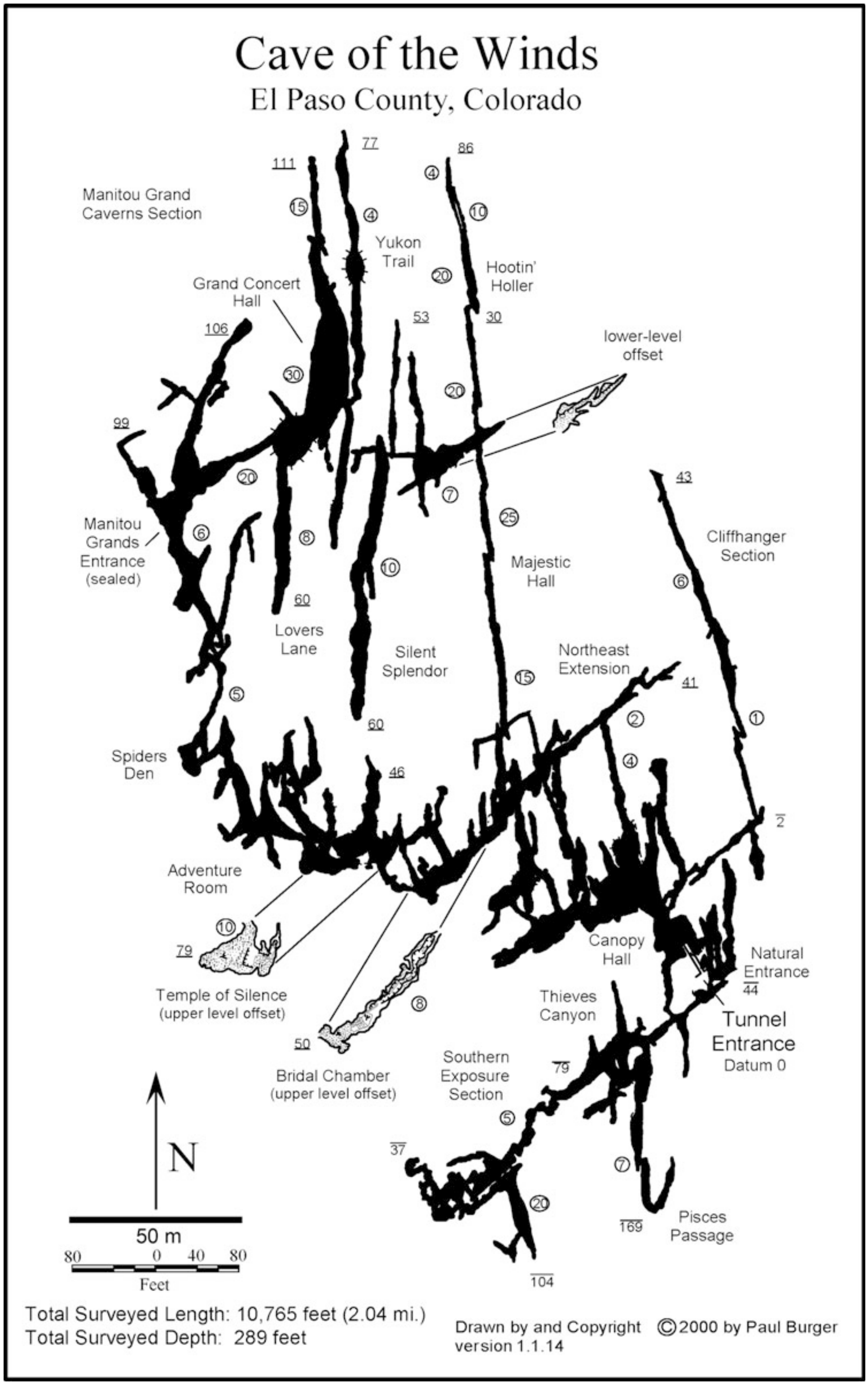

Fig. 8 Map of Cave of the Winds, courtesy of Paul Burger, National Park Service

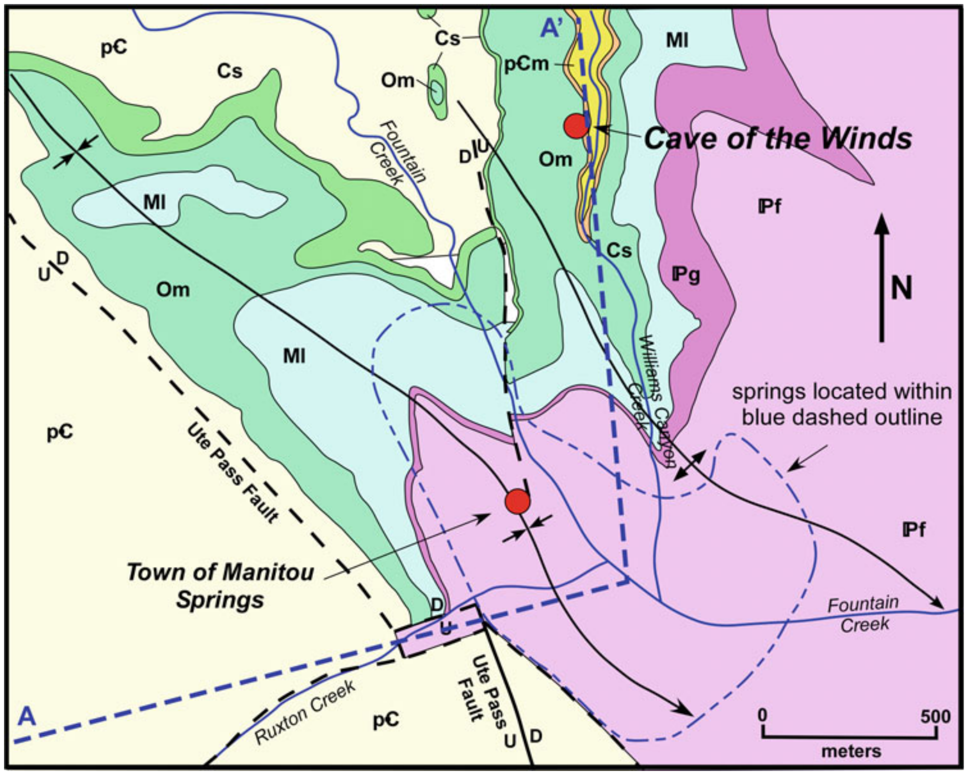

Fig. 9 Geologic Map and section of the Manitou Springs area from Luiszer (1997) after Bianchi (1967). Cave of the Winds is indicated in the upper center of the map. Note the northwest–southeast-trending Williams Canyon Anticline and adjoining syncline through Manitou Springs parallel with the northwest–southeast-trending Ute Pass Thrust Fault in the southwestern portion of the area. *Formation symbols IPf* Fountain Formation; *IPg* Glen