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Garden of the Gods at Colorado Springs: Paleozoic and Mesozoic sedimentation and tectonics

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ABSTRACT

Exposed along the southeast flank of the Colorado Front Range are rocks that beautifully illustrate the interplay of sedimentation and tectonics. Two major range-bounding faults, the Ute Pass fault and the Rampart Range fault, converge on the Garden of the Gods region west of Colorado Springs. Cambrian through Cretaceous strata upturned by these faults reveal in their grain compositions, textures, and bed-forms radically different styles of sedimentation. The Cambrian/Ordovician marine transgressive deposits appear to have come to rest on a passive and tectonically inactive craton. In contrast, coarse-grained Pennsylvanian/Permian marine deposits of the Fountain Formation and Lyons Sandstone reveal deposition by suspension and tractive currents in a very dynamic tectonic setting. These styles are contrasted with the alternating eustatics of the Western Interior Seaway which led to the local Cretaceous section. Finally, the powerful imprint of the Laramide orogeny is evident in the sandstone dikes of Sawatch Sandstone which are found within the hanging wall of the Ute Pass fault.

FIELD TRIP OVERVIEW

This field trip will visit six sites along the Rampart Range and Ute Pass fault zones west of Colorado Springs, Colorado. The purpose is to observe and discuss the processes of sedimentation and tectonics at superb exposures near Garden of the Gods and Red Rock Canyon Open Space. Our objectives at the six stops are to: (1) view the nonconformity below Cambrian strata at the base of the Sauk Sequence; (2) observe coarse, clastic sedimentary rocks of the late Paleozoic Fountain Formation and the upturned strata caused by Laramide tectonics along the Rampart Range fault; (3) examine the Permian Lyons Sandstone and consider its sedimentology; (4) review marine sandstone and shale deposition at Red Rock Canyon Open Space as evidence of the Cretaceous Western Interior Seaway; (5) view Majestic dike (sand “injectite”) within the Ute Pass fault zone near Woodland Park, Colorado; and (6) examine Crystola dike, also near Woodland Park, Colorado.

INTRODUCTION

The Garden of the Gods is located along the southern end of the Colorado Front Range near Colorado Springs. The Front Range is

a classic basement-involved, foreland uplift, running approximately north-northwest through Colorado from Golden in the north to Cañon City in the south (Erslev et al., 1999). Major development of the Rocky Mountain province occurred during the Late Cretaceous to Middle Eocene as part of the Laramide orogeny. This deformation resulted in the simultaneous uplift of the Front Range, including the formation of the Rampart Range fault (and similar faults), and the rapid subsidence of the asymmetrical Denver basin to the east. Many of the consequences of this upheaval will be observed on this field trip and discussed at Stops 1–6. Figure 1 shows the locations of the primary stops on this field trip.

Geologic Development of the Southern Front Range

The Precambrian rocks of Colorado have been described by Tweto (1977, 1980a) as a gneissic complex (1800 Ma) with three periods of granitic intrusion (dated at 1700 Ma, 1400 Ma, and 1000 Ma) and three episodes of sedimentary or sedimentary and volcanic activity (dated at 1720–1460 Ma, 1400 Ma, and 1000 Ma). Although the Colorado Front Range also has a complex Proterozoic history that includes several episodes of folding (Braddock, 1970), this field trip is primarily concerned

Figure 1. Index map showing the locations of the six field trip stops and major faults, south-central Colorado. pC—Precambrian, P—Paleozoic undivided, M—Mesozoic undivided.

with Phanerozoic sedimentation and tectonics. There were three major tectonic episodes in south-central Colorado during the Phanerozoic (Tweto, 1980b): (1) uplift of the Ancestral Rockies in the late Paleozoic; (2) development of uplifts and basins during the late Mesozoic–early Cenozoic Laramide orogeny; and (3) Neogene (Miocene and Pliocene) block faulting associated with the Rio Grande rift. Gerhard (1967) also speculated on tectonic activity prior to Early Ordovician time, which may have removed sedimentary rocks of Cambrian age west of the study area.

Ancestral Rocky Mountains

During the late Paleozoic, large uplifts developed in Colorado, as part of the Ancestral Rocky Mountains (Tweto, 1980b). The uplifts were interpreted to be part fault-bounded and part upwarings of the crystalline basement. Tweto (1980b) believed the uplifts had the profiles of broad cuestas, with the steep side to the southwest and only upwarped at a moderate angle to the east. De Voto (1980) reports that during the Pennsylvanian Period alone, mountain building in Colorado resulted in ranges with up to 10,000 feet (3000 m) of relief. The late Pennsylvanian landscape was interpreted to have contained uplifted mountainous areas roughly coincident with many of the present-day (Laramide) uplifts, including the southern Front Range (De Voto, 1980). The differential preservation and extent of many of the early Paleozoic sedimentary units on portions of the southern Front Range are believed to be caused by the uplifted Ancestral Rocky Mountains. Mississippian carbonates, that were thought to have covered much of Colorado (Tweto, 1980b), were totally removed from parts of the southern Front Range and nearby Royal Gorge arch (Clarey, 1996). This differential erosion is interpreted as a result of partial uplift during the development of the Ancestral Rocky Mountains in the Pennsylvanian Period.

Laramide Orogeny

The Laramide orogeny (Late Cretaceous to Middle Eocene) is responsible for most of the present-day mountainous regions of Colorado, including a major episode of deformation at Garden of the Gods. Tweto (1980b) reported that many uplifts were rejuvenations of earlier Precambrian and/or Paleozoic (Ancestral Rocky Mountains) tectonic features. The observed faulting and folding of the Cretaceous section is a direct result of the Laramide orogeny. Other uplifts in Colorado were newly created during this orogenic event, with no apparent prior tectonic history.

A series of north-northwest–trending, and east-directed, en echelon reverse faults bound the eastern edge of the Front Range, starting with the Golden fault in the north near Denver, the Perry Park–Jarre Creek fault farther south near Pikes Peak, and ending with the Rampart Range fault adjacent to Garden of the Gods. The Ute Pass–Cheyenne Mountain thrust follows this same north-northwesterly trend just to the west of the Rampart Range fault, and adjacent to Colorado Springs, before the southern Front Range plunges into the Cañon City Embayment. Collectively, these fault systems have absorbed much of the displacement associated with the uplifts of the Front Range during Laramide tectonic development.

