AN ANALYSIS OF THE SEDIMENTARY GEOLOGY OF THE JURASSIC RALSTON CREEK FORMATION AS IT IS EXPOSED IN THE VICINITY OF CANON CITY, COLORADO

By

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PREFACE

The purpose of this thesis is to describe the sedimentary geology of the Jurassic Ralston Creek Formation as it is exposed in the vicinity of Canon City, Colorado. This thesis includes a description of the lithofacies and lithologies, an analysis of the petrography and diagenesis of the lithologies, and an interpretation of the depositional environments.

I would like to express my sincerest thanks to Dr. R. Nowell Donovan for proposing this study and for his help and guidance throughout its completion. Dr. Donovan was my major advisor until he left for Texas Christian University. I would also like to thank Dr. Arthur Hounslow, who took over as my major thesis advisor after Dr. Donovan left, and Dr. Gary F. Stewart for their assistance and advice on the final manuscript.

Finally, I would like to express my deepest gratitude to my parents, John and Eleanore Richardson for their support during my many years of higher education. I could never have done it without their love ... and their money! This thesis is dedicated to them.

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CHAPTER I

INTRODUCTION

Purpose

The purpose of this thesis is to describe and interpret the sedimentary geology of the Jurassic Ralston Creek Formation as it is exposed in the vicinity of Canon City, Colorado. Primary objectives are: 1) to redefine the lithofacies, 2) to describe the lithologies, 3) to analyze the petrography and diagenesis of the various lithologies, and 4) to interpret the depositional environments.

Location of Study

The field work for this thesis was conducted in the Canon City embayment. It is located near Canon City, Colorado, in the eastern front of the Rocky Mountains between the southern end of the Front Range and the eastern flank of the Wet Mountains (Figure 1). The embayment is a structural re-entrant that was formed by the en echelon arrangement of two major anticlinal folds, which trend from northwest to southeast (Frederickson et al., 1956). Sedimentary rocks from Ordovician to Pliocene in age are found parallel to the margins of this embayment. Outcrops of the Ralston Creek Formation are well exposed and

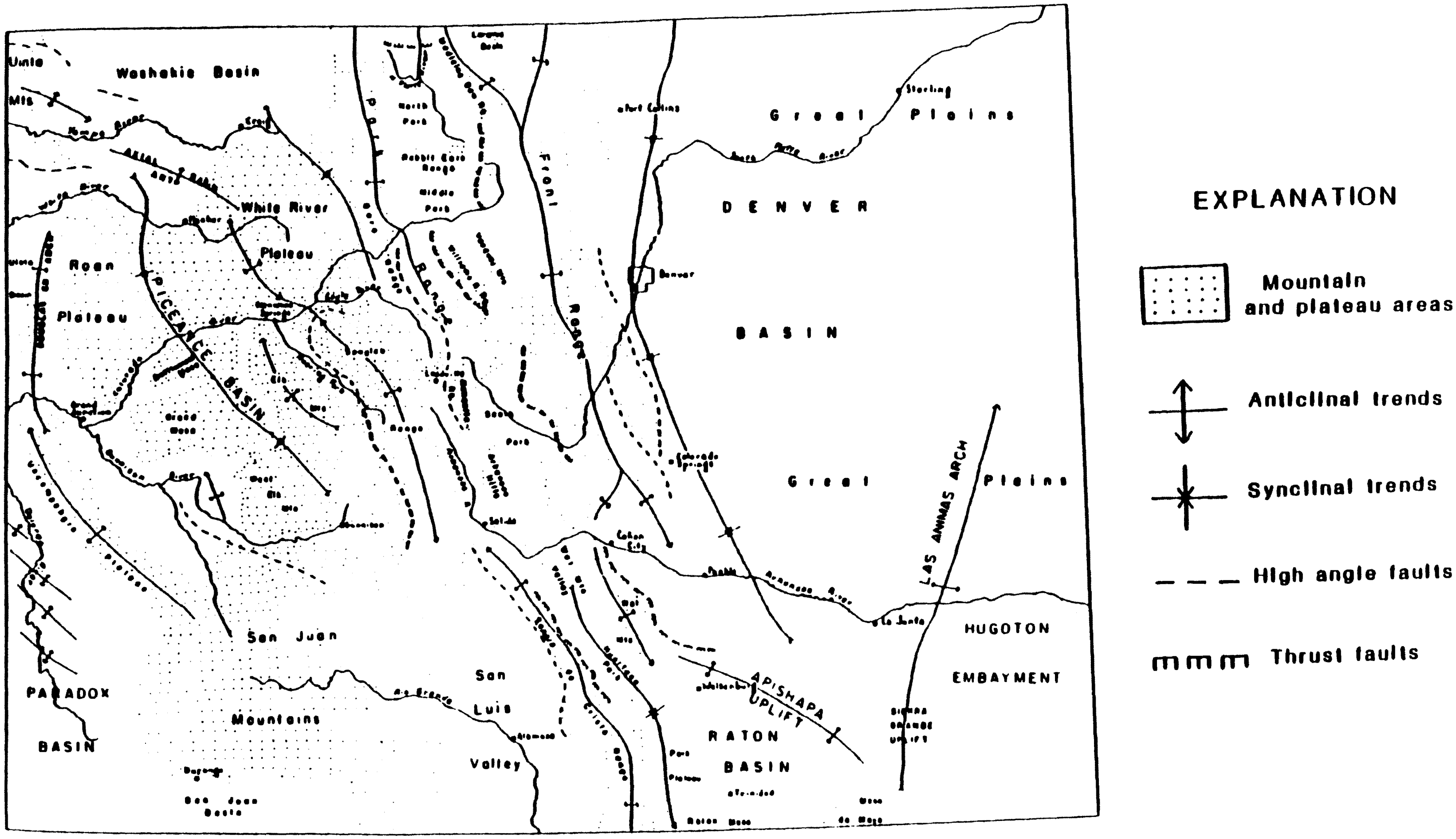


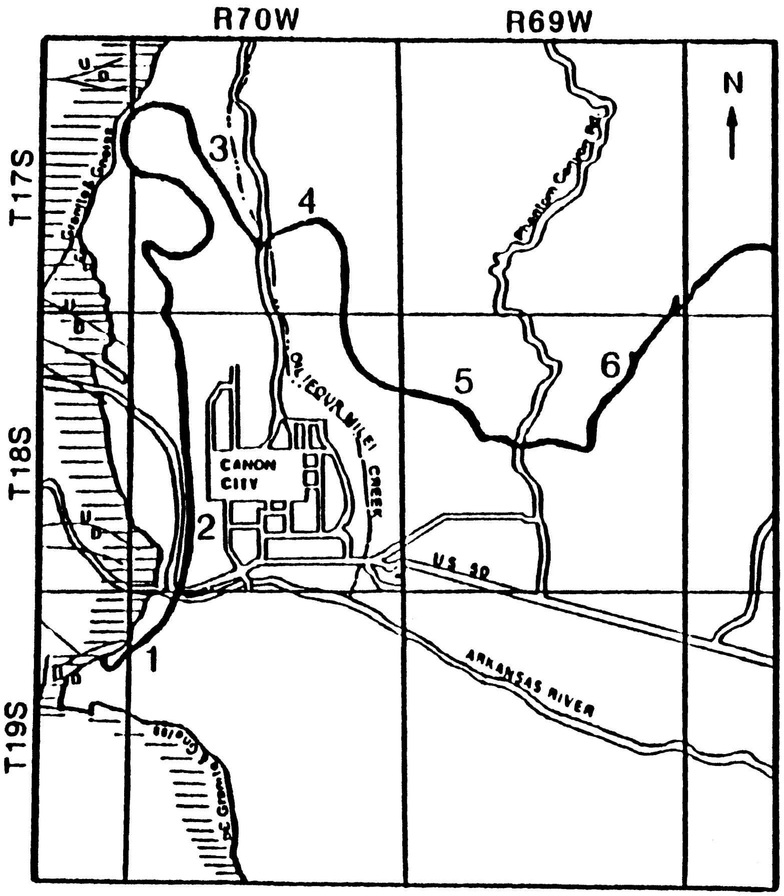
Figure 1. Major Physiographic and Structural Features of Colorado (after Curtis, 1960)

were measured in the area of T17-19S, R69-71W (Figure 2). The type section of the formation is located near Golden, Colorado, approximately 90 miles north of the study area.

Methods of Investigation

The field work for this thesis was conducted during May and June of 1984. An investigation of the vertical and lateral facies variations resulted in 6 representative measured sections (Appendix A). The sections vary in total footage from approximately 38 to 140 feet (Figure 3). They include information on lithology, sedimentary structures, color, and grain size. Samples of the various lithologies were collected to be used for laboratory analysis.

Lab work consisted of preparing and analyzing thin sections. Preparation techniques included selective staining of potassium feldspars using a solution of sodium cobaltinitrite and staining with Alizarin Red-S and potassium ferricyanide to differentiate calcite, dolomite, and ferroan varieties of each (Friedman, 1971). Seventy thin sections were analyzed using a petrographic microscope. Three hundred point counts were made for each thin section.



EXPLANATION

Outcrop of the Ralston Creek Formation

Sections measured:

1 - Grape Creek
2 - Skyline Drive
3 - West Garden Park
4 - East Garden Park
5 - Indian Springs
6 - Soda Ridge

Location of Canon City in Fremont County, Colorado:

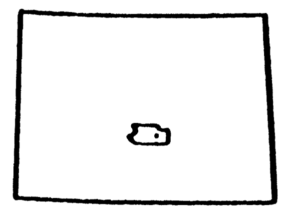


Figure 2. Location Map of Sections Measured in the Vicinity of Canon City, Colorado

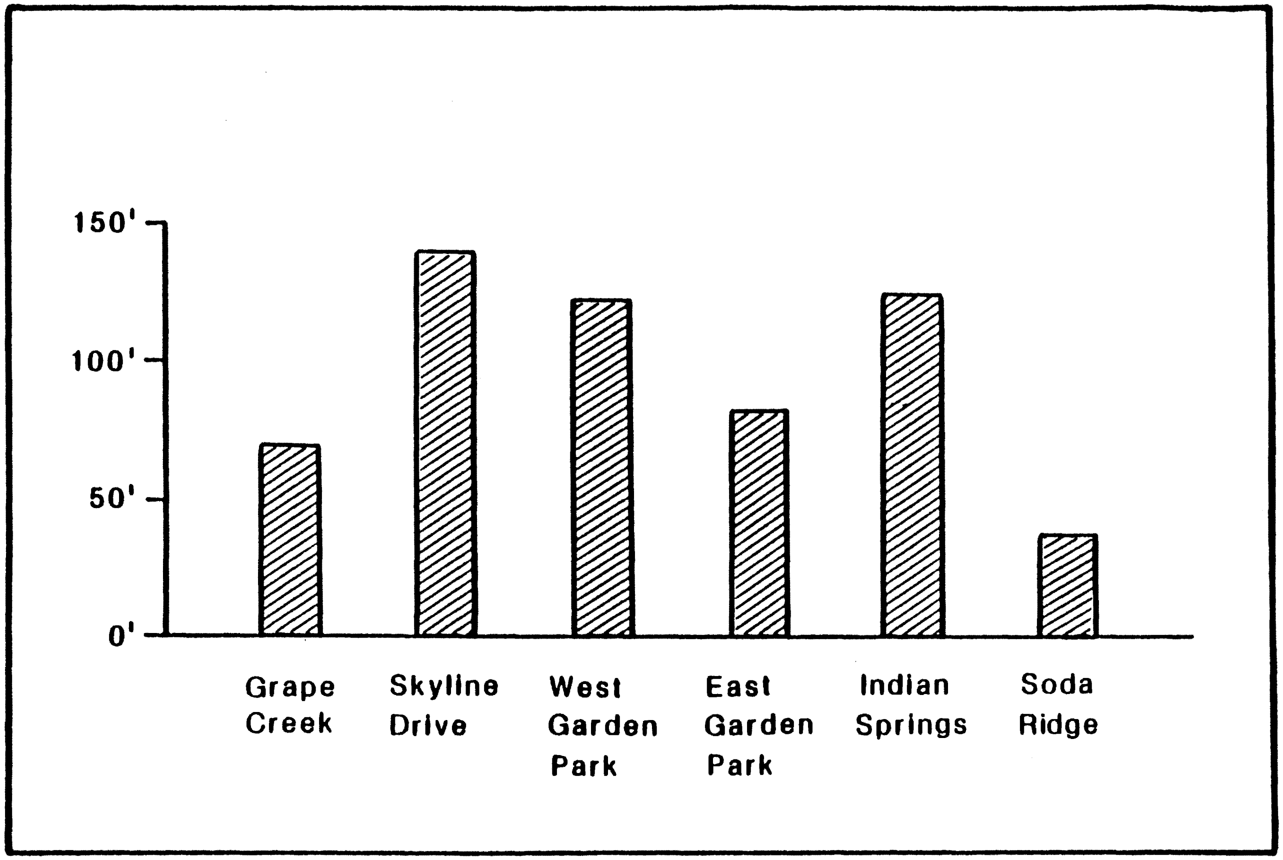


Figure 3. Relative Positioning and Thicknesses of Sections Measured in the Vicinity of Canon City, Colorado

CHAPTER II

PREVIOUS WORK

Prior to 1946, the strata of the Ralston Creek Formation were assigned to either the Morrison Formation (Heaton, 1939) or the Lykins Formation (Lee, 1927). Reeside (1931) described the gypsum beds in the Ralston Creek Formation as being closely related to the Morrison but did not assign them to either of the adjacent formations.