Eyrie Formation; *Ml* Leadville Limestone Formation and Williams Canyon formation; *Om* Manitou Limestone; *Cs* Sawatch Sandstone; *pC* Pikes Peak Granite; *pCm* biotite migmatite

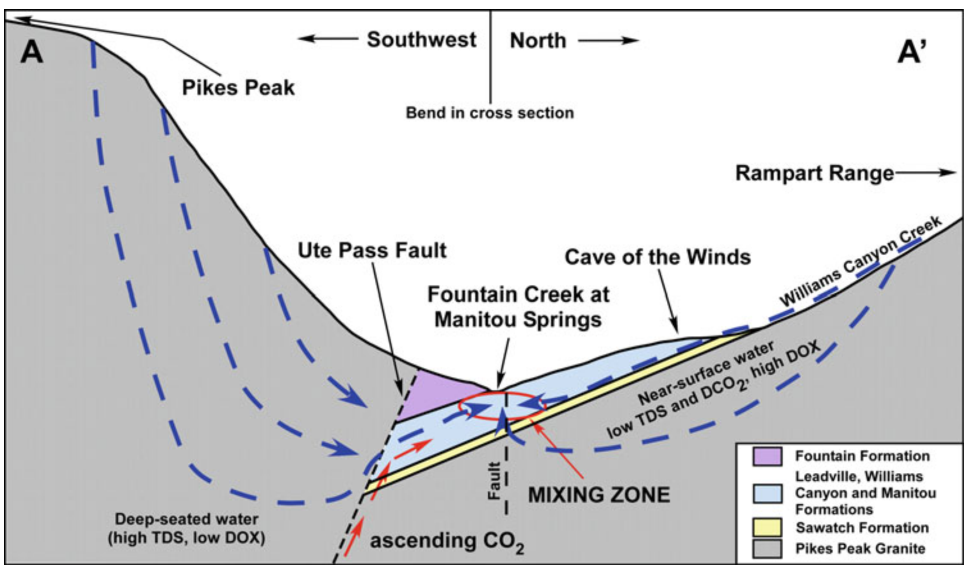

Fig. 10 Hypogenic water flow paths that are interpreted to have formed Cave of the Winds. Water descends along fractures in the Pikes Peak Massif to intersect the Ute Pass Fault and then traverses the fault to enter the Paleozoic cave-forming carbonates (after Luiszer 1997)

features as well as the outcrops of Paleozoic strata and Pikes Peak Granite (Luiszer 1997).