Sterne (2006) has recently interpreted the Rampart Range fault as a piercement fault dipping steeply to the west at 73° – 78° (Fig. 2). Displacement on the Rampart Range fault is minimal within Garden of the Gods park, but increases significantly northward (Sterne, 2006). Cross section A–A' (Fig. 2) shows a large portion of the displacement along this part of the Front Range being absorbed by an interpreted, blind triangle zone. This fault splays off the Rampart Range fault and flattens and follows a detachment in the Cretaceous Benton Shale to the east. A series of backthrusts, dipping steeply to the east, accommodate an additional 800 m of displacement at this location (Sterne, 2006). These east-dipping backthrusts create and offset the hogback-forming units in Garden of the Gods park (Fig. 2). Siddoway et al. (1999) have found the backthrusts dip between 44° and 77° east and southeast with kinematic data indicating east to west transport. The mapped extent of these faults is shown in Figure 3.

Neogene Tectonism

An episode of Neogene (Miocene and Pliocene) activity affected many of the uplifts in Colorado, resulting in rejuvenation of many of the Laramide uplifts (Tweto, 1979). Much of the present topographic relief along the Front Range is a result of this basin-and-range style faulting, associated with the Rio Grande rift, and more recent erosion (Tweto, 1980b). The Rio Grande rift is a graben system that followed a wide belt trending north-northwest across Colorado, extending from New Mexico through the upper Arkansas River valley to near Leadville, Colorado. Additional, but less extensive rifting extended almost to the Wyoming border (Tweto, 1980b).

Tweto (1980b) stated that many of Colorado's mountainous regions, including the Wet Mountains, were re-elevated as horsts during Neogene tectonism. He noted that both regional uplift and differential uplift accompanied the block-faulting, with some Laramide uplifts being elevated at least 600 m. Epis et al. (1980)

Figure 2. Structural cross-section A–A' drawn east-west across Garden of the Gods. Location shown on Figure 3. pC—Precambrian, LPz—Lower Paleozoic, Pf—Fountain, Pl—Lyons, Kd-Tl—Dakota through Lykins, Kb—Benton, Kn—Niobrara, Kph-Kpl—Lower Pierre through Hygiene Ss Member, Ku—Upper Pierre, Qal—Quaternary alluvium. Modified from Sterne (2006).

Figure 3. Geologic map of Garden of the Gods park. Cross-section A–A’ extends slightly beyond the shown mapped area. Pf—Fountain, Pl—Lyons, Tl—Lykins, Jm—Morrison, Kd—Dakota/Purgatoire undivided, Kb—Benton, Kn—Niobrara, Qal—Quaternary alluvium, Qmg—Quaternary mesa gravels. Geology modified from Grose (1960), and Sterne (2006).

reported that displacements due to block-faulting (both uplift and down drop) varied between 1000 m and 6000 m across Colorado. Oligocene rocks south of Cañon City were vertically offset by as much as 1080 m (Epis et al., 1980).

Overview of Phanerozoic Sedimentation

The Phanerozoic rocks around Garden of the Gods have been mapped by Scott and Wobus (1973), Carroll and Crawford (2000) and Keller et al. (2005), and discussed by Grose (1960), Noblett (1984), and most recently by Milito (2010). The lower Paleozoic rocks (Fig. 4) consist of several thin sedimentary units totaling less than 110 m thick (Cambrian Sawatch Sandstone, Ordovician Manitou Limestone, Devonian Williams Canyon Limestone, and Mississippian Hardscrabble Limestone). The Pennsylvanian to Permian Fountain Formation is irregularly distributed on the eastern flank

Figure 4. Generalized stratigraphic column of Garden of the Gods and Red Rock Canyon Open Space. Geology from Grose (1960) and diagram modified from Milito (2010).

of the southern Front Range but attains a thickness of 1340 m at Garden of the Gods if including the Glen Eyrie Member (Milito, 2010). The Permian Lyons Sandstone sits atop the Fountain Formation, reaching a thickness of 210 m. Both the Fountain and Lyons Formations will be observed at Stops 2 and 3, respectively.

The Permian to Triassic-age Lykins Formation and the Jurassic Morrison Formation were deposited next as sedimentation continued at what is now Garden of the Gods. The Lower Cretaceous Dakota Sandstone and Purgatoire Formation together form a continuous hogback along most the eastern flank of the Front Range. Where observed, the Dakota-Purgatoire Formation is always in depositional contact with the underlying Morrison Formation. These two units, for the most part, mark the final continental depositional episode prior to the development of the Cretaceous Western Interior Seaway.

The Upper Cretaceous Benton Shale, Niobrara Formation, and Pierre Shale complete the sedimentary units that are exposed in Garden of the Gods or the adjacent Red Rock Canyon Open Space. These three units total over 1800 m of marine fossil-bearing deposits and comprise the majority of the sediments deposited beneath the Western Interior Seaway.

STOP 1: NONCONFORMITY AT THE BASE OF THE PHANEROZOIC STRATA

Stop 1 is at the intersection of Highway 24 with Business 24 at the western end of Manitou Springs. The outcrop for Stop 1 occurs on public land within the highway triangle between the junction of Highway 24 with the two lanes of Business 24. Between the lane split of Business 24 at the intersection with Highway 24 is the old path of the Ute Trail leading to the outcrop. Parking and the walking access to the outcrop is found on the fork of Business 24 connecting to Highway 24 east. The Ute Trail with walk to the outcrop occurs at a hairpin turn in the division of Business 24 connecting to Highway 24 east.

The most appropriate way to begin field geologic investigations in the Colorado Springs area is to observe the lowest stratified rocks and the basement igneous rock on which they rest. These earliest strata occur within the regionally tilted sequence of strata and the basement rock complex between the Ute Pass fault and the Rampart Range fault. These strata now dip south-east. The stop shows five noteworthy features (Fig. 5): (1) Pikes Peak Granite, (2) the nonconformity beneath the Cambrian,

Figure 5. The Precambrian nonconformity on the west side of Manitou Springs, Colorado as seen at Stop 1. (a) Pikes Peak Granite. (b) Nonconformity. (c) Sawatch Sandstone, (d) Peerless Formation. (e) Manitou Limestone. Photo by Steven A. Austin.

(3) the Sawatch Sandstone, (4) the Peerless Formation, and (5) the Manitou Limestone.

Pikes Peak Granite is the Middle Proterozoic granitoid batholith that underlies the rocks in the Colorado Springs area. The batholith is exposed in the Front Range and the Rampart Range more than 40 mi (65 km) north of Colorado Springs. This exposure extends southward through Colorado Springs. Granitoid rocks are exposed 40 mi (65 km) to the west of Colorado Springs within the mountains. Values of magnetic intensities on an aeromagnetic survey indicate the batholith continues 50 mi (80 km) eastward in the subsurface of Denver Basin to a depth of 2 miles (3 km) (Zietz et al., 1969). Compositions of the granitoid rocks are typically granite and granodiorite (Clarey, 1996). At Stop 1 the batholith is a coarse-grained biotite-hornblende granite with very pink feldspars.