The Ralston Formation was first defined by LeRoy in 1946. The type section, near Golden, Colorado overlies the Lykins Formation and is described as being disconformably overlain by the Morrison Formation. LeRoy places the upper boundary at the "basal Morrison sandstone". Two lateral facies variations characterize the formation: a shale-marlstone facies composed of thinly bedded marlstone and variously colored shales and a gypsiferous facies composed of thinly bedded white gypsum with interbedded siltstone, sandstones, and shales. He tentatively assigned a Jurassic age to the formation based on scattered fossil evidence and its similarity to the Morrison.

In 1950, Heaton described the Ralston Formation as being of marginal marine origin and time equivalent with the marine Curtis Formation of northwestern Colorado. He interpreted the evaporitic limestone, gypsum and gypsiferous shales of the Ralston and other time equivalent formations as deposits of a marine transgression that extended along the Front Range of Colorado and over much of southeastern Colorado, northern New Mexico, and northeastern Arizona. He assigned the western conglomerate-sandstone facies to the lower Morrison Formation.

Imlay (1952) included the Ralston Formation of LeRoy in the Wanakah Formation. He described the deposits as being of marginal marine origin and correlative with the Curtis and Summerville Formations of western Colorado and eastern Utah. On the basis of faunal evidence, he suggested that the two facies of LeRoy may not be correlative, and that the marlstone facies may be younger.

Frederickson, DeLay, and Saylor (1956) conducted a detailed lithologic and stratigraphic study of the Ralston Formation from Canon City to Colorado Springs. They measured thirty-one sections and described four sedimentary facies. These included, from west to east: a conglomerate facies, a sandstone facies, a gypsum-shale facies, and a sand-shale facies. A brief paleoenvironmental interpretation defined the Wet Mountains as the source of the alluvial fan conglomerates, the sandstones as beach deposits, and the two eastern facies as deposits of the Late Jurassic sea. Analysis of Ralston sedimentation provided the following observations: 1) that variations in thickness are a result of the irregular erosional surface on which the formation was deposited, 2) that the irregular surface had over 100 feet of relief, 3) that the unconformity resulted from the erosion of the Fountain and Lykins Formations during Triassic and Early and Middle Jurassic time, 4) that the upper and lower Crinkled Limestones of the Lykins Formation controlled the development of the pre-Ralston topography, and 5) that a northward trending stream divide near Garden Park served as a barrier to restrict eastward transport of the conglomerate facies. Finally, they suggested new criteria to distinguish the upper contact of the formation, stating that the "basal Morrison sandstone" was inapplicable in the study area because of the lenticular nature of the sandstones and their varying stratigraphic positions.

The name Ralston Formation was changed to Ralston Creek Formation by Van Horn in 1957.

In a study of Permian to Jurassic strata east of the Colorado Front Range, Ogden (1954, 1958) selected two key beds as time-surface markers to be used for regional correlation. They are the Falcon Limestone member as the base of the Lykins Formation and a chert zone as the top of the Ralston Formation. Ogden stated that the chert zone could be correlated from western Kansas to the Uinta Mountains in northeastern Utah and from Wyoming to central New Mexico. On the basis of stratigraphic evidence, he concluded that the gypsum beds in the Ralston Formation are lateral equivalents of the gypsum beds associated with the two thin limestone members of the Lykins Formation, that the sediments between the two key beds represent a more or less continuous slow sedimentation from Late Permian to Late Jurassic, and that no significant post-Lykins unconformity exists in this region.

Cramer's (1962) study of the Ralston Formation from Canon City to Colorado Springs included twenty measured sections and focused primarily on lithologic and stratigraphic descriptions. He suggested that the use of "welded chert zone" as the base of the Morrison was questionable because of its varying stratigraphic position and because it may have been introduced by replacement. On the basis of pollen analysis, Cramer stated that a definite correlation could be made between the conglomerate and gypsum facies and that the basal limestone bed in the Garden Park and Shaws Park areas, which had previously been correlated with limestones in the Lykins Formation, was Jurassic in age. His interpretation of the depositional environments represented by the various lithologies includes: alluvial fan conglomerates, shoreline deposits of sandstones, restricted marine deposits of gypsum and limestone, lagoonal deposits of sandy shale and marlstone, and possible deltaic deposits of some of the finer clastic sediments. The changes in lithologies from west to east were attributed to the gradual eastward regression of the Ralston sea. He considered Ralston sediments to be time transgressive in a northeasterly direction.

In 1984, Carter measured seventeen sections in the

Canon City embayment. He divided the Ralston Creek into two facies: a western conglomerate/sandstone facies and an eastern gypsum-sand/shale facies. The western conglomerate/sandstone facies was subdivided into two subfacies: 1) a trough cross-stratified, pebble to boulder, arkosic conglomerate in the extreme west, and 2) a moderately sorted, medium grained, parallel laminated sandstone in the east. Carter concluded that the western facies was deposited in an alluvial fan environment and the eastern facies was deposited in a marine sabkha environment. He described the rare parallel laminated gypsum as being deposited in a standing body of super saturated saline water, but did not elaborate any further. On the basis of petrographic analysis and point counts of quartz and feldspar in sandstone/shale pairs, Carter suggested: 1) that Ralston Creek sediments were derived from multiple sources, 2) that the Wet Mountain granite primarily contributed to the shales and siltstones, and 3) that the Entrada Formation was the major source for the quartz-rich sandstones.

In studies of the regional geology of the area, the paleoenvironment of the Ralston Creek has been described as restricted marine by Kocurek and Dott (1983) and Peterson (1974) and nonmarine by Haun (1960).

CHAPTER III

REVIEW OF OVERALL GEOLOGIC SETTING

Regional Geology

The paleogeography of the Western Interior of North America during the Jurassic was influenced by tectonic activity taking place along the western margin of the continent. Subduction of the Pacific plate beneath the North American plate and the emplacement of a magmatic arc complex resulted in the uplifting of Paleozoic rocks east of the magmatic arcs. These rocks formed the margin of a large interior seaway that extended from the north (Figure 4). Sediments were deposited in a retroarc to craton-margin basin (Brenner, 1983; Kocurek and Dott, 1983).

Four major marine transgressions have been recorded for the Jurassic. These conform well to the global rises in sea level postulated by Vail et al. (1977). The last and most extensive transgression began in the Callovian and reached its maximum limits during the Oxfordian (Brenner, 1983).

During Pliensbachian to Middle Oxfordian time, the central and southern Rocky Mountains region occupied a paleolatitude range of 5^{o} to 25^{o} north (Steiner and Helsley, 1972, 1975; Steiner, 1975, 1978; Lienert and Helsley, 1980; Kocurek and Dott, 1983). Outcrop evidence suggests a hot

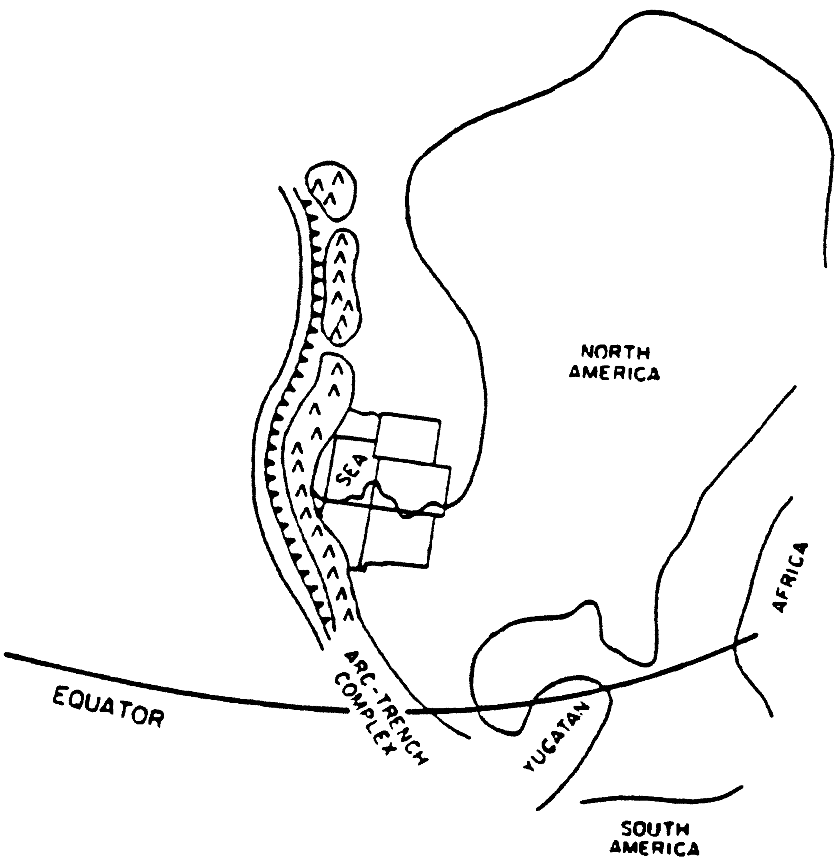


Figure 4. Paleogeography of the Western Interior of North America During the Middle to Late Jurassic (after Kocurek and Dott, 1983)

and arid paleoclimate (Kocurek and Dott, 1983).

Analysis of the lithofacies and biofacies in the area shows that a complex of paleoenvironments existed simultaneously. During the Early Callovian, widespread eolian environments were established in the southern portion of the region. In the northwest, alluvial systems prograded eastward into shallow hypersaline marine to sabkha environments. Normal marine conditions were present only in the central northern area. From Middle Callovian through Middle Oxfordian time, the paleoenvironmental distributions included alluvial fans, shallow marine, and marine deposits in the north, shallow marine, tidal flats, and restricted marine deposits in the south, and eolian, coastal and inland sabkha, and tidal flat deposits at the southern end of the basin (Figure 5).

A major shift in depositional style occurred in the later Jurassic. Non-marine conditions prevailed, and the extensive, relatively thin blanket of continental sediments of the Morrison Formation was deposited. The causes for this change were related to the following climatic and tectonic developments: 1) the probable initiation of eastward thrusting west of the Late Jurassic interior sea, 2) continued uplift of western source areas, 3) relatively low subsidence rates in the region, 4) a lowering of eustatic sea level, and 5) accelerated drift of the North American plate which moved the region into a cooler, more humid climate (Brenner, 1983; Kocurek and Dott, 1983).

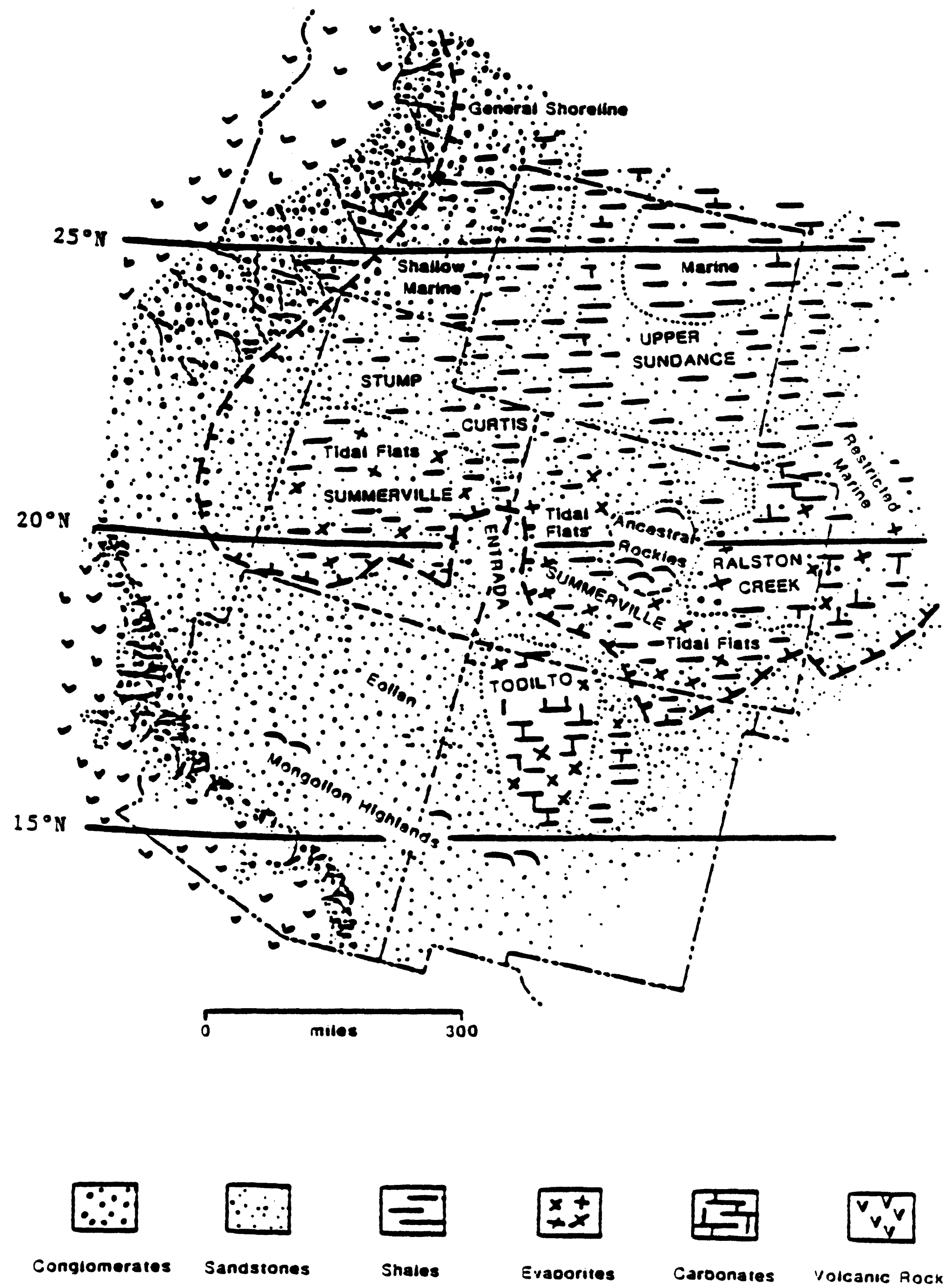


Figure 5. Paleogeographic Map of the Central and Southern Rocky Mountain Region and Paleolatitudes of the Middle to Late Jurassic (after Kocurek and Dott, 1983)

Local Geology

Exposed rocks in the Canon City embayment range in age from Precambrian to Recent (Figure 6). Precambrian crystalline basement rocks are made up of metamorphic gneisses and schists which were intruded by sizable granitic masses. Ordovician and Devonian rocks are primarily carbonates with some fine to medium grained clastics, which were deposited under marine shelf conditions. Several sizable uplifts developed during the late Paleozoic. Their elevation and erosion are indicated by Pennsylvanian and Permian fanglomerates composed of red arkosic conglomerates and other clastics.