3.2 Speleogenesis

Cave of the Winds was formed where ancestral Fountain Creek crossed Paleozoic carbonate strata near the axis of the Williams Canyon anticline, allowing oxygenated surface water to mix with deep-seated anoxic water. Cave development began ~4.5 mA, as determined by aminostratigraphy, magnetostratigraphy, and interpretation of geomorphic features (Luiszer 1997). At that time, springs similar to those in Manitou Springs today emerged from sediments in the paleo-valley north and up-slope from Cave of the Winds. Mineral water high in CO_2 from these springs mixed with

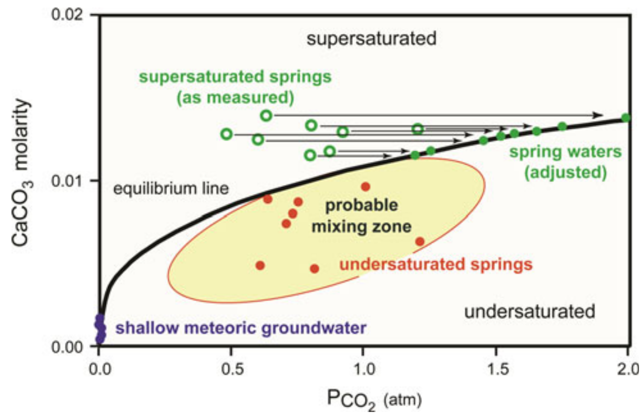

Fig. 11 Water chemistry at Manitou Springs. PCO_2 of supersaturated springs has been adjusted to what they must have been at depth, before degassing. Undersaturated springs fall in the probable mixing zone between shallow and deep groundwater. From Luiszer (1994)

dilute surface water from ancestral Fountain Creek to form a chemically aggressive solution that dissolved the carbonate rocks.

Present-day hydrologic processes in the town of Manitou Springs reflect the ancient cave-forming processes. The hydrologic system responsible for the Cave of the Winds is long-lived and still active. Evidence includes several terrace levels that record the positions and elevations of ancestral Fountain Creek descending from the north and above Cave of the Winds, in steps down to the town of Manitou Springs. Many of these terrace levels are marked with iron-stained alteration associated with hypogene water flow in the cave. Evidence that speleogenesis continues today is found in water-well drilling logs where bit drops into caverns beneath the city are reported. This is evidence that in the past a similar hydrologic system was located above the present-day Cave of the Winds.

Waters in the present Manitou—Williams Canyon—Leadville aquifer below the town of Manitou Springs can be divided into four groups on the basis of water chemistry, reflecting the sources and amount of surface water mixing with the ascending mineral water (Fig. 11). Water chemistry and precipitates from the mixing of surface and hypogenic waters support the hypogenic mixing hypothesis (Luiszer 1997). Precipitates in the cave include iron and manganese oxides. Luiszer (1994) documented that the iron oxide deposits were bacterially produced.

Speleogenetic sediments from two episodes of paleokarst development are found at and near Cave of the Winds. These episodes karstified the Lower Ordovician Manitou and along the interface between the Manitou and the overlying Mississippian Williams Canyon (Forster 1977), and at the contact of the Williams Canyon with the overlying Mississippian Leadville Limestone. Preserved features include filled caves and bedding-plane fissure fills, which provided some of the earliest and most permeable routes for local water flow. However, the majority of cave development took place along fractures developed during the Laramide orogeny (Blanton 1973).

Ascending hypogenic waters were confined in the Manitou—Williams Canyon—Leadville aquifer by the overlying Fountain Formation aquiclude. Confinement concentrated the dissolution of carbonates of the aquifer and illustrates the classic interbedded aquifer/aquiclude hypogenic flow model. In the town of Manitou Springs, a thin remnant of the Fountain Formation is breached in three places, allowing mineral water to emerge from the surface adjacent to Fountain Creek.