At our present stop, the granite is truncated by the nonconformity that was tilted tectonically between the two primary Laramide faults. The surface is not an intrusive contact, because it lacks baking at the boundary with strata. The surface is a demonstrable nonconformity. The nonconformity was a very low-relief surface of erosion that expressed the configuration of the widespread and stable craton of North America during the late Precambrian. Locally, much less than 1 m of relief can be seen on the nonconformity.

The Sawatch Sandstone (Upper Cambrian) is 4.5 m (14 ft) thick and directly overlies the nonconformity. It is coarse, buff-colored sand with pebbles cemented by fine dolomite crystals. Sand composition as seen in thin section is typically greater than 90% quartz. Bedding at this stop within the Sawatch Formation is planar coarse sandstone with thickness of 0.1–1.0 m (up to 3 ft). Planar bedding with internal laminations, brachiopod fossils, ichnofossils, and very minor glauconite argue that the Sawatch Sandstone here at Manitou Springs is marine, probably expressing the deepening of ocean water during deposition (Myrow et al., 1999). Absence of lenses of sand with trough cross-bedding argue against a fluvial origin of Sawatch Sandstone on a broad braidplain.

The Peerless Formation is 15.5 m (51 ft) thick and conformably overlies the Sawatch Sandstone. The Peerless Formation is also sandstone but here is distinctively colored reddish or greenish. The deepening during the marine transgression is indicated by the trough cross-bedding and increase in the abundance of glauconite.

Manitou Limestone (Lower Ordovician) is thin bedded wackestone, locally dolomitic, with slight disconformity above the Peerless Formation. The wackestone contains skeletal grains of marine fossils. Although the Manitou Limestone is not fully exposed at the stop, the uppermost beds are supposed to represent a marine regression and, therefore, complete the transgressive cycle (Noblett et al., 1987).

Observers at this stop may want to reflect upon the continental distribution of the Sauk Sequence on the North American craton. The Sauk Sequence expresses the eustatic process, with stable craton tectonics, that allowed the continent to be submerged in Cambrian and Early Ordovician time. The threefold succession of sandstone-shale-limestone within the Sauk Sequence is

seen in such diverse places as the Mojave Desert of California, the Grand Canyon of Arizona, the midcontinent states, and the Great Lakes states. That succession is also expressed here at Manitou Springs, Colorado, within the Rocky Mountains.

STOP 2: SEDIMENTOLOGY OF THE FOUNTAIN FORMATION

Stop 2 is reached from Stop 1 by returning to Highway 24. At the intersection of Highway 24 and Business 24 on the west side of Manitou Springs, go 1 mile southeast on Highway 24. Turn left at the sign marking Cliff Dwellings (Sunshine Trail). Then, immediately turn left again into the road cut. The road cut is at the intersection on the northern side of Highway 24.

Early Spanish-speaking pioneers explored the Front Range of the Rocky Mountains and saw the distinctive upturned red sandstone strata on the east side of the Front Range. They named the territory of these red rocks Colorado. Today, geologists call these red strata the Fountain Formation, deriving the name from the outcrops on Fountain Creek in Manitou Springs. They are dominantly pebble sandstone, but also contain cobble conglomerate and boulder conglomerate. A total measured thickness was recently calculated at 914 m (3000 ft) by Sweet and Soreghan (2010). These strata are assigned to both Pennsylvanian and Permian systems (Atokan to Wolfcampian).

Within the late Paleozoic strata of the Rocky Mountains, an intraplate series of predominantly northwest-trending Precambrian basement highs have been identified along with large-scale basin-bounding fault zones (McKee, 1975). These structures define the Ancestral Rocky Mountains, and the Fountain Formation is believed to be the proximal sedimentary deposit of this orogenic event. For 100 years, it has been popular to imagine the Fountain Formation being an alluvial fan deposit. Within the Manitou Springs area, the Fountain Formation is recognized as a diamond-shaped outcrop with the Ute Pass fault on the southwest side and the Rampart Range fault on the northeast side. Fountain Formation strata between the two faults dip southeast. Highway 24 delivers an extraordinary display of these Fountain strata because it crosses perpendicular to strike of the dipping Fountain Formation.

The outcrop at Stop 2 exposes the lower Fountain Formation (Figs. 6 and 7). Upper strata are exposed within the Garden of the Gods. There are three dominant lithologies described by Sweet and Soreghan (2010) in the lower and middle Fountain: (1) muddy sandstone characterized by massive stacked beds, (2) sandy conglomerate dominated by granite pebbles, cobbles and boulders, and (3) sorted and bedded sandstone with fining-upward sequence.

Muddy maroon sandstone characterized by massive stacked beds. The dominant lithology of the entire Fountain is the muddy sandstone. It is the chief lithology in the lower 700 m of the formation (Sweet and Soreghan, 2010). The very poorly sorted granule-, sand-, and mud-sized debris contains matrix-supported granite pebbles up to 3 cm diameter. Clay-size particles compose 5–20% of the lithology (Sweet and Soreghan,

Figure 6. Coarse clastic debris-flow deposits within the lower Fountain Formation as seen at Stop 2. Photo by Steven A. Austin.

Figure 7. Detail of the coarse clastic debris-flow deposits within the lower Fountain Formation as seen at Stop 2. Photo by Steven A. Austin.

2010). Beds are typically horizontally continuous and are 1–4 m thick. These beds are deep-maroon color and outcrop recessively.

Sandy conglomerate dominated by granite pebbles, cobbles, and boulders. This second lithology is massive, light greenish-gray or light brownish-gray, matrix-supported, pebble and cobble conglomerate. The matrix is coarse sand, lacks bedding or lamination, and is deficient in finer silt or clay. Large rip-up clasts of the maroon muddy sandstone are included in this lithology. Beds are discontinuous laterally and bear strong evidence of load deformation, injection features, and shrinkage cracking. The infolded masses of maroon muddy sandstone suggest horizontal sliding of beds. Higher in the section this lithology includes matrix-supported granite boulders up to 20 cm diameter in beds 0.75–2 m thick.

Sorted and bedded sandstone with fining-upward sequence. This third lithology is characterized by a cycle having lag-cobble base, overlain by hummocky cross-bedded sand, and overlain by plane-bedded fining-upward sand (Suttner et al., 1984). Marine ichnofossils occur (Maples and Suttner, 1990). These cycles are typically 2–5 m thick.