An erosional unconformity separates the Jurassic Ralston Creek Formation from the underlying Permian and Pennsylvanian formations. This unconformity is considered to be of regional scale. Following erosion, the topography of the land surface had as much as 100 feet in relief. This had a direct effect on Ralston Creek sedimentation and explains some of the variations in thickness found within the formation (Frederickson et al., 1956).

Ralston Creek sediments were derived from the Ancestral Rocky Mountains, the Ancestral Uncompahgre Highlands (both of which are Precambrian), and from the reworking of older neighboring sedimentary deposits such as the Fountain and Entrada Formations. In the western part of the Canon City area, the Ralston Creek Formation is composed of

PERIOD	EPOCH	AGE	STRATIGRAPHIC UNIT
Jurassic	Late Jurassic		Morrison
		Oxfordian	Ralston Creek
Permian			Lykins
Pennsylvanian			Fountain
Devonian ?			Williams Canyon
Ordovician			Fremont
			Harding
			Manitou
Precambrian			

Figure 6. Generalized Stratigraphic Section of Pre-Cretaceous Rocks in the Canon City Embayment (after Fredrickson et al., 1956)

conglomerates and sandstones. These are a local feature associated with the Wet Mountain uplift area which was tectonically active at this time (Oriel and Craig, 1960). Eastward and north of the embayment the lithology changes to one composed primarily of gypsum with interbedded sandstones and shales and minor carbonates.

Stratigraphy

Outcrops of the Ralston Creek Formation have been recognized in central-northern, central, and south-central Colorado. The age of the formation has been difficult to establish because fossils are very rare. Those reported date the Ralston Creek as Jurassic, but are insufficient to allow a more specific age determination. They include: fossil fish (Schoewe, 1930; Dunkle, 1942), pelecypods, a single gymnosperm (Imlay, 1945), and twig impressions of a conifer (Frederickson et al., 1956). An Oxfordian age was assigned to the formation by Imlay (1952) and McKee (1956) on the basis of regional correlations (Figure 6). Time equivalent formations include: 1) the Swift Formation in Montana, 2) the "Upper" Sundance Formation in Wyoming, 3) the Curtis and Summerville Formations in Utah and Colorado, 4) the Stump Formation in western Wyoming, southeastern Idaho and northern Utah, 5) the Todilto Formation in northern New Mexico, and 6) the Entrada Formation in Utah and Colorado (Frederickson et al., 1956; Kocurek and Dott, 1983) (Figure 7).

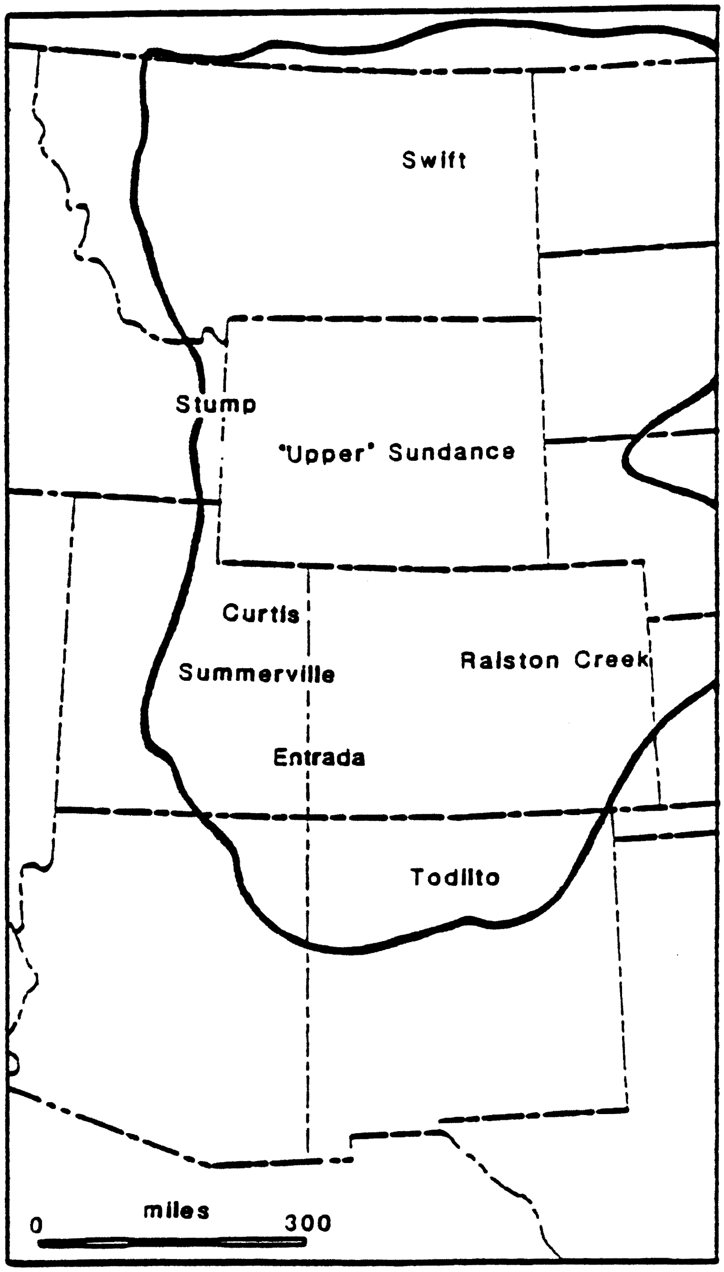


Figure 7. Nomenclature Map of Oxfordian Rocks (after Peterson, 1972; Kocurek and Dott, 1983)

In the Canon City area, the Ralston Creek Formation unconformably overlies the Pennsylvanian Fountain Formation in the west and the Permian Lykins Formation in the east. The Fountain Formation is composed of red arkosic conglomerates, sandstones, siltstones, shales, and a few nodular limestones. The Lykins Formation consists primarily of reddish orange siltstones and shales. Thin gypsum beds are present in a few localities near the base and two persistent limestone beds, termed the "Crinkled Limestones" by Heaton (1933) and Iglehart (1948), are present in the upper part of the formation.

Overlying the Ralston Creek Formation, with apparent conformity, are the continental sediments of the Morrison Formation. The Morrison is composed primarily of varicolored claystones and shales. Also present are a few thin sandstone beds, micritic limestones, and dolomite-rich micrites. Thinly bedded cherts are found near the base of the formation at a few localities. Criteria which can be used to differentiate the Morrison from the Ralston Creek Formation include: 1) an increase in shale and carbonate lithologies in the Morrison, 2) a decrease in arkosic fragments, and 3) the complete absence of gypsum (Sweet, 1984).

CHAPTER IV

LITHOLOGIC DESCRIPTION

Characteristics of Exposures

Well exposed sections of the Ralston Creek Formation are common in the Canon City area. The formation forms a resistant unit which outcrops in a sinuous belt near the base of prominent hogbacks and ridges. It is overlain by the Morrison Formation. The higher dip slopes of the hogbacks are formed by the resistant Dakota Group sandstones which overlie the Morrison.

Lithofacies

Two major lithofacies are present in the Canon City area: a western conglomeratic facies and an eastern gypsiferous facies.

These can be subdivided into a number of *ad hoc* "members" which are locally persistent. The western conglomeratic facies includes:

1) A basal conglomerate "member".

2) A white limestone "member".

3) An upper sandstone "member".

4) An upper conglomeratic "member".

The eastern gypsiferous facies includes:

1) A basal sandstone "member".

2) A laminated dolomite and gypsum "member".

3) An upper gypsiferous "member".

A diagram illustrating the correlation of the various members in the western conglomeratic and eastern gypsiferous facies is shown in Figure 8.

Description of Lithologies

Western Conglomeratic Facies

Basal Conglomerate Member

The basal conglomerate member is present in all of the western sections (the western sections include measured sections 1 through 3, from Grape Creek to West Garden Park). The bed ranges in thickness from 1 1/2 to 7 1/2 feet. The contact between the Ralston Creek Formation and the underlying Fountain Formation is abrupt or slightly erosive. At outcrop scale, there is no apparent difference in dip between the two formations.

At Grape Creek and Skyline Drive, the bed is composed of a grain supported, arkosic conglomerate that is well cemented by calcite. It is red brown and contains numerous black heavy mineral bands. Grain size ranges from fine sand to very large pebble gravel. The sorting is bimodal. The clasts are angular to subrounded. Sedimentary structures include small to medium scale trough cross bedding with set heights of up to 5 inches.

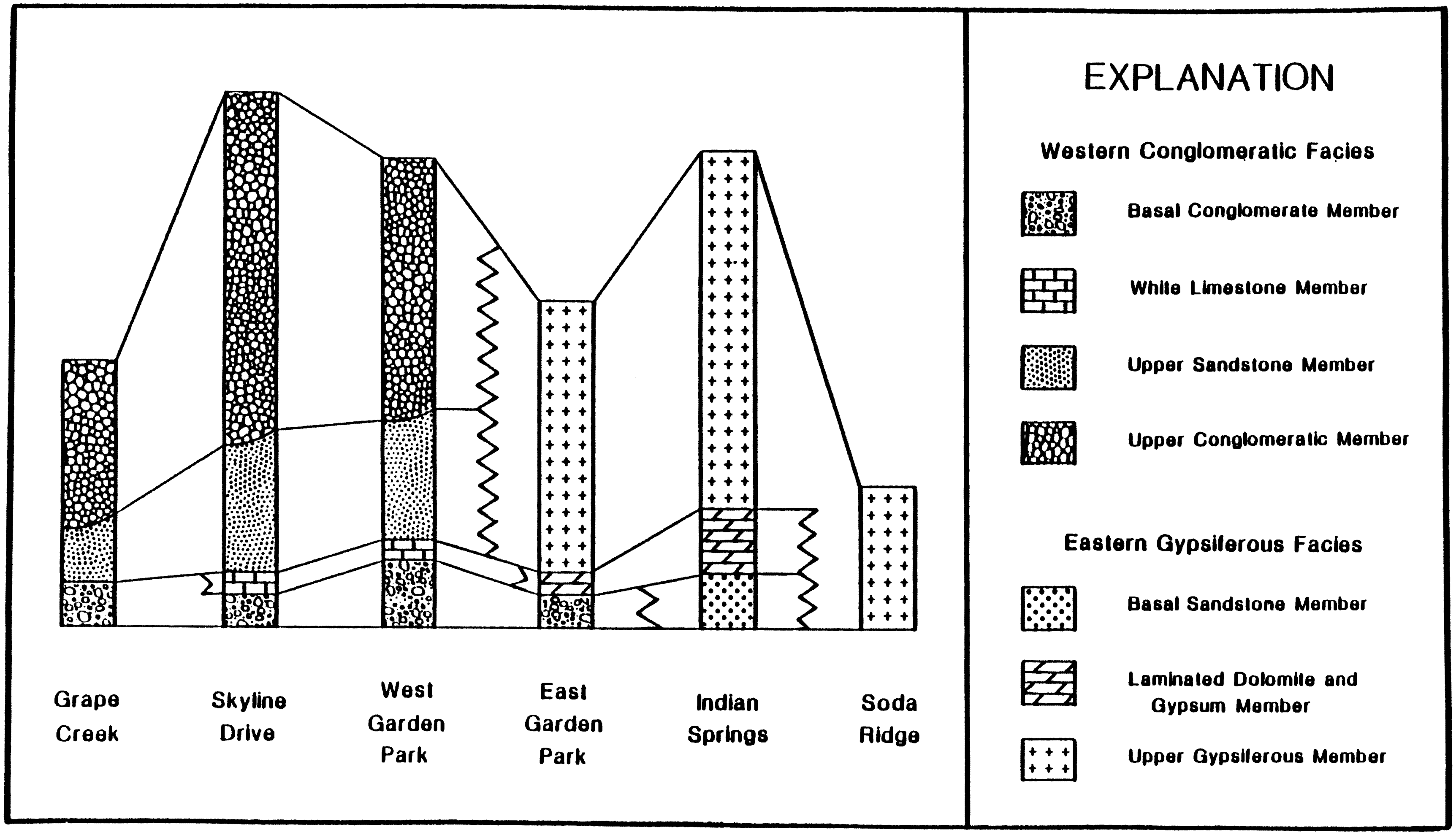


Figure 8. Diagram Illustrating the Correlation of the Various Members in the Western Conglomeratic and Eastern Gypsiferous Facies

Characteristics of the bed change in an eastward direction. At West Garden Park, these changes include: a decrease in grain size, feldspar content, and calcite cement, and an increase in the amount of quartz. The color of the bed is reddish yellow. The dominant sedimentary structure changes to parallel bedding.