3.3 Interpretation of Groundwater Flow Paths

The water that formed Cave of the Winds initially entered fractures in the granite of the Pikes Peak massif south of Manitou Springs (Luiszer 1997). This granite mass (which includes the 4302 m Pikes Peak itself) towers almost 2130 m above the elevation of Cave of the Winds. After descending through fractures in the granite, this water was diverted northward and upward along the Ute Pass Fault toward the town of Manitou Springs. Where the fault intersected the Paleozoic carbonates, water entered the fractured and soluble strata and moved northward until it reached the Fountain Creek paleo-valley (Luiszer 1997). Mixing of the hypogene water with the surface water in the paleo-valley produced chemically aggressive waters in the mixing zone and can account for the origin of Cave of the Winds (Fig. 11).

4 Glenwood Caverns

Glenwood Caverns contains 4.8 km of mapped passages in southwest-dipping Mississippian Leadville Limestone (Fig. 12). It is a show cave under its present name, but originally was known as Fairy Cave. It is located in Iron Mountain above the town of Glenwood Springs, where the southwest-flowing Colorado River crosses the Grand Hogback Monocline on the southwest side of the White River Uplift (Fig. 13; Kirkham et al. 1996). The area lies at the western end of Glenwood Canyon, which has been incised through Paleozoic Precambrian rocks at the boundary between the Rocky Mountain orogenic province and the Colorado Plateau.

4.1 Geologic Setting

The Colorado River cuts across the regional structural grain east of Glenwood Springs, but it flows subparallel to the

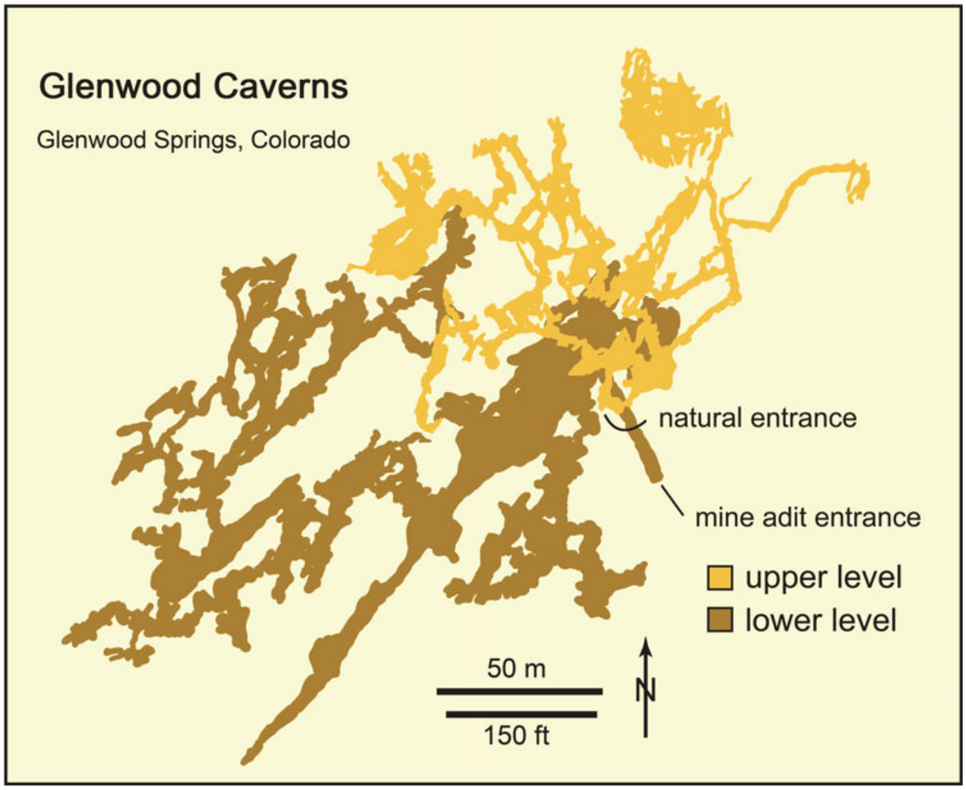

Fig. 12 Map of Glenwood Caverns, Glenwood Springs, Colorado (after Anderson and Barton 2002)