Figure 6 shows the outcrop at Stop 2. At the top of the outcrop is the sorted and bedded sandstone (lithology 3). That bed is not easily accessible and is not described further here. The muddy maroon sandstone (lithology 1) and the sandy conglomerate (lithology 2) are well displayed and easily inspect at the base of the cliff outcrop. Figure 7 shows the detail of a channel-shaped mass of sandy conglomerate (lithology 2) and its associated muddy maroon sandstone (lithology 1).

Lithologies 1 and 2 have matrix-supported cobbles and poorly sorted texture, and are best interpreted by assuming a non-newtonian rheology of the depositional agent. These lithologies and textures are not deposited by the normal flow in a braided river or alluvial fan. They appear to be like modern mudflows and debris flows. These interpretations make sense of the data but hardly support the popular notion of alluvial fan deposition of the Fountain Formation. Lithology cycle 3 argues convincingly for marine deposition. Perhaps lithologies 1 and 2 are marine (subaqueous debris flows) as well. Sweet and Soreghan (2010) believe that paleosols with terrestrial plant rooting occurs on top of beds of lithology 1. The vertical pipes could be fluid escape structures (not plant roots) and the fines that drape over the debris flows could be clay and silt elutriated by dewatering of the muddy matrix (not a soil weathered in place). Fluid escape pipes in slurry deposits were studied experimentally by Druitt (1995). Thus, some very different environmental interpretations can be offered in response to the notion of deposition on an alluvial fan.

The close association of the muddy maroon sandstone (lithology 1) and the sandy conglomerate (lithology 2) suggest that their depositional process was linked. It might be supposed the slurry-flow process produced both lithologies as a facies of each other. Could the sandy conglomerate be the proximal deposits of a debris flow? We might suppose the coarsest sand would settle first and be deposited in a fluidized condition where the fines would be swept away as water was ejected rapidly. The resultant flow, as coarse sand deposition occurred, would

be enriched in water and mud, thereby forming a mudflow of increased mobility. Flow transformation is known from studies of volcanic mudflows at Mount St. Helens and Mount Rainier (Scott et al., 2001). During these catastrophic flood flows, turbulent, hyperconcentrated suspensions were observed to transform to laminar mudflows. Suspension flows have the ability to transport and deposit boulders and cobbles.

Where is the source of the granite cobbles and boulders? Paleocurrent indicators for the lower Fountain Formation in Manitou Springs suggest that the nearby Ute Pass fault just south of the city was the boulder source (Suttner et al., 1984). Compare the different styles of tectonics and sedimentology of the Pennsylvanian/Permian Fountain Formation to the Cambrian/Ordovician Sawatch Sandstone at the nonconformity.

STOP 3: PERMIAN LYONS SANDSTONE IN GARDEN OF THE GODS PARK

Stop 3 can be reached by turning north on Ridge Road, off Highway 24 (Cimarron Street), on the west side of Colorado Springs and just north of Red Rock Canyon Open Space. Follow Ridge Road north for ~3 km until the park is reached. The lower, middle, and upper Lyons Sandstone is exposed in the park.

The Permian Lyons Sandstone forms outcrops along the Colorado Front Range from south of Colorado Springs to the Wyoming border; a distance of ~250 km. It forms the spectacular red sandstone hogbacks in Garden of the Gods, where the bedding stands nearly vertical (Fig. 8). It has a similar outcrop pattern at many other places along the Front Range. The type section of the sandstone is in Lyons, Colorado, (~60 km northwest of Denver) where it has been quarried for more than a century as building

Figure 8. The Lyons Sandstone is the main hogback forming rock in the Garden of the Gods in Colorado Springs, Colorado. The rock stands nearly vertical, and some is slightly overturned. The photo is looking south from the northwest corner of the loop road. The hogback in the immediate foreground and the hogback on the far right is the lower portion of the Lyons Sandstone. The hogback to the far left is upper Lyons. Units according to mapping by Morgan et al. (2003). Photo by John Whitmore.

stone. Its greatest thickness is in the Colorado Springs area where it is ~210 m thick. The formation usually has a gradational contact with the underlying Fountain Formation (coarse arkoses). It is overlain by the Lykins Formation (red shales and sandstones), which is usually a gradational contact as well. A number of different facies occur in the Lyons Formation, including arkosic conglomerates, red, tan, and white cross-bedded sandstones, and occasional mudstones. The sandstones display both tabular planar and wedge planar cross stratification. A variety of depositional environments have been proposed for the formation including fluvial, eolian, beach, near-shore, and littoral. Most authors generally agree that the bulk of the Lyons Sandstone was deposited somewhere in the proximity of a marine shoreline either as eolian dunes or subaqueous deposits along the shore, or both. Our thin-section data shows the typical cross-bedded Lyons Sandstone is moderately to very poorly sorted; a result contrary to what others have reported (McKee and Bigarella, 1979; Milito, 2010).

Stratigraphy and Texture of Lyons Sandstone

From the Front Range area, where the Lyons Formation is best known, it extends into the subsurface of southeastern Colorado, western Kansas, and parts of Wyoming and Nebraska (Maher, 1954). It is believed the Lyons Formation also extends into New Mexico and is correlative with the Glorieta Sandstone (Brill, 1952; Dimelow, 1972) which has been long recognized to correlate with the Coconino Sandstone in Arizona. To the east, the Lyons transitions into red shales, carbonates and various saline deposits (Adams and Patton, 1979).

At most locations where the Lyons has been studied and mapped, it has been divided into three units: a lower, middle, and upper. These units typically display different characteristics from the southern exposures to the northern exposures. Changes in Lyons lithology can even be noted between Red Rock Canyon Open Space and the Garden of the Gods, a distance of only 3 km.

The dominant rock types within the Lyons Sandstone are fine to medium grained arkoses and quartz sandstones that contain significant amounts of microcline. Grains vary from subangular to rounded. Hubert (1960, p. 101) reports that the Lyons Sandstone also contains miscellaneous rock types (less than 1% of the formation) including thickly bedded dolomitic feldspathic quartzites, numerous thin red and green micaceous shaly siltstone lenses, reddish-orange feldspathic sandstones (middle third of the Garden of the Gods section), thinly bedded redstones interbedded with arkose and various types of intraformational conglomerates. Hubert (1960, p. 172) documented that the amount of quartz in the sandstone gradually increased northward along the Front Range with the Garden of the Gods section having 69%, Roxborough Park 74% (30 km south of Denver), Morrison 86% (20 km southwest of Denver) and Eldorado Springs 88% (38 km northwest of Denver). Occasionally crudely sorted arkoses can occur as channels within the main body of the Lyons (Thompson, 1949, p. 61).