A 1 foot thick, buff colored, conglomerate-pebbly sandstone bed is present at the base of the section at East Garden Park. This bed is transitional between the western basal conglomerate member and the eastern basal sandstone member.

<u>White Limestone Member</u>

The white limestone member is present at Skyline Drive and West Garden Park (Figure 9).

The bed ranges in thickness from 6 inches to a foot. In some areas, post depositional deformation has caused pronounced symmetrical folding of the bed as a whole. Where this has occurred the bed thins to 1 to 2 inches in the troughs of the folds.

The bed is composed of a thinly laminated, white, micritic limestone. Penecontemporaneous (soft sediment) deformation produced small internal folds and localized disruption of the laminae. The limestone is cut by a few low amplitude (1 to 2 mm) stylolites which formed parallel to bedding. In some areas, particularly Skyline Drive, the top of the limestone is disrupted by salt pseudomorphs.

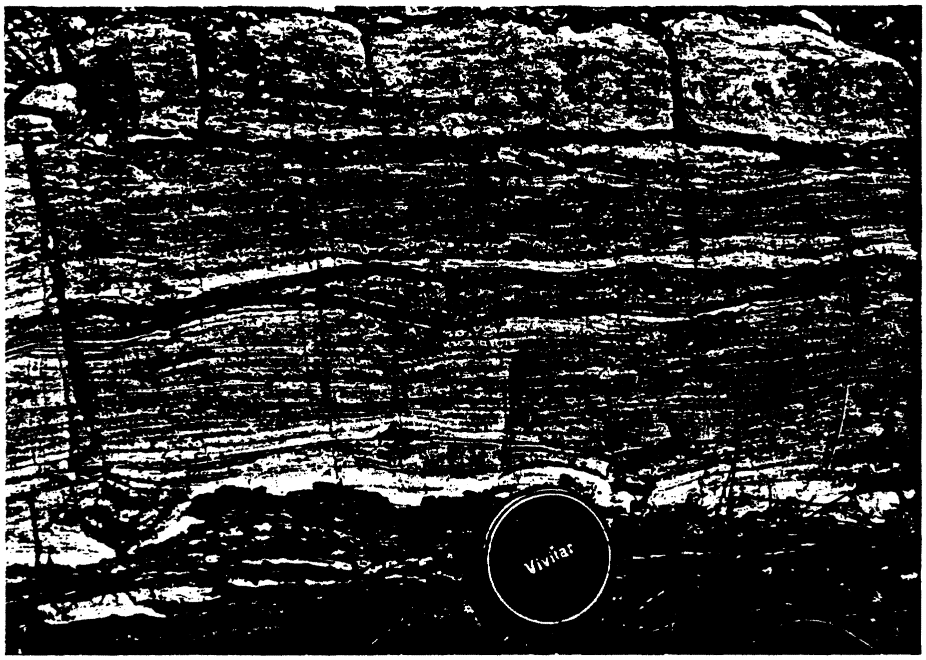


Figure 9. The White Limestone Member at Skyline Drive

There is a small, massive, micritic limestone bed at Grape Creek. It is buff colored and approximately 2 inches thick. This bed is not correlative with the white limestone member. It is interpreted to be a Type 4 calcrete (Steel, 1974).

Upper Sandstone Member

The upper sandstone member is present in all of the western sections (Figure 10). It ranges in thickness from 10 to 57 feet.

At Grape Creek, the sandstone is tannish orange. It weathers to a buff color in outcrop. It is fine to medium grained and moderately sorted. Sedimentary structures include parallel laminations, small scale planar and trough cross bedding, ripple marks, and some climbing ripples. The laminations are defined by changes in grain size between the laminae and range in size from less than 1/4 inch to 1 inch. Coarse grained sand and some granules are associated with the troughs.

Characteristics of the bed change in an eastward direction. At Skyline Drive, the sandstones are greenish grey to greyish pink. They weather to a buff or a variegated but overall tan color in outcrop and contain numerous black heavy mineral bands. Grain size ranges from fine sand to medium pebble gravel and averages fine to coarse sand. The sorting is bimodal. Some of the grains are well rounded. The dominant sedimentary structure

Figure 10. The Upper Sandstone Member at Skyline Drive

changes from parallel laminations to graded parallel bedding (Figure 11). Both normal and reverse graded bedding were observed. The beds range in thickness from 2 to 8 inches. In some areas, soft sediment deformation features such as slump structures and dewatering structures have disrupted the bedding planes (Figure 12). Very thin (<1 cm) layers of shale are present between a few of the beds.

At West Garden Park, the grain size ranges from fine to coarse sand and averages fine sand. The amount of interbedded shale increases substantially. Beds range in thickness from 6 inches to 5 feet.

Upper Conglomeratic Member

The upper conglomeratic member is present in all of the western sections. It ranges in thickness from 46 to 98 feet. It is composed of conglomerates, sandstones, siltstones, shales, and limestone.

Clast-supported and sandy matrix-supported conglomerates make up the dominant lithologies of this member. The conglomerates are pink, well cemented by calcite, and contain numerous black heavy mineral bands. Grain size ranges from fine sand to cobble gravel. The average size of the gravel is granule to medium pebble (2 mm to 1.6 cm). The 10 largest clasts within an individual bed range in size from 2 cm to 21 cm (large pebble to large cobble) and average 4 cm (very large pebble). The sorting is bimodal. The clasts are angular to subrounded. They are

Figure 11. Graded Parallel Bedding in the Upper Sandstone Member at Skyline Drive

Figure 12. Slump Structure Disrupting the Bedding Planes in the Upper Sandstone Member at Skyline Drive

composed of: large angular feldspars, rounded quartz grains, some frosted quartz grains, granitic fragments, volcanic, chert, and shale rock fragments, gneisses, schists, various types of carbonates, and just west of the study area, dinosaur bones.

The conglomerates occur as single to multistoried, erosive based, channel deposits (Figure 13). They are often deeply incised into the underlying sediments (Figure 14). Bed geometry is lenticular. Medium scale trough cross bedding with set heights of up to 15 inches are abundant throughout (Figure 15).

Interbedded with the clast-supported and sandy matrix-supported conglomerates are muddy sandy matrix-supported conglomerates, sandstones, siltstones, and shales. They are dominantly red brown in color. Some of the beds are green or a combination of red brown and green. Some of the sandstones are buff colored.

The muddy sandy matrix-supported conglomerates have essentially the same textural characteristics and clast composition as previously described in the clast-supported and sandy matrix-supported conglomerates. Some of the differences include: the beds occur as single deposits, they are generally massive and very friable, and the basal contacts are not erosive.

There are several different types of sandstones: very fine to fine grained and moderately sorted sandstones, medium grained and poorly sorted sandstones, and pebbly and

Figure 13. Multistoried, Erosive Based, Channel Deposits and a Debris Flow Deposit in the Upper Conglomeratic Member at Skyline Drive

Figure 14. Channel Deposits in the Upper Conglomeratic Member Overlie and are Deeply Incised into the Parallel Laminated Sandstone (Upper Sandstone Member) at Grape Creek

Figure 15. Medium Scale Trough Cross Bedding in the Conglomerates at Skyline Drive

poorly sorted sandstones (containing up to 30 percent gravel). The beds range in thickness from 6 inches to 16 feet. Some of the sandstones are massive. Others contain sedimentary structures such as small scale trough cross bedding, medium scale trough cross bedding, and ripple marks.

Siltstones and shales are present in minor amounts. The beds range in thickness from 6 inches to 4 feet.

At West Garden Park, limestone nodules and thin continuous limestone layers were observed within clastic sediments at two horizons in the upper conglomeratic member. These are interpreted to be Type 1, 2, 3, and 4 calcretes (Steel, 1974) (Figure 16).

Eastern Gypsiferous Facies

Basal Sandstone Member

The basal sandstone member is only present at Indian Springs (Figure 17). It is buff, very friable, and approximately 5 feet thick. Grain size ranges from very fine to very coarse sand. The sorting is bimodal. Some of the grains are well rounded. A 1 inch layer of granule to small pebble gravel is present at the base of the bed.

Sedimentary structures include graded parallel bedding, small scale planar and trough cross bedding with set heights of up to 3 inches, ripple marks, and symmetrical ripples at the base. The beds range in size from 1 1/2 to 12 inches and average 4 to 5 inches. Very thin layers of shale (1 to 2

Figure 16. Calcrete Nodules and Layers in a Sandstone Bed at West Garden Park

Figure 17. The Basal Sandstone Member and Laminated Dolomite and Gypsum Member at Indian Springs

mm) are present between the beds.

Laminated Dolomite and Gypsum Member

The laminated dolomite and gypsum member is present at Indian Springs and East Garden Park.

At Indian Springs, the member is approximately 7 feet thick (Figure 17). At the base is a dark brown pyritic shale layer which contains abundant organic material (oil shale). Freshly broken surfaces emit a faint hydrocarbon odor. The layer is 1/2 inch thick and very thinly laminated. It is overlain by a 4 inch thick, very thinly laminated dolomite bed. Small internal folds and localized disruption of the laminae were produced by soft sediment deformation. The dolomite bed is overlain by a 1/2 inch thick shale layer. Above the shale layer, the member is composed of alternating tan micritic dolomite and white alabastrine gypsum (Figure 18). Thicknesses of the laminae increase upward. The top 6 inches of the bed are composed of massive gypsum. Small gypsum "selenite" crystals are present within the massive gypsum (Figure 19). They also form a thin crust on top of the bed.

At East Garden Park, the laminated dolomite and gypsum member is represented by a 6 inch bed of thinly laminated dolomitic shale. It contains some salt casts but no gypsum layers. Three hundred feet east of East Garden Park, the bed is 8 inches thick and composed of laminated dolomite and gypsum. Five hundred feet to the east, the bed is 3 feet thick.

Figure 18. Horizontal Laminations in the Laminated Dolomite and Gypsum Bed at Indian Springs. The Laminae are Composed of Alternating Tan Micritic Dolomite and White Alabastrine Gypsum

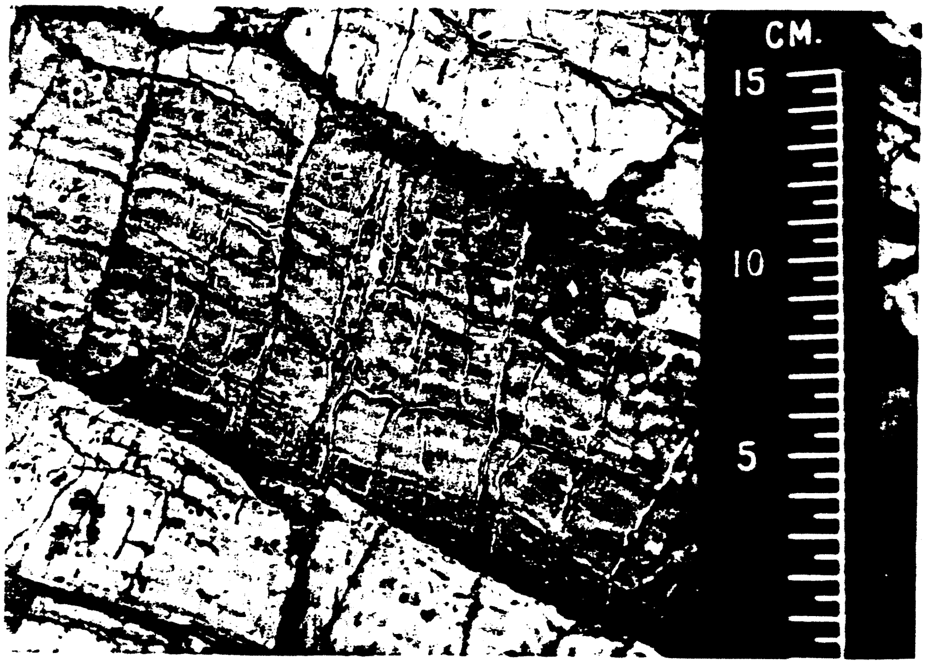


Figure 19. Horizontal Laminations, Small Gypsum "Selenite" Crystals, and Massive Gypsum at the Top of the Laminated Dolomite and Gypsum Bed at Indian Springs

Upper Gypsiferous Member

The upper gypsiferous member is present in all of the eastern sections (the eastern sections include measured sections 4 through 6, from East Garden Park to Soda Ridge). It ranges in thickness from 38 1/2 to 111 feet. It is composed of gypsum, sandstones, siltstones, shales, limestone, and dolomite.

At East Garden Park, the member is composed primarily of interbedded sandstone and shale. The sandstone beds are red brown and range in thickness from 6 inches to a foot. Sedimentary structures include small scale planar and trough cross bedding and ripple marks. The shale beds are red brown, green, and/or grey and range in thickness from 2 to 12 feet. Varying amounts of white to orange gypsum nodules are present within the shales (Figure 20).