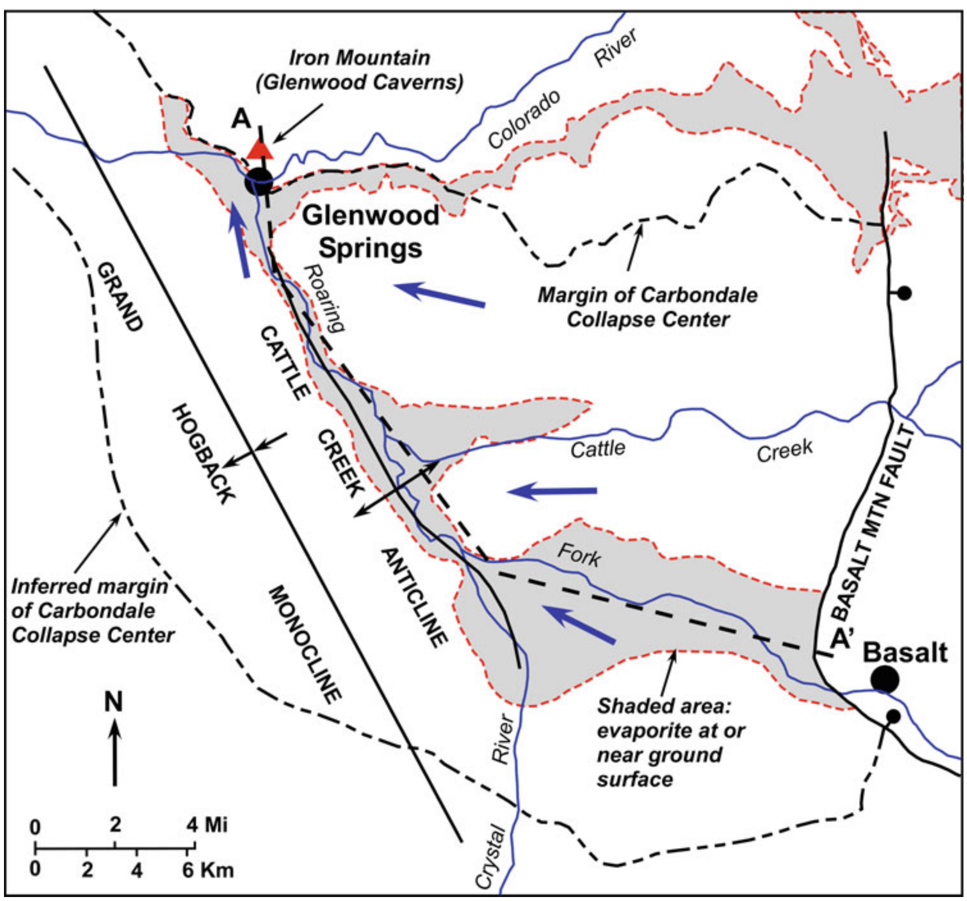

Fig. 13 Generalized geologic map of the Glenwood Caverns area showing water flow within Pennsylvanian evaporites in the Carbondale Collapse center. The dashed line *A–A′* indicates the trace of the cross section shown in Fig. 14. The White River Uplift lies north and east of Glenwood Springs. Modified from Kirkham et al. (2001)