At Red Rock Canyon Open Space (~100 km south of Denver), the Lyons Formation does not make spectacular hogbacks;

instead it makes rather low-lying rounded hogbacks. Milito (2010) describes the upper Lyons as being a well-sorted, fine- to medium-grained, pink to red sandstone that is strongly cross bedded. We collected a sample (RRC-3) of “white” Lyons sandstone from this horizon for thin section study and X-ray diffraction (XRD) analysis (Fig. 9, Tables 1 and 2) and found it was moderately sorted, not well-sorted. Milito (2010) reports that the middle Lyons Sandstone is an arkosic conglomerate with mudstone layers similar to the Fountain Formation. It is not well exposed and usually forms strike valleys. She reports that the lower Lyons is a well-sorted, fine- to medium-grained, pink to red sandstone that is massively bedded. We also collected a sample (RRC-1) for thin section study from this horizon (Fig. 10) and found it was moderately sorted (Table 2). At first glance the sandstone may appear to be well-sorted, but often small grains occur between the bigger ones and occasionally larger grains occur mixed within the fine sand. When grain size measurements are made and the standard deviations are calculated, the statistics show the sandstone is moderately sorted (at best), not well-sorted.

Only a few kilometers north of Red Rock Canyon Open Space is the Garden of the Gods. Here, the Lyons Formation has been mapped into three distinct units, which were described by Morgan et al. (2003, p. 12). The upper unit is described as being a white to red, well-sorted, fine-grained sandstone that is moderately cemented, strongly cross bedded and ~46 m thick. The middle unit is a crimson red to white arkosic conglomerate and

Figure 9. Upper unit of the Lyons Sandstone from Red Rock Canyon Open Space, Colorado Springs, Colorado. This rock is the “whiter” cross bedded eolian facies of the Lyons according to Milito (2010). The lighter colored grains are quartz and the darker grains are microcline. The sandstone is quite immature and angular. It is not very well-sorted, contrary to what has been reported previously. Our data (Table 2) shows it is moderately sorted. Note the occurrence of many smaller grains between the larger grains. X-ray diffraction analysis (weight fraction of the bulk powder) showed the rock was 88% quartz, 11% microcline, and 1% dolomite. Photo by Calgary Rock and Materials Inc.

TABLE 1. BULK POWDER XRD ANALYSIS (WEIGHT FRACTION) OF VARIOUS LYONS SANDSTONE SAMPLES (LSS)

Sample and location information	Quartz	Microcline	K-Feldspar	Kaolinite	Dolomite
LSS-1, N40.21995° W105.26130°	0.98	0	0	0.02	0
LSS-2, N40.22005° W105.26153°	0.98	0	0	0.02	0
LSS-3, N40.22059° W105.26264°	0.98	0	0	0.02	0
LSS-4, N40.22563° W105.15000°	0.98	0	0	0.02	0
LSS-5, N40.22563° W105.15000°	0.98	0	0	0.02	0
RRC-1, N38.85212° W104.87883°, red lower unit of Lyons	0.86	0.12	0	0	0.03
RRC-2, N38.85167° W104.87760°, red upper unit of Lyons	0.90	0.10	0	0	0
RRC-3, N38.85158° W104.87730°, white upper unit of Lyons	0.88	0.11	0	0	0.01

Note: LSS samples are from Lyons, Colorado, from the reddish, cross-bedded sandstone that is commonly found there. RRC samples are from Red Rock Canyon Open Space, Colorado Springs, Colorado.

TABLE 2. GRAIN SIZE STATISTICS FOR THE LYONS SANDSTONE

Sample #	No. of field of views sampled on slide (100x)	No. of total grains measured	Mean grain size (ϕ)	Grain size range (ϕ)	Name of mean grain size	Sorting (std. dev.) of mean grain size (σ)	Sorting name
LSS-1	10	673	3.08	1.22–5.21	very fine sand	0.67	moderately sorted
LSS-2	5	412	3.32	1.27–5.72	very fine sand	0.77	poorly sorted
LSS-3	5	388	3.25	0.95–5.32	very fine sand	0.80	poorly sorted
LSS-4	10	625	3.25	1.25–5.38	very fine sand	0.68	moderately sorted
LSS-5	5	406	4.00	1.17–5.80	very coarse silt	1.01	very poorly sorted
RRC-1	4	703	3.70	1.83–6.64	very fine sand	0.59	moderately sorted
RRC-2	10	610	2.89	1.54–5.32	fine sand	0.55	moderately sorted
RRC-3	10	656	3.00	1.78–5.44	very fine sand	0.58	moderately sorted

Note: Data reported are the long axes of sand grains, measured in ϕ units. Every grain was measured in 4 to 10 different “field of views” with a petrographic microscope attached to a digital camera with measuring software for easy and accurate measurement. Areas were chosen at preselected intervals perpendicular to bedding. The entire breadth of the thin section was always sampled with a goal of at least 400 grains (most authors think about 300 grains is sufficient). If 400 grains were not obtained on the first pass, a second pass in another area of the slide was completed. We used Johnson’s (1994) definitions for sorting when long axis lengths of grains are measured on thin sections. Location information for the sample numbers is the same as in Table 1.

micaceous silty sandstone ~30 m thick. It is not very resistant to erosion and is rarely exposed at the surface. It forms a strike valley in most places. The lower unit consists of massive fine-grained sandstone with poorly defined cross bedding. The unit is ~46 m thick. It makes most of the hogbacks in the park. Morgan et al. (2003) state that this unit is also well-sorted, but this does not appear to be the case in some of the easily accessible park exposures. As one enters the park from the main parking lot on the north side of the park, the high cliffs to the west will be the lower Lyons, the sidewalk covers middle unit, and the small white sandstone ridge to the east is the upper unit. A good place to study exposures of lower Lyons is Sentinel Spires which is surrounded by a circular cement walkway. The “Tower of Babel” and the “Kissing Camels” are all of Lower Lyons. “Gray Rock” is an exposure of upper Lyons ~1 km south of the north parking area. It is easily seen if you take the driving loop all the way around the park. It will be on the west side of the road ~1 km north of the main southern parking lot. Maps of the Central Garden area with photographs of the main landmarks are posted at many locations around the park. A detailed geologic map of this complex area can be found on p. 20 of Morgan et al. (2003). Several faults transect the area.