There is a 20 inch thick conglomerate bed near the top of the section.

Also present are two limestone beds. One is 6 inches thick; the other is 1 1/2 feet thick. These are interpreted to be Type 4 calcretes (Steel, 1974).

At Indian Springs, the member is composed primarily of interbedded gypsum and shale. The bedded gypsum ranges in thickness from 1 to 17 feet. It is composed of white, and some orange, alabastrine gypsum with a chicken-wire texture. Some of the beds or layers have enterolithic textures. Small gypsum nodules are present within a few sandstone and siltstone beds. The shale beds are grey, green, and brown

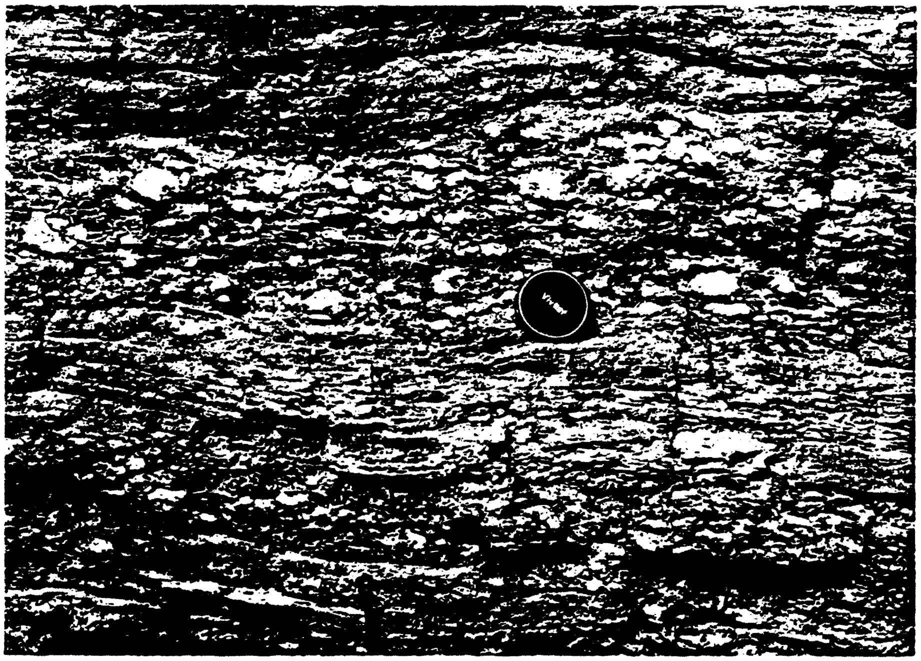


Figure 20. White to Orange Gypsum Nodules Within Shales at East Garden Park

and range in thickness from less than 6 inches up to 15 feet. Two dark grey shale beds are present near the top of the section.

There are approximately 17 feet of interbedded sandstones and siltstones at the base of the member. The sandstone beds range in thickness from 7 inches to 4 feet. They are either grey, very fine to fine grained, and moderately sorted or red brown, medium grained, and poorly sorted.

The grey sandstones contain small scale planar cross bedding and climbing ripples. The red brown sandstones are massive and friable. The siltstone beds are green and red brown and range in thickness from 6 inches to 2 feet. The sandstones and siltstones are cemented by gypsum and contain abundant fracture filling "satin spar" gypsum cement.

There are two 3 inch, massive, micritic dolomite beds. One lies directly over the laminated dolomite and gypsum member. The other is present 16 feet above the base of the upper gypsiferous member.

At Soda Ridge, the member is composed primarily of interbedded gypsum and shale (Figure 21). The bedded gypsum ranges in thickness from 1 to 11 feet. The shale beds range in thickness from less than 1 inch to 2 feet. Small gypsum nodules are present within the shales. Other characteristics of the gypsum and shale beds are similar to those previously described at Indian Springs (Figure 22).

There is one 3 1/2 foot thick sandstone bed at the top

Figure 21. The Upper Gypsiferous
Member at Soda Ridge.
Note the Abrupt
Contact Between the
Ralston Creek
Formation and the
Underlying Lykins
Formation (in Orange)

Figure 22. Chicken-Wire Texture in the Gypsum Beds at Soda Ridge

of the section. It is tan, fine grained, moderately sorted, and contains some ripple marks.

CHAPTER V

PETROGRAPHY AND DIAGENESIS OF SANDSTONES AND CONGLOMERATES

Petrography of Sandstones

Texture

The sandstones exhibit a wide variety in grain size, sorting, and roundness. Observations of grain size both in thin section and in outcrop indicate a range from very fine sand to medium pebble gravel. Types of sorting include: 1) a bimodal distribution of grains, 2) moderately, and 3) poorly sorted grains. The majority of grains are subangular to subrounded with low sphericity. Rounded to well rounded grains with medium to high sphericity are present in some samples (Figure 23). Overall, the sandstones are texturally submature.

Mineralogy

Sandstones in the Ralston Creek Formation can be classified as subarkoses (Folk, 1980). The average percentages of detrital and authigenic constituents are summarized in Table I.

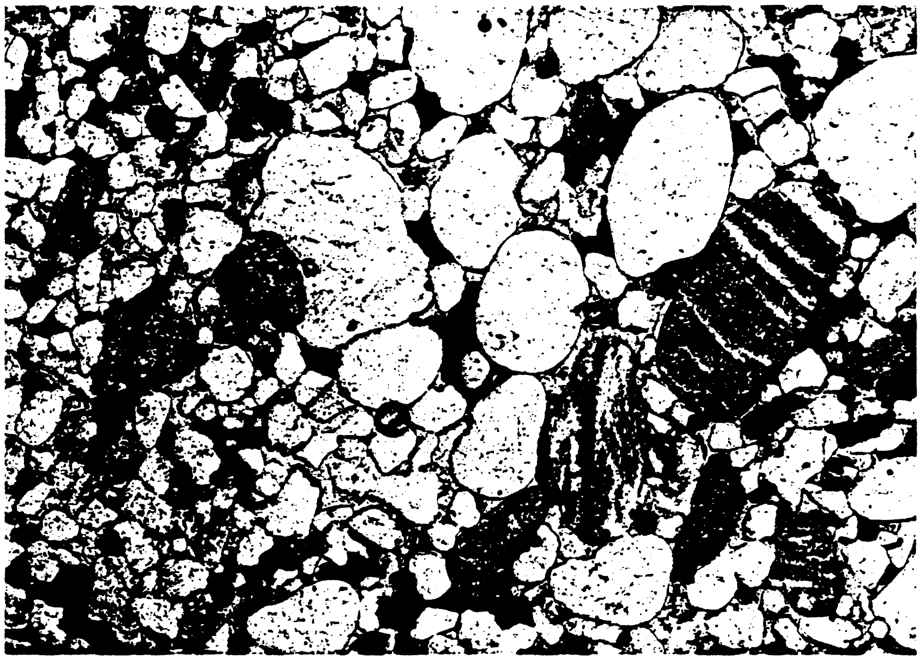


Figure 23. Photomicrograph of a Sandstone Showing the Bimodal Distribution of Grains, Rounded to Well Rounded Grains, Stained Feldspars, Opaque Minerals, and Porosity Resulting From the Dissolution of Calcite Cement (Plane Polarized Light, 40X)

TABLE I

AVERAGE PERCENTAGES OF DETRITAL AND AUTHIGENIC CONSTITUENTS IN THE SANDSTONES AND CONGLOMERATES

Constituents	Western Sandstones	Eastern Sandstones	Clast Supported Conglomerates
Detrital Constituents:			
Quartz	70	65	46
Feldspar	18	18	41
Rock Fragments	TR	TR	1
Muscovite	TR	TR	TR
Biotite	TR	TR	TR
Chlorite	TR	TR	TR
Zircon	TR	TR	TR
Opaque Minerals	1	1	1
Authigenic Constituents:			
Calcite	10	2	10
Illite	0-TR	TR-1	
Gypsum		12	
Hematite	0-1	0-1	0-1

Detrital Constituents

Quartz. Quartz is the most abundant detrital constituent. It averages 68 percent of the samples. Monocrystalline quartz is the dominant quartz type. Polycrystalline quartz ranges from a trace to 3 percent and averages 1 percent. Extinction of the grains ranges from straight to undulose.

Feldspar. Feldspar is the second most abundant detrital constituent. It averages 18 percent of the samples. Of this, between 13 and 17 percent is orthoclase, a trace to 2 percent is plagioclase, a trace to 2 percent is microcline, and a trace is perthite (Figure 23).

Rock Fragments. Chert, indeterminate volcanic, and shale rock fragments are present in trace amounts.

Other Constituents. Muscovite, biotite, chlorite, and zircon are present in trace amounts. Opaque minerals are common in most thin sections. They range from a trace to 5 percent, and average 1 percent (Figure 23).

Authigenic Constituents

The western sandstones include authigenic calcite, illite, and hematite. Calcite ranges from 0 to 20 percent and averages 10 percent. Illite ranges from 0 to a trace. Hematite ranges from 0 to 1 percent.

The eastern sandstones include authigenic calcite, illite, gypsum, and hematite. Calcite ranges from a trace to 10 percent and averages 2 percent. Illite ranges from a trace to 1 percent. Gypsum averages 12 percent. Hematite ranges from 0 to 1 percent.

Petrography of Clast-Supported Conglomerates

Texture

Observations of grain size both in thin section and in outcrop indicate a range from fine sand to cobble gravel. The average size of the gravel is granule to medium pebble. The sorting is bimodal. The grains are angular to subrounded with low sphericity. Overall, the conglomerates are texturally submature.

Mineralogy

The conglomerates can be classified as arkoses (Folk, 1980). The average percentages of detrital and authigenic constituents are summarized in Table I.

Detrital Constituents

Quartz. Quartz averages 46 percent of the total rock. Monocrystalline quartz is the dominant quartz type. It occurs either as single grains or in association with feldspars in granitic rock fragments.

Polycrystalline quartz is more abundant in the conglomerates than it is in the sandstones; it accounts for up to one fourth of the total amount of quartz. Several different types were observed including polycrystalline, recrystallized metamorphic, and schistose metamorphic quartz (Figure 24).

Extinction of the grains ranges from straight to undulose.

Feldspar. Feldspars are far more abundant in the conglomerates than they are in the sandstones. They average 41 percent of the samples. The dominant feldspar type is microcline. Orthoclase is the second most abundant feldspar. Plagioclase is less abundant and perthite is present only in trace amounts (Figure 24). Feldspars occur either as single crystals or in association with quartz in granitic rock fragments.

Rock Fragments. Rock fragments are abundant in the conglomerates and include: igneous rock fragments, both plutonic and volcanic, metamorphic rock fragments, and sedimentary rock fragments.

Coarse grained plutonic and metamorphic rock fragments are included in the percentages of quartz and feldspar according to Folk's classification (1980).

Rock fragments other than these make up an average of only 1 percent of the samples. They include: chert, various types of carbonates, shale fragments, and indeterminate volcanic rock fragments.

Figure 24. Photomicrograph of a Conglomerate Showing Monocrystalline Quartz, Schistose Metamorphic Quartz, and Microcline (Crossed Nicols, 40X)

Other Constituents. Muscovite, biotite, chlorite, and zircon are present in trace amounts. Opaque minerals range from a trace to 5 percent and average 1 percent.

Authigenic Constituents

Authigenic constituents include calcite and hematite. Calcite ranges from 5 to 20 percent and averages 10 percent. Hematite ranges from 0 to 1 percent.

Petrography of Matrix-Supported Conglomerates

Two types of matrix-supported conglomerates are present in the Ralston Creek Formation: sandy conglomerates and muddy sandy conglomerates.

The textural characteristics and mineralogic constituents of the matrix-supported conglomerates are essentially the same as those previously described for the clast-supported conglomerates. The differences are listed below:

1) The muddy sandy conglomerates are texturally immature.

2) The average percentage of detrital constituents varies according to the amount of sand present.

3) The amount of sand present ranges from 20 to 70 percent; the clast-supported conglomerates contain up to 20 percent sand (Folk, 1980).

4) With decreasing grain size (from pebble gravel to

sand), there is a decrease in the amount of feldspar and an increase in the amount of quartz. As a result, the matrix-supported conglomerates can be classified as either arkoses or subarkoses (Folk, 1980).

5) Detrital illite averages 10 percent in the muddy sandy conglomerates (Figure 25).

6) The muddy sandy conglomerates are commonly stained red by hematite.

Diagenesis of Sandstones and Conglomerates

The Ralston Creek Formation has been affected by both chemical and physical diagenetic processes. The chemical processes include: precipitation, alteration, dissolution, and replacement. The constituents that have been affected by one or more of these processes include: calcite, illite, gypsum, hematite, feldspar, and volcanic rock fragments. The only physical diagenetic process was compaction.

Chemical Processes

Calcite

Calcite occurs as a pore filling cement. It is the most abundant authigenic precipitant in the western sandstones and conglomerates. Textures observed include: sparry, poikilotopic, finely crystalline, and micritic calcite. Evidence of dissolution of calcite cement was observed in a few of the sandstones.