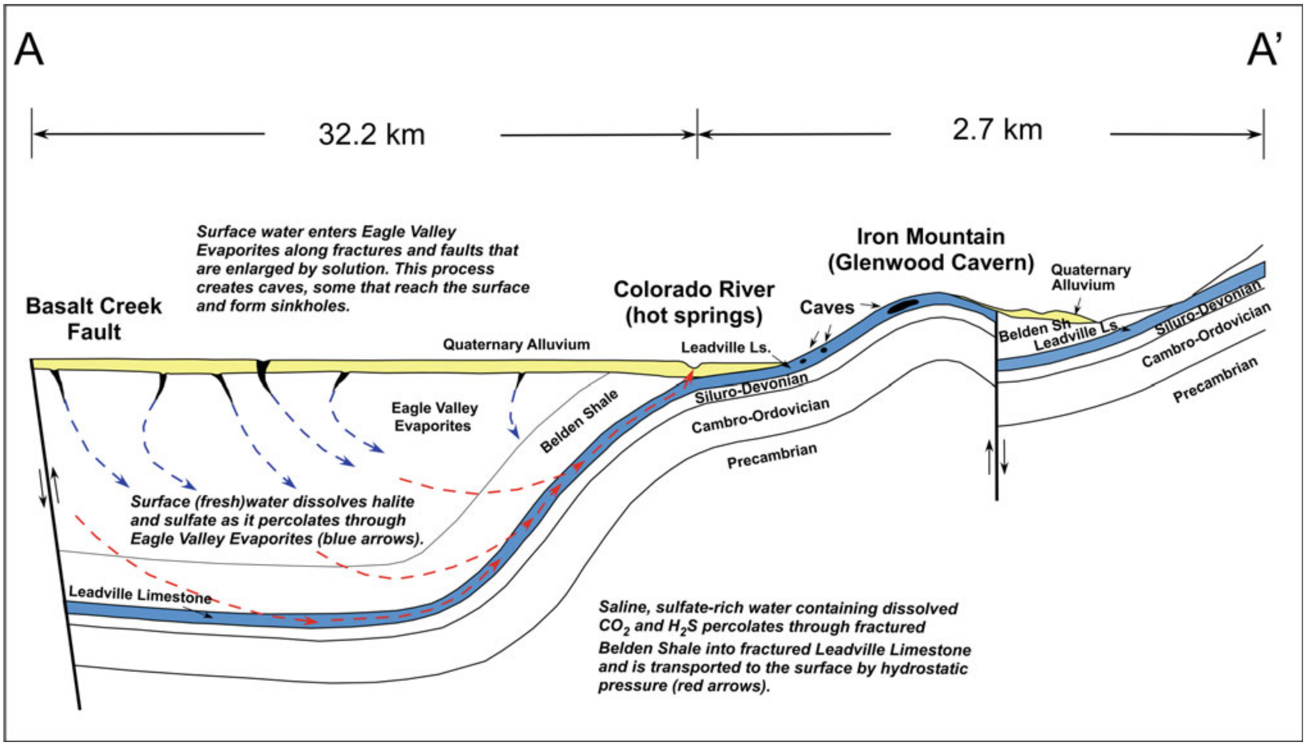

Fig. 14 Diagrammatic cross section of hypogenic water flow paths from the Carbondale Collapse Center into the Mississippian Leadville Limestone, and upwards into the Glenwood Caverns area. Derived from Kirkham et al. (1997)

structural strike where it crosses the Grand Hogback Monocline. Roaring Fork, a tributary, flows northward along the strike of the monocline to form part of a topographic low known as the Carbondale Collapse Center (Kirkham and Scott 2002). The floor of the Collapse Center is composed of Tertiary and Quaternary gravels covering remnants of Pennsylvanian evaporites and Tertiary basalt flows. The gravel and basalt partly overlie an elongate diapir composed of Eagle Valley formation evaporites in the core of the anticlinal bend of the Grand Hogback Monocline.

The Carbondale Collapse Center collects runoff from surrounding mountains, which drains to the Colorado River via the Roaring Fork River and its tributaries. In the subsurface, water moves through permeable zones within Eagle Valley evaporites, dissolving halite and sulfates. Over time, water carrying large amounts of dissolved sulfate and halite enters older Paleozoic sediments, in particular the Leadville Limestone, on its way to springs. In the subsurface, water warms with increasing depth as it moves from south to north (Figs. 13 and 14).

4.2 Speleogenesis

Thermal water containing CO_2 and H_2S reaches the surface at twelve springs and at least six seeps at or near the Colorado River at Glenwood Springs. These springs provide a modern analog for the water that formed the cave. Carbonic acid in rising thermal water was responsible for most speleogenetic dissolution in Iron Mountain, although some dry passages in Glenwood Caverns have a sulfuric acid overprint.

The hot springs and seepage areas along the Colorado River in Glenwood Springs have a cumulative discharge is 15–19 m^3/s migrating up through fractures and faults from the Leadville Limestone (Barrett and Pearl 1976; Gelden 1989). Water temperatures range from 44 to 47 °C (111–117 °F) (Gelden 1989). Water from two test wells on the north side of Glenwood Springs, near the Colorado River, contains dissolved H_2S ranging from 1.2 to 2.1 mg/L. A CO_2 concentration of 110 mg/L was reported in water from one of these wells (Gelden 1989).

Mississippian Leadville Limestone and older formations overlie Precambrian crystalline rocks (Figs. 2 and 14). The Leadville Limestone at Glenwood Caverns is 61 m thick and is composed of gray, coarse to finely crystalline, fossiliferous limestone in the upper part, and dolomite with chert nodules in the lower part (Kirkham et al. 1997). Glenwood Caverns is developed in the Leadville near the top of Iron Mountain (Fig. 13). The historic Fairy Cave entrance is near the top of the mountain, 399 m above Glenwood Springs and the Colorado River. The cavern has a vertical relief of 84.7 m (Anderson and Barton 2002; Fig. 12).

Base level gradually fell in response to downcutting by the Colorado River. As this occurred, the zone of active cave enlargement migrated downward as well, while progressively deeper phreatic cave passages became air filled. At the water table, H_2S escaped into the cave atmosphere, to be reabsorbed into films of oxygenated meteoric and condensation water on gallery walls and other surfaces. Here, H_2S was oxidized to sulfuric acid, which immediately reacted with the limestone and the calcite speleothems, partially altering them to gypsum. Most of this gypsum was dissolved and removed from the cave, but gypsum crust is preserved in areas protected from water (DuChene et al. 2003).