Blood (1970) divides the Lyons Sandstone into three units in the Morrison area (~20 km southwest of Denver) for a total

Figure 10. Lower unit of the Lyons Sandstone, Red Rock Canyon Open Space, Colorado Springs, Colorado. This has been reported as a fluvial unit by most authors, similar in nature to the Fountain Formation. The rock is immature and moderately sorted. X-ray diffraction analysis (weight fraction of the bulk powder) showed the rock consisted of 86% quartz, 12% microcline and 3% dolomite. Photo by Calgary Rock and Materials Inc.

thickness of ~45 m. The uppermost unit is a quartzose sandstone ~18 m thick. The middle unit is also a ~22-m-thick quartzose sandstone which displays tabular-planar and wedge-planar type cross stratification. The lower unit is ~4 m thick and is similar in nature to the Fountain Formation. It contains local cross stratification.

The Lyons Sandstone at the type section in Lyons, Colorado, (~60 km northwest of Denver) has a very different character than that observed in the Colorado Springs area. Many authors have suggested an aqueous deposition for most of the Lyons (either fluvial, beach, or shallow marine), but the similarities of the Lyons Formation to other eolian sandstone formations have led authors like McKee and Bigarella (1979) to see it as a classic example of coastal dune deposits, at least in the Lyons, Colorado, area. The authors acknowledge that this sandstone closely resembles the Coconino Sandstone of Arizona as it contains many of the same characteristics (such as the high angle tabular and wedge cross strata; Fig. 11), is fine-grained and has asymmetrical ripple marks, occasional “slump” features, structures that resemble raindrop prints, and trackways similar to those found in the Coconino Sandstone. Lockley and Hunt (1995, p. 44) consider the Lyons Sandstone to be the “Twin of the Coconino.” Thompson (1949) reports that the Lyons is ~113 m thick at the type locality and that it contains numerous arkose lenses. As in other parts of the Lyons Formation, the type section can also generally be divided into three units (Dimelow, 1972), although the clean cross-bedded sandstone facies comprises most of the section at this locality. We collected several samples for thin section study and XRD analysis from this location; a thin section is shown in Figure 12 and the XRD results are in Table 1. Grain size statistics of these samples can be found in Table 2. We collected typical Lyons Sandstone for our thin section analyses, and found the sandstone was moderately to very poorly sorted. None of our five samples was “well-sorted” as other authors have reported.

The Lyons Sandstone continues to thin toward the Wyoming border. At Horsetooth Reservoir (~96 km north of Denver) Adams

and Patton (1979) report the Lyons is ~21 m thick. They report three distinct facies (not three units) consisting of thick cross-bedded sandstones (interpreted as eolian), thin silty sandstones (interpreted as forming in a flat damp sebkha environment), and thin well-sorted horizontally bedded sandstones (interpreted as sheet sands blown across the sebkha).

Paleontology of Lyons Sandstone

As is common in many of the Permian cross-bedded sandstones of the western United States, no body fossils are known from the Lyons Formation. However, several types of invertebrate and vertebrate trackways have been reported. Henderson (1924) reported vertebrate trackways that are similar to those found in the Coconino. Lockley and Hunt (1995) consider the Lyons tracks to be the same genus as those common in the Coconino, *Laoporus*. Dorr (1955) reported possible scorpionid tracks from the Lyons. Brand and Tang (1991) presented compelling evidence to suggest that the common Coconino tracks were formed underwater.

Depositional Interpretations of Lyons Sandstone

Nearly all authors who have studied the petrology of the Lyons Sandstone have recognized that at least parts of it are sub-aqueous. However, most authors believe the extensive and thick cross-bedded portion of the Lyons Formation is eolian in origin. For example, McKee and Bigarella (1979) use this as one of their

Figure 11. Wedge-planar cross stratification that can commonly be found in the Lyons Formation. This photo was taken in Lyons, Colorado; the location for the type section of the formation. Photo by John Whitmore.

Figure 12. Thin section from the Lyons Sandstone, Lyons, Colorado. Collected near the location of Figure 11. Many of the grains are rounded, but the sandstone is poorly sorted (Table 2); an unexpected result if the formation formed from eolian conditions. X-ray diffraction analysis of this sample (weight fraction of the bulk powder) showed the rock consisted of 98% quartz and 2% kaolinite; the same result obtained from all the other Lyons samples from this location (see Table 1). Photo by Calgary Rock and Materials Inc.

criterion for the eolian deposition of the Lyons. One other criterion that is often cited for eolian deposition is the presence of well-sorted sandstones. Although our thin section study has not been thorough or comprehensive, we were surprised to find that the thin sections we cut from the thick cross-bedded portion of the Lyons (Figs. 9 and 12; samples LSS 1–5 and RRC-3) were moderately to very poorly sorted (Table 2). This may suggest water, rather than eolian deposition for the cross-bedded portion of the Lyons. A possibility that has not yet been considered, but that might be explored, is deposition of the Lyons by subaqueous sandwaves. Large subaqueous sandwaves are rather common features on the continental shelf (e.g., see Barnard *et al.*, 2006). A model like this may help us understand (1) why the Lyons does not appear to be particularly well-sorted in the cross-bedded facies as we might expect from eolian sands, (2) why so many aqueous facies are present within the Lyons, (3) why the Lyons transitions into aqueous facies to the east in the subsurface, and (4) why channels of crudely sorted arkoses occasionally occur in the main cross bedded body of the Lyons. Such a model has been proposed for other cross-bedded sandstones, like the Navajo (Freeman and Visser, 1975), but has been met with little acceptance. This hypothesis should make for interesting discussion on our field trip.

STOP 4: CRETACEOUS WESTERN INTERIOR SEAWAY DEPOSITS IN RED ROCK CANYON OPEN SPACE

Red Rock Canyon Open Space (RRCOS) is a 789-acre recreational area acquired by the City of Colorado Springs in 2003.

Located south of Route 24 (Cimarron St.) and west of South 31st Street, RRCOS straddles the Colorado Springs and Manitou Springs quadrangles. Steeply east-dipping to near-vertical strata form a series of north-south-trending hogbacks and valleys (Fig. 13), which provides excellent exposures of Permian through Cretaceous sedimentary deposits (Fig. 14). Our focus here will be on marine Cretaceous deposits. The field excursion traces a ~1.5 km (>1 mile) hike along the Lower Hogback trail, on the Northern portion of RRCOS from the park entrance on 31st Street to the main entrance at South Ridge Road. Geologic units encountered and discussed below are, in descending order: the Pierre Shale, Niobrara Chalk, Colorado Group (Including the Carlisle and Graneros Shales), and Dakota Sandstone.