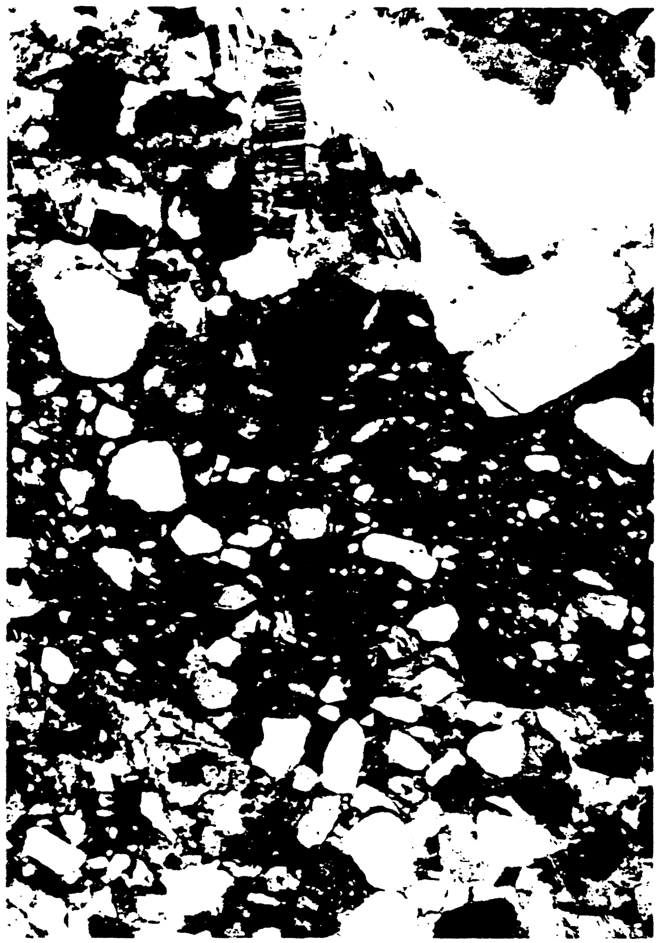


Figure 25. Photomicrograph Showing the Detrital Illite in a Muddy Sandy Matrix-Supported Conglomerate (Crossed Nicols, 40X)

Calcite cement is much less abundant in the eastern sandstones. It has a patchy distribution and a predominantly poikilotopic texture (Figure 26). Some sparry calcite cement is also present.

The precipitation of calcite occurs when the solubility product of the mineral is exceeded. The types of cement observed indicate that this may have taken place in the meteoric phreatic zone, through the evaporation of ground water or at depths, by an increase in the pH (>7) (Tucker, 1981). Patchy poikilotopic cement is commonly the result of irregularly distributed nuclei for calcite crystallization (Scholle, 1979).

Illite

Illite is present as a grain rimming cement in the eastern sandstones (Figure 26). It is present in the western sandstones where dissolution of calcite cement has occurred. It was not observed in the conglomerates.

The formation of authigenic illite requires alkaline pore fluids together with sufficient K, Si, and Al. These ions are largely derived from the alteration of labile detrital minerals, particularly feldspars (Tucker, 1981).

Gypsum

Gypsum is the most abundant authigenic precipitant in the eastern sandstones. It occurs as a pore filling cement. Textures observed include: large poikilotopic crystals,

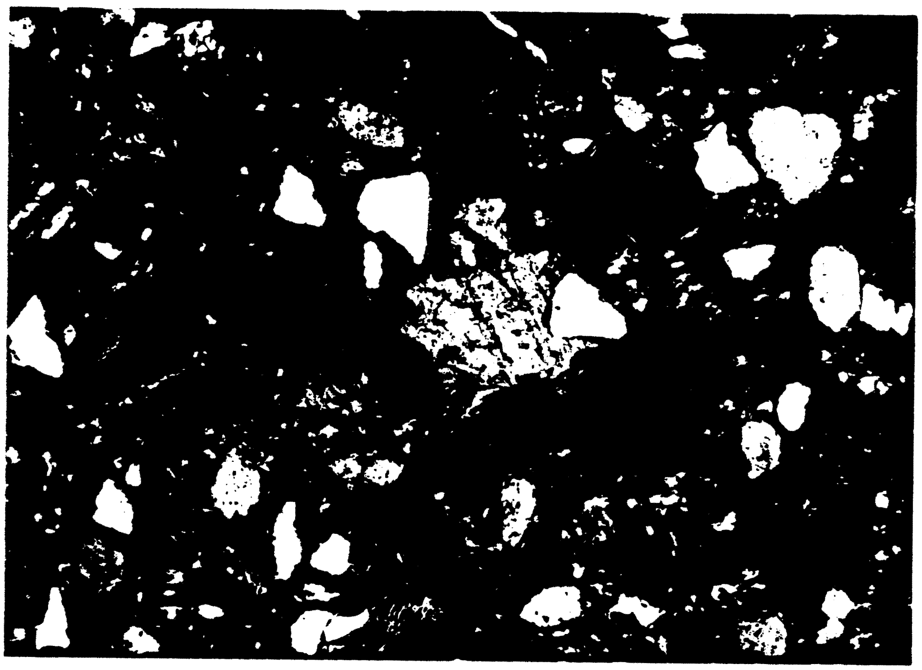


Figure 26. Photomicrograph of a Sandstone From Indian Springs Showing the Patchy Distribution and Poikilotopic Texture of Calcite Cement and Grain Rimming Illite Cement (Crossed Nicols, 100X)

fine aggregates of granular crystals and vein or fracture filling fibrous "satin spar" gypsum (observed in outcrop) (Figure 27). Partial dissolution of gypsum cement was observed in some of the sandstones.

Gypsum cement is precipitated from supersaturated calcium sulfate brine. This type of cement is rare in sandstones, except where associated with evaporite beds. Gypsum diagenesis is discussed in detail in Chapter VI.

Hematite

Hematite occurs as a grain coating cement and as localized patches of pore filling cement in the clast-supported conglomerates and sandy conglomerates. It occurs as localized patches of pore filling cement in the sandstones and as a pervasive red stain in the red brown sandstones and muddy sandy conglomerates.

Hematite is generally indicative of oxidizing conditions. The diagenetic iron oxides are derived from the interstratal dissolution of unstable detrital ferromagnesian minerals such as hornblende, biotite, chlorite, magnetite, and pyrite (Scholle, 1979; Tucker, 1981). This is particularly true under arid conditions where such grains are not removed during initial weathering. The localized distribution of cement may be the result of "in situ" disintegration of these minerals.

There are two oxidation states for iron: ferric (Fe^{3+}) and ferrous (Fe^{2+}). Where ferric iron is present, as

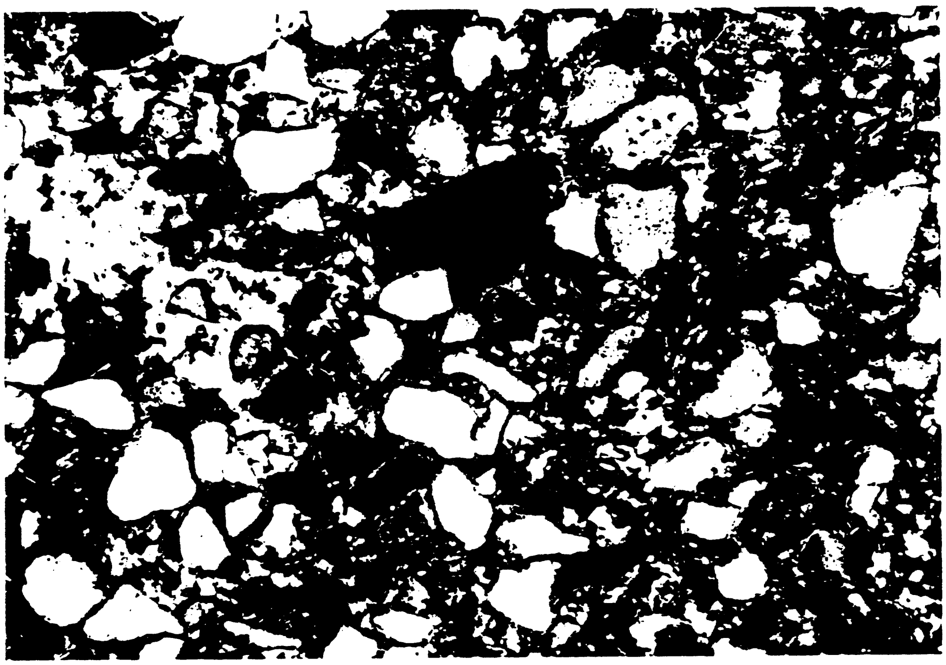


Figure 27. Photomicrograph of Gypsum Cement in the Eastern Sandstones. Textures Include: Large Poikilotopic Crystals and Fine Aggregates of Granular Crystals (Crossed Nicols, 100X)

hematite, even small amounts (less than 1%) will add a red color to the rock. Many of the sandstones and matrix supported conglomerates observed in outcrop are stained red. A few are colored green or are red with localized green layers or lenses. The green color is indicative of reducing conditions and the ferrous state of iron (Tucker, 1982).

Feldspar

The majority of feldspars are fresh and unaltered. Altered grains have been partially replaced by illite and/or calcite (Figure 28). The combination of fresh and altered grains may indicate that the process took place in the source area where only some of the grains were affected (Scholle, 1979).

Volcanic Rock Fragments

Volcanic rock fragments have been partially replaced by chlorite, calcite, and/or illite.

Physical Processes

The only physical diagenetic process was compaction. Though relatively minor, the effects of compaction include: reduction of pore space, deformation of micas, fracturing of plagioclase grains, interpenetration of detrital quartz grains, and fracturing (Figure 28).

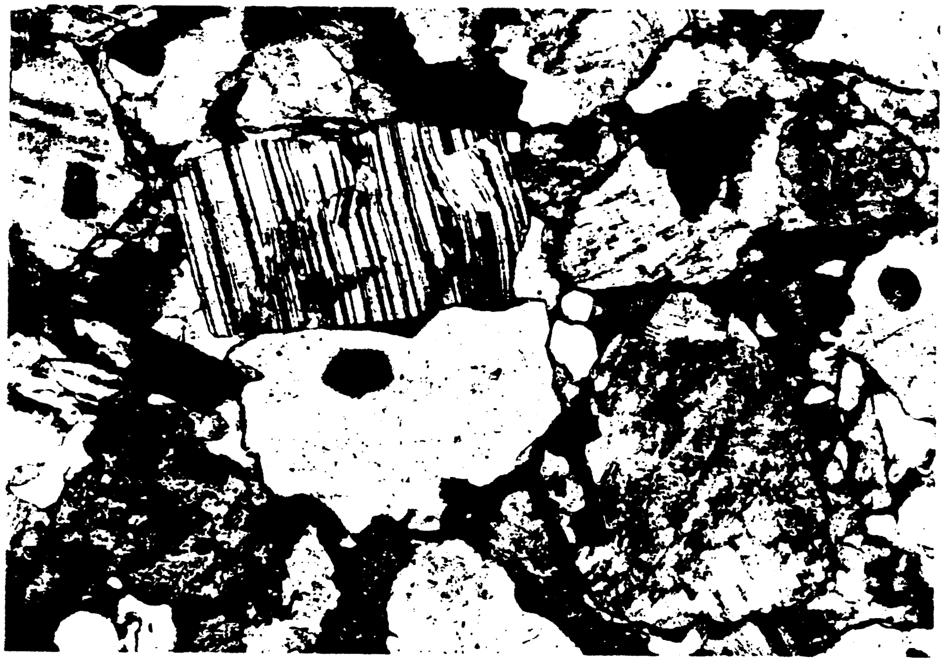


Figure 28. Photomicrograph of a Conglomerate Showing Feldspar Grains That Have Been Partially Replaced by Illite or Calcite and a Fractured Plagioclase Grain (Crossed Nicols, 40X)

Porosity

Primary porosity was virtually destroyed during early diagenesis as a result of calcite and/or gypsum precipitation.

Secondary porosity was observed in a few of the sandstone thin sections. Where present, the percentage ranges from a trace to 5 percent and averages 2 percent. Secondary porosity resulted from the dissolution of calcite and gypsum cements. No porosity was observed in the conglomerates.

Paragenesis

The paragenetic sequences were determined by thin section analysis of constituent relationships. The general orders of events are listed below.

Western Sandstones

1) Formation of localized pore filling hematite cement.
2) Precipitation of calcite as a pore filling cement.
3) Dissolution of calcite cement.
4) Precipitation of illite as a grain rimming cement.
5) Precipitation of hematite as a stain.

Eastern Sandstones

1) Formation of localized pore filling hematite cement.
2) Precipitation of calcite as a pore filling cement.
3) Precipitation of illite as a grain rimming cement.

4) Precipitation of gypsum as a pore filling cement.

5) Dissolution of gypsum cement.

6) Precipitation of hematite as a stain.

7) Fracturing.

8) Precipitation of gypsum as a fracture filling cement.

Conglomerates

1) Precipitation of hematite as a grain coating cement and the formation of localized pore filling hematite cement.

2) Precipitation of calcite as a pore filling cement.

3) Precipitation of hematite as a stain.