Late in the developmental history of the cave, while the cave was enlarging at depth by calcite dissolution, carbon dioxide was simultaneously lost to the atmosphere near the water table. This caused the remaining water to become supersaturated with respect to calcite, resulting in subaqueous deposition of calcite in mammillary layers that range up to 10 cm thick. Calcite mammillaries from Glenwood Caverns have been age-dated using Uranium series analysis. Dates of 1.36 ± 0.25 Ma and 1.72 ± 0.25 Ma were determined for two samples (Polyak et al. 2013). These dates show the time of calcite mammillary deposition and establish a minimum age for the cave.

4.3 Biogenic Deposits

Both Cave of the Winds and Glenwood Caverns have biogenic features and/or deposits. Biogenic processes are suggested by the authors for the enrichment of the limonite ore bodies at the Orient Mine Caves but have not been studied there. Luiszer (1994, 1997) included scanning electron microscope photos of one of these deposits at Cave of the Winds showing that it is composed of *Leptothrix* bacteria (Fig. 15). Luiszer (1994) included a similar photo from Glenwood Caverns stating “The filaments are indicative of the bacteria *Leptothrix*. The mammillary growths coating the filaments are probably the result of inorganic precipitation of Fe-oxide.”

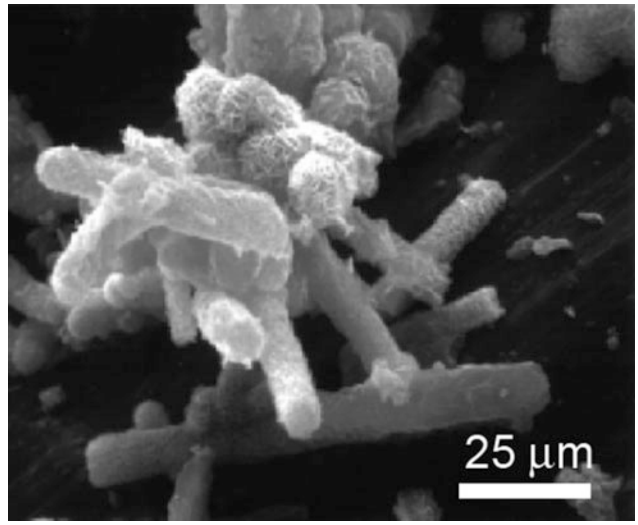

Fig. 15 Scanning electron microscope image of *Leptothrix* bacteria in an iron deposit in Cave of the Winds. From Luiszer (1997)

Limonite deposits are contained in the Barn, the largest room in Glenwood Caverns, and in nearby Discovery Glenn. In one area, large cavities between early-stage breccia blocks are filled with iron oxide and calcite. Luiszer (unpublished) states that “All of the iron oxide deposits … contain elevated concentrations of arsenic … and lead. The uniform small size (1–2 µm) and the globular morphology of the grains … suggest biologically mediated precipitation by bacteria such as *Siderocapsa* or *Pediomicrobium*” (see Fig. 16, an iron deposit in the Discovery Glenn section of the cave).

Pool fingers and U-Loops are also present in Glenwood Caverns. Fossilized DNA was not found in the pool fingers, so no relationship could be made between them and similar present-day features in nearby Glenwood Hot Spring. However, more than 50 new candidate Bacterial, and three new Archaeal species were identified (H. Barton *in* DuChene et al. 2003).