Our understanding of the geology of RRCOS has benefited greatly from updated regional geologic mapping (e.g., Carroll and Crawford, 2000, Keller *et al.*, 2005) and recent park-specific investigations (Milito, 2010; Weissenburger *et al.*, 2010). Most of the Cretaceous strata exposed in RRCOS were formed during the inception and diverse expression of the Western Interior Seaway, which spanned from the present-day Gulf of Mexico to the Arctic Ocean, completely bisecting the North American continent (see Kauffman, 1984, for an overview). During the Cretaceous (especially the late Cretaceous), a series of eustatic sea level cycles produced numerous limestone, shale, and sandstone units reflective of changing shorelines and water depth. For the units described below, allocation to Cretaceous Western Interior sea level cycles is given, along with third-order cycles following Haq *et al.* (1987). Unit

Figure 13. South-facing photograph of Paleozoic and Mesozoic strata exposed in Red Rock Canyon Open Space. Photo courtesy Don Ellis and Friends of Red Rock Canyon.

thicknesses are from Milito (2010) and Weissenburger et al. (2010) unless otherwise noted.

Pierre Shale

The Pierre Shale is an immense unit of gray, organic-rich shales and mudstones, weathering brown to olive-green. Within RRCOS, the Pierre Shale (90 m thick) occurs in only small, inconspicuous exposures along the easternmost edge of the park (Fig. 14). Member assignments are difficult, but based on regional mapping of ammonite species (Scott and Cobban, 1986), these exposures likely belong to the middle Campanian *Baculites scotti* ammonite zone or older. Given this age, the RRCOS portion of the Pierre Shale was deposited during early Bearpaw Cycle (UZA 4.2). Outside of RRCOS, the Pierre Shale underlies most of Colorado Springs, and is ~1400–1500 m thick (Carroll and Crawford, 2000, Keller et al., 2005). Older portions of the unit are found to the south-southwest of the park, extending to Pueblo, Colorado (Scott and Cobban, 1986).

Niobrara Chalk

The Niobrara Chalk (140 m thick) is composed of two conformable members, the lower Fort Hays Limestone and the upper Smoky Hill Chalk. The entire unit is at least Coniacian to Santo-

nian in age (Carroll and Crawford, 2000), though it may extend into the lower Campanian (see Gill et al., 1972). In RRCOS, the Niobrara Chalk has produced clams (esp. *Inoceramus* sp.), oysters, fish bones and scales, and trace fossils (Milito, 2010). The unit was deposited during the Niobrara Cycle (UZA 3.1–3.4)

The Smoky Hill Chalk is exposed along the east flank of easternmost ridge in RRCOS. Yellow-orange to brown shales alternate with white chalk beds and occasional thin limestone beds (Carroll and Crawford, 2000). The Fort Hays Limestone is a dominantly micritic limestone with thin calcareous marine shale layers. It crops out as a prominent, light-colored ridge along the easternmost edge of RRCOS, forming a hogback with the underlying Codell Sandstone Member of the Carlisle Shale.

Colorado Group

The Colorado Group is also referred to as the Benton Group or Benton Shale. The varied terminology is a result of the exposures in the Colorado Springs area being much smaller than elsewhere, where several of the members are recognized as formations. In RRCOS, the Colorado Group is 150 m thick, and composed of four units (in increasing age): the Codell Sandstone Member, Carlisle Shale, Greenhorn Limestone, and Graneros Shale. These Cenomanian through Turonian units were deposited during the Greenhorn Cycle (UZA 2.3–2.7), which included the largest transgression of the Western Interior Seaway during the early Turonian (see Kauffman, 1984; Haq et al., 1987).

The Codell Sandstone Member is medium- to coarse-grained, yellow-brown, calcareous, often bioturbated, and highly fossiliferous. Milito (2010) reported fish bones, shark teeth, ammonite imprints, and pelecypods. The Codell Sandstone is 2–4 m thick in RRCOS and forms the easternmost hogback in RRCOS with the overlying Fort Hays Limestone.

The underlying Carlisle Shale has a gradational upper contact with the Codell Sandstone. The Carlisle Shale and Graneros Shale are undifferentiated here. They are soft, dark gray, thinly bedded, fossiliferous marine shales with occasional bentonite stringers. The Greenhorn Limestone, typically found between the Carlisle and Graneros shales and representative of peak Western Interior Seaway transgression, has not been identified within RRCOS (Milito, 2010), but is recognized elsewhere in the area as dark- to light-gray limestone with occasional silt and shale beds (Carroll and Crawford, 2000; Keller et al., 2005). These units form the strike valley between the Codell Sandstone/Fort Hays Limestone to the east and the Dakota Sandstone to the west.

Dakota Sandstone

Lower Cretaceous (Aptian-Albian) Dakota Sandstone forms the most prominent hogback in eastern RRCOS (Fig. 13), producing the highest elevation in the park of 1972 m (6740 feet) above sea level. Two medium- to massive-bedded sandstone units form the lower portions of the Dakota Sandstone, and the upper portion is composed of thin-bedded sandstones and organic-rich

Figure 14. Bedrock geologic map of Red Rock Canyon Open Space. Modified from Milito (2010).

gray shales. The unit is 65 m thick in RRCOS, dominated by yellow, brown, and gray quartz sandstones. The Dakota Sandstone is typically understood as a regressional delta environment, including estuary and tidal channels, with the upper sand/shale unit formed during the transgressive phase of the Kiowa/Skull Creek cycle (UZA 2.1–2.2). This marks the first complete connection of the Western Interior Seaway (Kauffman, 1984) during the Cretaceous.

Both body and trace fossils are common in the Dakota Sandstone (see Milito, 2010, for a full discussion). Tree trunks and roots, conifer cones and pollen (*Arucaria* sp.), ferns (*Anemia* sp.) and abundant leaf imprints have all been documented in RRCOS, as have dinosaur tracks, likely produced by ankylosaurs and iguanodontids. Trace fossils include *Ophiomorpha*, *Planolites*, and *Rhizocorallium*. In addition, ripple marks are common, particularly in the upper portion of the formation.