CHAPTER VI

PETROGRAPHY AND DIAGENESIS OF CARBONATES AND GYPSUM

Petrography

White Limestone Bed

The white limestone can be classified as a micrite (Folk, 1962). The dominant texture consists of horizontal laminations which range in thickness from 0.3 to 1 mm. The laminae are composed of alternating layers of micritic calcite and clastic grains. The clastic grains define the lamination and average 10 percent of the rock. Muscovite, biotite, and stringers and flakes of brown organic material are present in trace amounts. Traces of finely crystalline calcite cement are present in small fractures and associated with some of the layers of clastic grains (Figure 29). Localized patches of hematite cement are present in trace amounts. Observations made at a few localities in outcrop indicate that the top of the limestone was disrupted by salt pseudomorphs which are now filled in by sparry calcite cement. The pseudomorphs are up to 3 inches in length. They exhibit monoclinic crystal morphologies which suggests that the precursor salt may have

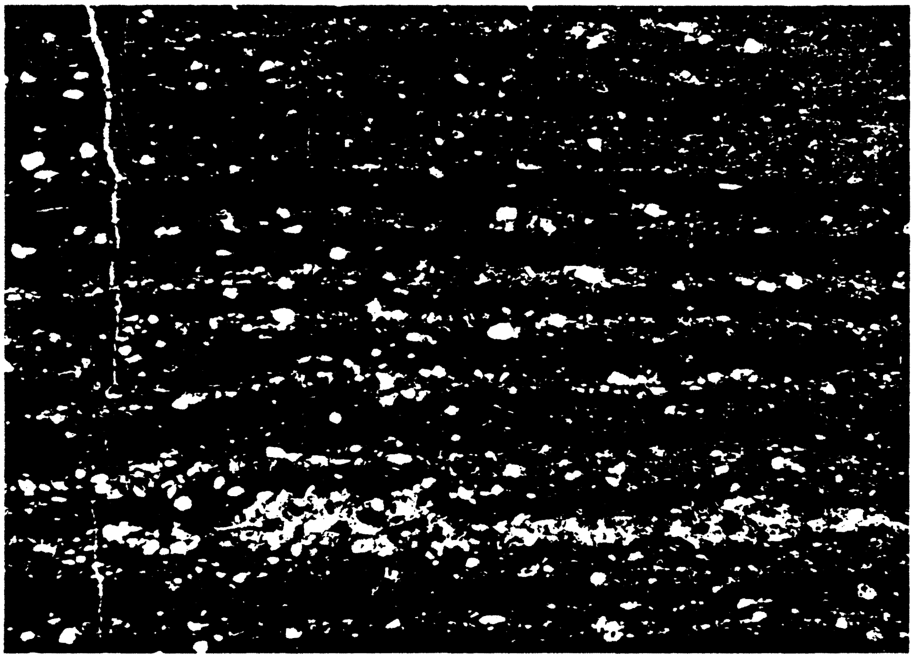


Figure 29. Photomicrograph of the White Limestone Bed Showing the Alternating Layers of Micritic Calcite and Clastic Grains and Finely Crystalline Calcite Cement (Crossed Nicols, 20X)

been gypsum.

Laminated Dolomite and Gypsum Bed

The dominant texture of this bed consists of horizontal laminations. The laminae are paper thin at the base of the bed and increase in size progressively up section. Small internal folds and localized distruption of the laminae were produced by soft sediment deformation. At the top of the section, massive disruption of the laminae has taken place and the original texture of the rock is almost completely obliterated.

The mineralogic constituents observed in thin section include: dolomite, clastic grains, organic material, and gypsum.

The laminae at the base of the section are composed of clastic grains and abundant organic material (oil shale).

Above the oil shale, the laminae are composed of alternating layers of micritic dolomite and clastic grains. Stringers of brown organic material are present parallel to bedding. The average percentages of the various constituents are as follows: 75 percent dolomite, 24 percent clastics, and 1 percent organic material. This is overlain by a 1/2 inch dolomitic shale layer which contains the same constituents in different percentages.

These constituents decrease in abundance up section. The average thickness of the laminae increases. The laminae are composed of micritic dolomite, clastic grains, and finely crystalline dolomite cemented by alabastrine gypsum (Figure 30). The finely crystalline dolomite was preserved by early cementation, and may represent the original fabric of the rock prior to compaction. Organic material is present in trace amounts.

As the percentage of gypsum increases continually up section, laminae are disrupted, the dolomite is displaced by the diagenetic growth of sulfate, the amount of dolomite decreases, and clastics and organic material are present only in trace amounts (Figure 31). Gypsum textures include: large porphyroblasts, fine aggregates of granular crystals (alabastrine gypsum), and vein or fracture filling fibrous gypsum (Figures 32). The veins quite clearly cut earlier textures and may be a late recrystallization effect.

At the top of the section, the rock is composed of gypsum and traces of clastic grains. The gypsum is composed of fine aggregates of granular crystals, which show signs of flowage and distortion (Figure 33). In addition, two types of porphyroblasts are present: large anhedral crystals and much smaller euhedral crystals (Figures 34 and 35). The large anhedral crystals have irregular boundaries, and were probably once gypsum crystals that altered to anhydrite and then altered back to gypsum (see section on gypsum diagenesis). The small euhedral crystals are probably a late diagenetic product.

Another late diagenetic product was the growth of a thin crust of gypsum "selenite" crystals on top of the bed

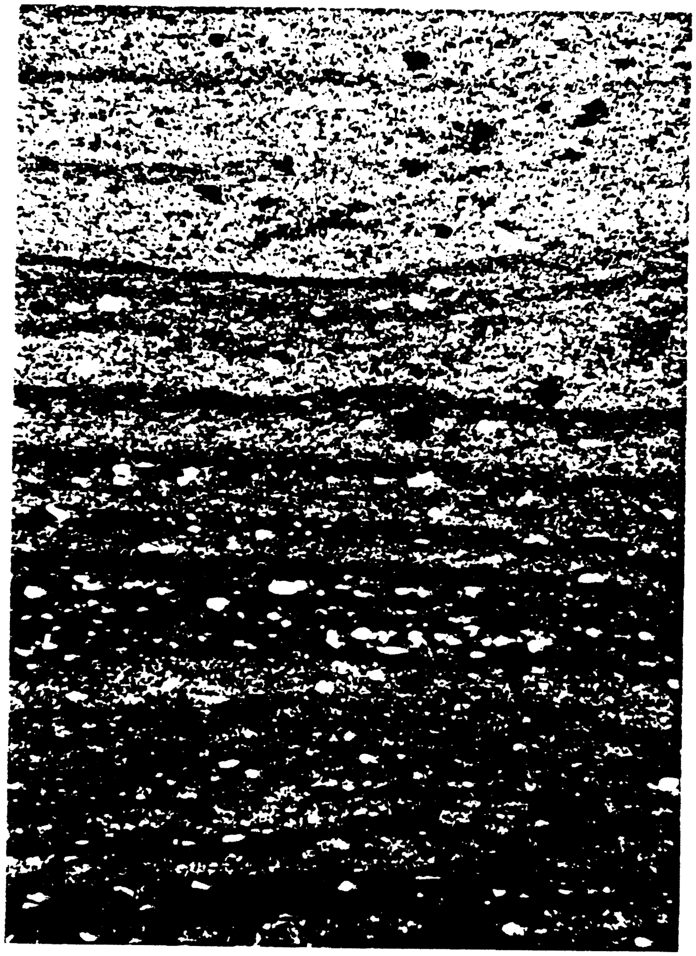


Figure 30. Photomicrograph of the Laminated Dolomite and Gypsum Bed. The Laminae are Composed of Micritic Dolomite, Clastic Grains, and Finely Crystalline Dolomite Cemented by Gypsum (Crossed Nicols, 20X)

Figure 31. Photomicrograph of the Laminated Dolomite and Gypsum Bed Showing the Disruption of Laminae and Displacement of Dolomite by the Diagenetic Growth of Sulfate (Crossed Nicols, 20X)

Figure 32. Photomicrograph of the Laminated Dolomite and Gypsum Bed Showing the Increase in the Percentage of Gypsum Up Section. Note the Cross Cutting Relationship of the Fracture Filling Fibrous Gypsum (Crossed Nicols, 20X)

Figure 33. Photomicrograph of the Laminated Dolomite and Gypsum Bed Showing Flowage and Distortion of the Massive Gypsum at the Top of the Bed (Crossed Nicols, 40X)

Figure 34. Photomicrograph of a Large Anhedral Porphyroblast in the Massive Gypsum at the Top of the Laminated Dolomite and Gypsum Bed (Crossed Nicols, 10X)

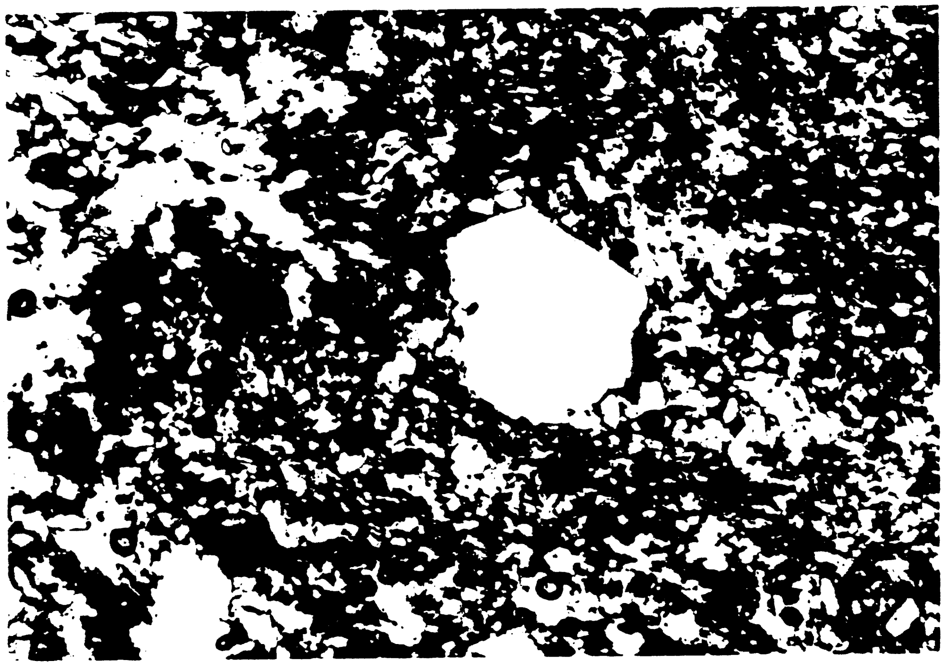


Figure 35. Photomicrograph of a Small Euhedral Porphyroblast and Alabastrine Gypsum at the Top of the Laminated Dolomite and Gypsum Bed (Crossed Nicols, 100X)

(observed in outcrop).

Dolomite Beds

Two dolomite beds at Indian Springs were analyzed in thin section.

The bed directly above the laminated dolomite and gypsum bed can be classified as a dolodismicrite (Folk, 1962). It is composed of micritic and finely crystalline dolomite, 10 percent clastic grains, and 1 percent detrital illite. The micritic dolomite is cemented by large poikilotopic calcite crystals. The massive fabric is cut by numerous fenestrae, which formed as gas escaped from freshly deposited sediments. They are filled with 1 percent pore lining hematite cement, 15 percent pore filling sparry calcite cement, and 1 percent gypsum cement (Figure 36).

The dolomite bed higher in the section can be classified as a dolomicrite (Folk, 1962). It is also massive but contains a higher clastic content, up to 30 percent, and no fenestrae.

Corrosion of clastic grain boundaries was noted in both dolomite beds.

Diagenesis

Carbonates and gypsum in the Ralston Creek Formation have been affected by both chemical and physical diagenetic processes. The chemical processes include: precipitation, recrystallization, replacement, solution, dehydration, and

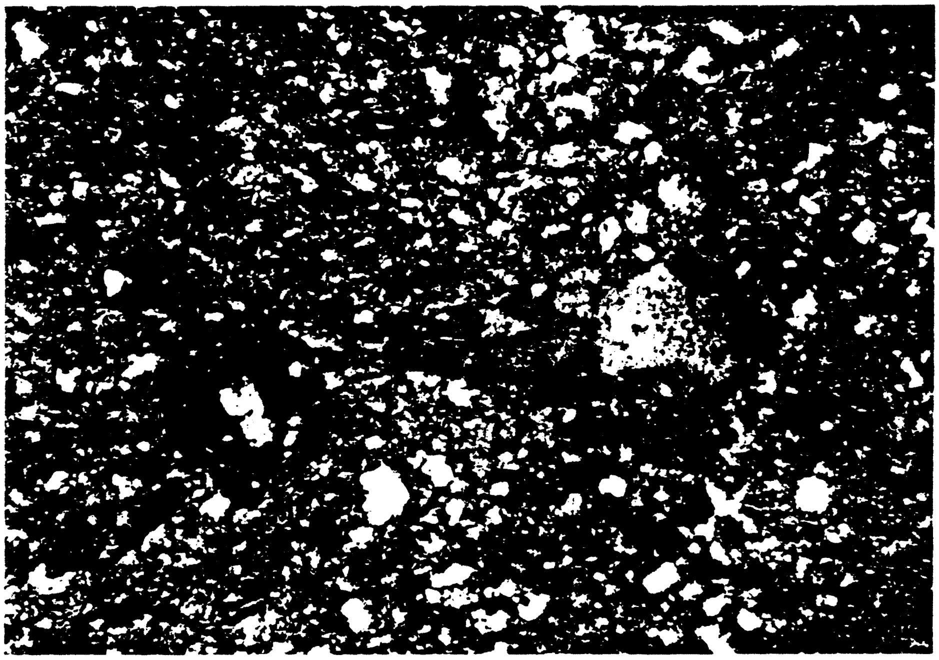


Figure 36. Photomicrograph of a Dolomite Bed Showing Micritic Dolomite Cemented by Large Poikilotopic Calcite Crystals, Clastic Grains, and a Fenestrae Filled with Pore Lining Hematite and Pore Filling Sparry Calcite Cement (Crossed Nicols, 20X)

rehydration. The constituents that have been affected by one or more of these processes include: calcite, dolomite, gypsum, and hematite. The only physical diagenetic process was compaction.