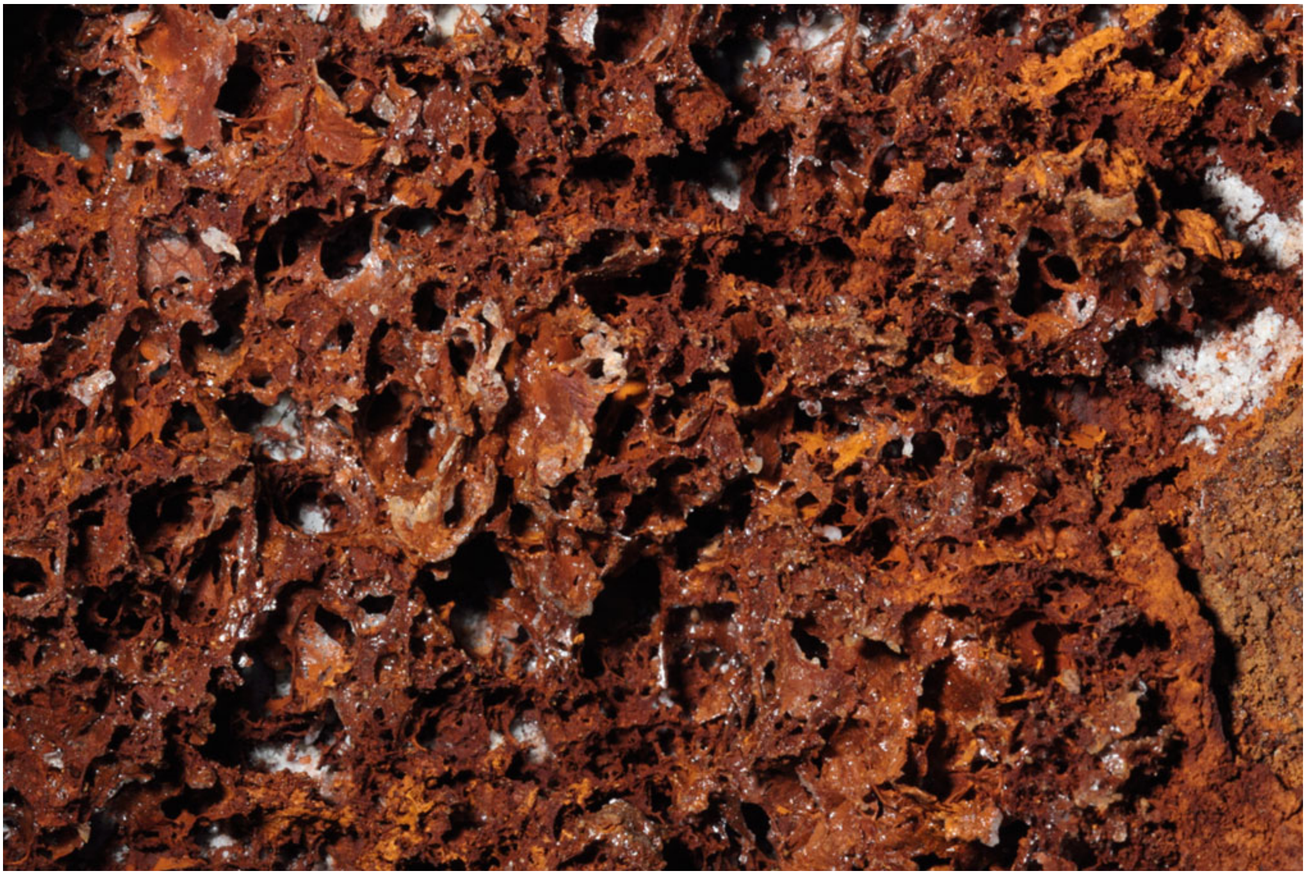

Fig. 16 Bacterially produced iron deposit in Discovery Glenn at Glenwood Caverns. Photo by Norm Thompson

5 Conclusions

Western Colorado contains Paleozoic limestone formations exposed in uplifts within the Colorado Rocky Mountain province, where they have been subjected to both epigenic and hypogenic cave origin. Where those processes are hypogenic, cave and karst development is associated with rising thermal water containing dissolved CO_2, and, at Glenwood Caverns, H_2S. Cave of the Winds and Glenwood Caverns resulted from dissolution caused by mixing of ascending warm or hot water with oxygenated surface water. The Orient Mine caves are partly the result of paleokarst development that may (or may not) have been hypogenic. However, mixing-zone processes associated with rising water during the Neogene caused hypogenic cave development at the Orient Mine. It is likely that caves in similar geologic settings in Colorado owe at least part of their origin to hypogenic processes. In Cave of the Winds and Glenwood Caverns, microbiological studies of iron and manganese deposits indicate that microbes were active during speleogenesis.

Acknowledgements Several individuals and organizations contributed to the preparation of this chapter. All caves described here are privately owned, and their owners graciously provided access and information. Norm Thompson provided copies of the survey notes and maps of the Orient Mine caves, and Paul Burger contributed a version of his Cave of the Winds survey map specifically formatted for this article. Donald Davis provided information on the Orient Mine caves from his explorations in 1961 and 1986. He and Richard Rhinehart provided references to articles published in Rocky Mountain Caving, as well as helpful comments on early drafts of this chapter. Arthur and Margaret Palmer contributed valuable feedback and suggestions.

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