STOP 5: MAJESTIC DIKE

Sandstone dikes of the Front Range have been a source of amazement since 1894, when they were first described in an early volume of the *GSA Bulletin* (Cross, 1894). The more than 200 dikes of the Front Range dike belt closely parallel the reverse-faulted eastern flank of the mountain range for more than 75 km, inferring a tectonic cause-and-effect relationship. The dikes collectively indicate the mobilization and injection of up to 1.2 cubic kilometers of sand. These are among the world's largest sedimentary "injectites." No longer academic curiosities, sand injectites represent important reservoir targets in several offshore petroleum basins, most notably the North Sea (Hurst and Cartwright, 2007). In contrast to most dikes which are found in sedimentary successions, the Front Range dikes are emplaced in Proterozoic crystalline rocks. So far as this author knows, they are unique in the world.

Individual dikes range in thickness from a few centimeters to 275 m, in length from a few meters to more than 10 km, and in exposed height more than 300 m. Alignment of long axes of sand grains and granite fragments in the dikes suggests forceful injection of fluidized sand into granite walls that apparently opened by simple dilation. The dikes are generally unfaulted, and wall rocks show little evidence of shearing or granulation. Dikes are composed of fine- to medium-grained, well-rounded, and poorly sorted sandstone with occasional angular granite fragments, quartz pebbles, and rare but significant fragments of red mudstone. The Upper Cambrian Sawatch Sandstone is universally regarded as the primary parent bed for the quartzose sand and pebbles, with trace contributions from mudstone strata higher in the section, perhaps as high as the Fountain Formation. Angular granite fragments are obviously broken pieces of wall rock. It is relatively undisputed that the dikes are genetically related to the range-bounding Ute Pass and Rampart Range faults, and that the Sawatch Sandstone was the primary parent bed for the dike material. However, there is much less agreement on the timing of sand mobilization. Cambrian movement on these faults and a Cambrian injection has been offered by many as the only means to explain the Sawatch Sandstone compositional affinity, although positive support from the structural geology community for this position is not strong. Dike attitudes are perfectly consistent with extensional stresses expected from Laramide reverse faults that steepen with depth (Harms, 1965). Such fault geometry is not popular (Erslev et al., 2004) in tectonic schemes that call for major Rocky Mountain faults to flatten with depth, in accordance with current plate tectonic models, but it does offer a consistent structural model for dike injection.

The largest dikes occur along the western margin of the Manitou Park half-graben. Two stops will be made in this district; the first at a small-scale dike that demonstrates the injectite nature, and the second at a large-scale body of 100 m in thickness

Figure 15. Generalized cross section of Manitou Park showing structural relations of the dikes. No vertical exaggeration. Ypp—Proterozoic Pike's Peak Granite, Cs—Cambrian-derived sandstone dike, PPf—Pennsylvanian-Permian Fountain Formation, C-M—Cambrian Sawatch Sandstone, Ordovician Manitou Formation, and Mississippian Leadville Limestone. Modified from Temple et al. (2007).

that is impressive for its scale. The Manitou Park half-graben is bounded on its east by monoclinaly dipping Cambrian strata that rest on Pikes Peak Granite, on the west by the Ute Pass fault, and is floored mostly by gently dipping Fountain Formation strata. Structural relations are depicted in Figure 15. At least 1000 m of Laramide reverse movement can be demonstrated for the steeply dipping Ute Pass fault, which places Pikes Peak Granite over the Pennsylvanian-Permian Fountain Formation (Temple et al., 2007). The dikes are concentrated along the hanging wall of the Ute Pass fault, usually within a kilometer of the main line of displacement. They strike parallel to the fault, and dip more steeply but in the same direction. In this respect they are consistent with all the Front Range dikes.

Stop 5 is exposed in the gated community of Woodland Park. It is an outstanding example of a one-meter-thick dike that displays its injectite nature. The Ute Pass fault lies ~600 m to the northeast. The dike walls are parallel and unsheared. The fine-grained and poorly sorted sand is homogenous from wall to wall, a very consistent feature of the Front Range dikes. Some noticeable angular granite fragments to several centimeters are preferentially aligned with dike walls. The sand-sized grains also show extraordinary alignment as seen in petrographic thin-section (Vitanage, 1954; Scott, 1963; Harms, 1965). The maroon and buff discoloration of dikes on weathered surface is probably

related to the iron oxide cement, which was the subject of a paleomagnetic study (Kost, 1984) that favored a Cambrian-Ordovician injection event.

There is little controversy that this dike originated when fluidized Sawatch Sandstone was forcefully injected into fissures that opened in response to movement along the Ute Pass fault. The nature and timing of that movement remain controversial. The close compositional match to the Cambrian Sawatch Sandstone, paleomagnetic data, and the existence of some dikes in areas where the Sawatch Formation was erosionally removed (in Late Pennsylvanian) have been used to argue for a Cambrian or perhaps Ordovician injection event. The structural compatibility of the dikes with reverse faults that steepen with depth (Harms, 1965), and the mudstone fragments from much higher in the stratigraphic section, argue for a Pennsylvanian or later injection event.

STOP 6: CRYSTOLA DIKE

Stop 6 is on public land at the end of the 2.2-km Crystola Canyon Road. The road departs west from U.S.-24 in the small town of Crystola, Colorado.

The 100-m-thick sand body near Crystola forms an erosionally resistant ridge (Fig. 16); it is an example of a large sand injectite. Some dikes along the western part of Manitou Park are as

Figure 16. The well-indurated Crystola dike enclosed within Pikes Peak Granite walls. Photo by Bill Hoesch.

thick as 275 m. These are large sand bodies! Here the full thickness of the dike can be examined from wall to wall but requires a little scrambling. The dike dips $\sim 75^\circ$ west and strikes parallel to the Ute Pass fault, which passes ~ 750 m to the northeast. Note its similarity in texture to the Woodland Park dike, including its mottled appearance, and great homogeneity. Evidence for faulting of dike walls or internal shearing of the sandstone is not extensive, if present at all.

Recent examination (Temple et al., 2007) of nearby geological quadrangles makes a distinction between the small-scale dikes such as at Stop 5 and the large sand bodies such as here at Crystola. The larger sand bodies, interpreted for more than a century as injectites have been reinterpreted as “fault panels” or “fault slices” of Cambrian Sawatch Sandstone caught up in past movements of the Ute Pass fault zone. The great textural homogeneity, absence of graded beds as seen in the Sawatch Sandstone, and the considered opinion of dozens of geologists since the end of the nineteenth century (Cross, 1894), are contrary to this interpretation. However, if the Crystola body originated as fluidized Sawatch Sandstone, as appears to be the case, how could the Sawatch Sandstone with a regional thickness of 20 m supply dikes of hundreds of meters in thickness? Dike injection must have been either (1) preceded by great lateral movement of sand in the parent bed, or else (2) there was a “draw down” of the regional Sawatch thickness from a much greater value in the past.

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