Chemical Processes

Calcite

The lithification of fine grained limestones is thought to take place through the precipitation of isochemical micritic cement (Steinen, 1978). It is considered to be an early diagenetic process because of the almost total lack of compaction (Bathurst, 1970).

Calcite also occurs as pore filling cement. Textures observed include: finely crystalline, sparry, and poikilotopic calcite. Calcite cement was observed in small fractures, associated with some layers of clastic grains in the white limestone bed, and in fenestrae in one of the dolomite beds.

Calcite also occurs as a replacement of salt pseudomorphs in the white limestone bed. Corrosion of clastic grain boundaries by calcite was noted in both dolomite beds.

Calcretes. Calcretes are accumulations of authigenic carbonate which form as an early diagenetic phase within ancient soil horizons.

Calcretes were observed in outcrop at various localities including: East Garden Park, West Garden Park, and Grape Creek. They are generally white to light buff and occur either as nodules within sandstones, siltstones, and shales or as thin continuous layers.

In thin section, calcretes are composed of micritic and finely crystalline calcite and varying amounts of clastic grains. The clastic grains appear to be "floating" in the calcite cement. A few have been split or fractured and corrosion of grain boundaries is common. These textures are characteristic of the replacive and displacive nature of calcrete development.

The massive fabric is sometimes replaced by sparry calcite and crossed by irregular dilation fractures which have been filled with sparry and/or fibrous calcite cement (Figure 37).

In one thin section, the calcite has been partially replaced by micritic, ferroan dolomite. The dolomite appears to have formed before the fractures were cemented (Figure 38).

Calcretes develop in the stable segments of alluvial fans, in floodplain sediments, in aeolian and lacustrine deposits, and in marine carbonate sediments if subaerially exposed (Tucker, 1981; Steel, 1974). They form in semi-arid climates where precipitation ranges from 10 to 60 cm. Less water will not carry carbonates into the subsoil. More water causes leaching of the carbonate. The temperature must be hot enough to promote subsurface evaporation (Steel, 1974).

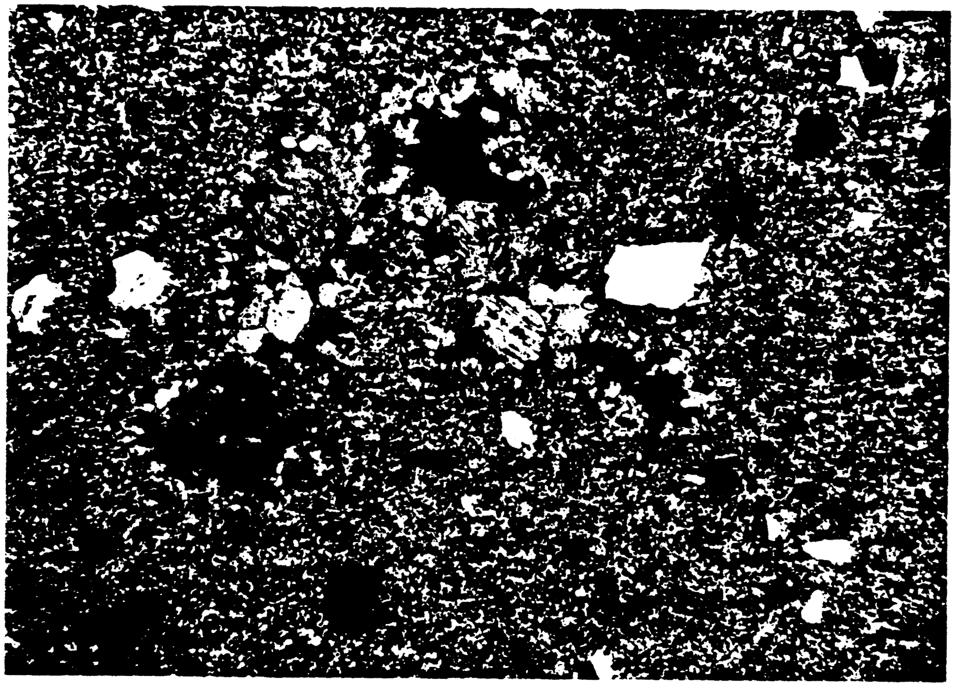


Figure 37. Photomicrograph of a Calcrete Showing Finely Crystalline Calcite Being Replaced By Sparry Calcite (Crossed Nicols, 20X)

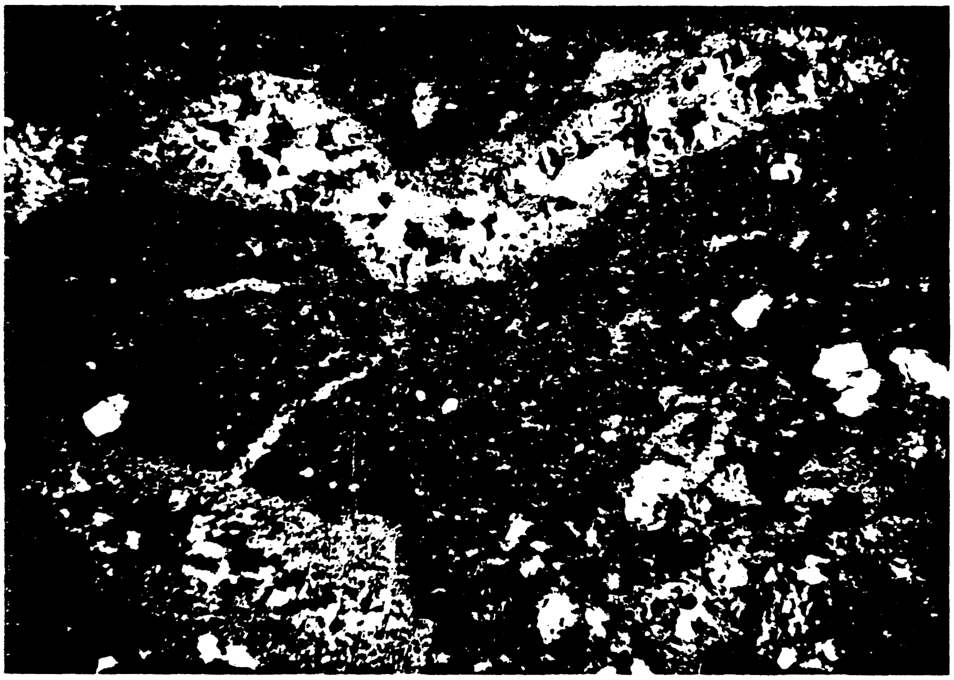


Figure 38. Photomicrograph of a Calcrete Showing Irregular Dilation Fractures Which Have Been Filled With Sparry and/or Fibrous Calcite Cement. The Micritic Calcite Has Been Partially Dolomitized (Blue Stain) (Crossed Nicols, 10X)

Calcretes develop gradually with time. The amount of time involved can range from a minimum of one thousand years to greater than ten thousand years (Leeder, 1975). They occur in several forms, from small nodules which compose less than 10 percent of the original clastic sediment to continuous layers or beds in which only rare patches of sediment are seen. Textures can be massive, laminated, or pisolitic (Steel, 1974). The successive stages of calcrete formation and the amount of time required for development are summarized in Tables II and III.

Other factors which influence calcrete development include: carbonate supply, geomorphic stability, sedimentation rate, relief, and erosion.

A source of carbonate is necessary for the initiation of calcrete formation. Formation begins when the soil carbonate is dissolved by carbonic acid which forms from rain water and CO_2 in the atmosphere and soil (Reeves, 1970). It is then carried into the soil horizon and reprecipitated during dry periods.

Calcretes can not form if the soil profile is buried too rapidly. Development is therefore enhanced by low rates of subsidence with long periods of nondeposition between sedimentation episodes. Too much local relief would promote surface run-off and erosion. Erosion must be minimal in order for the calcretes to be preserved (Steel, 1974).

TABLE II

PROGRESSIVE STAGES OF CALCRETE DEVELOPMENT ACCORDING TO STEEL (1974)

Type 1:	The carbonate appears as small (1 to 6 cm in diameter), irregularly shaped nodules which compose less than 10 percent of the rock.
Type 2:	The carbonate nodules are larger (up to 10 cm in diameter) and often vertically elongate. They occupy less than 50 percent of the rock in the upper part of the profile. There is usually a downward gradation into Type 1 calcrete.
Type 3:	The carbonate appears as nodules, horizontal sheets or vertical pipes. It occupies greater than 50 percent of the rock but clastic sediment can still be clearly seen within the carbonate framework. There is a downward gradation into Type 2 calcrete.
Type 4:	The carbonate exists as beds within which only rare patches of clastic sediment are seen. There is usually a downward gradation into Type 3 calcrete.
Type 4a:	Distinct horizons of laminar, brecciated or pisolitic carbonate exist, usually as a capping to Type 4 calcretes. The carbonate is sometimes partly silicified. Occasionally, thin beds of carbonate may alternate with chert.

TABLE III

DEVELOPMENT TIME REQUIRED OF STAGES
ACCORDING TO LEEDER (1975)

Stages	Minimum	Maximum
1	1,000 years	4,500 years
2	3,500 years	7,000 years
3	6,000 years	10,000 years
4	10,000 years	

<u>Dolomite</u>

Dolomitization of carbonate sediments in the Ralston Creek Formation probably took place soon after deposition. The process involved is the secondary replacement of calcium carbonate ($CaCO_3$) by dolomite ($CaMg(CO_3)_2$).

The theory most applicable to the Ralston Creek Formation is penecontemporaneous hypersaline dolomitization (Adams and Rhodes, 1960; Deffeyes et al., 1965; Hsu and Siegenthaler, 1969; Friedman and Sanders, 1967; and others). Evidence supporting hypersaline dolomitization includes: close association with supratidal features such as fenestrae, dessication cracks, and evaporites, and petrographic features such as a fine grain size and some preservation of structures.

The evaporite brine-residue model is based on chemical and mineralogic changes taking place just under the surface of the supratidal (sabkha) environments. Dolomite is produced through evaporation and precipitates at elevated Mg/Ca ratios. The precipitation of gypsum and/or anhydrite involves large scale removal of Ca^{2+} and SO_4^{2-} ions from the porewater. The removal of Ca^{2+} increases the Mg/Ca ratio. The removal of SO_4^{2-} may also be essential since dolomite dissolves in sulfate rich ground waters (Leeder, 1982).

Dolomitization in the Ralston Creek Formation probably took place near the surface, penecontemporaneously with large scale evaporite deposition. Hypersaline dolomitization occurs when Mg rich brines sink down through the underlying sediments dolomitizing the rocks as they pass through.

<u>Gypsum</u>

Rocks composed of gypsum are susceptible to extensive post depositional change. Diagenetic processes that take place during burial and uplift include: dehydration, recrystallization, replacement, plastic flow, rehydration, and solution (Leeder, 1982).

The stable phase of gypsum-anhydrite is determined by the activity of water (related to salinity) and temperature (Hardie, 1967). Gypsum unaffected by early diagenetic dehydration to anhydrite will completely recrystallize to anhydrite at depths in excess of approximately one kilometer. This results in a volume loss of up to 38 percent (Leeder, 1982).

Increasing pressure and temperature with depth can cause evaporites to deform plastically. Flowage may cause fluctuations in the thickness of beds and the formation of a foliated fabric in the rock (Leeder, 1982).

Both plastic flow and the recrystallization of gypsum to anhydrite may result in the obliteration of original depositional textures.

Uplift of evaporite sequences to the earth's surface results in the hydration of anhydrite to secondary gypsum. There is little evidence for an increase in volume during this procedure. The process is thought to occur by solution-precipitation replacement with excess sulfate removed in solution (Leeder, 1982).

There are two varieties of secondary gypsum: porphyroblastic and alabastrine. Gypsum porphyroblasts are single euhedral or anhedral crystals with uniform extinction. They can be various shapes and sizes and occur scattered through the rock. Relict corroded anhydrite grains may be seen within the gypsum crystals. Alabastrine gypsum consists of fine aggregates of granular crystals, which may have undulose to irregular extinction. This type of gypsum generally comprises the bulk of secondary gypsum rocks (Holliday, 1970). The original nodular or laminated textures of anhydrite are invariably preserved.

Veins of displacive or intrusive fibrous "satin spar" gypsum form as a late recrystallization effect. It is thought that they grow under pressure in water filled veins produced by hydraulic fracture (Shearman et al., 1972). They are commonly seen parallel or subparallel to bedding, are a few millimeters or centimeters in thickness, and consist of fibers arranged with their long axes normal to the vein margins.

Dissolution of evaporitic sequences may result in massive regional or local collapse breccias.

<u>Nodular and Bedded Gypsum</u>. Gypsum only occurs as a primary precipitant in the laminated dolomite and gypsum bed previously described. Most of the gypsum in the Ralston Creek Formation formed as an early diagenetic phase within

deposited clastic sediments.

This type of gypsum is abundant throughout the eastern part of the study area. In outcrop, it is generally white to orange and occurs in several forms including: 1) small discrete nodules within clastic sediments, 2) coalescent nodules, which form a chicken-wire texture, and 3) beds or layers of coalescent nodules which are sometimes contorted or buckled, forming an enterolithic texture.

Evaporites form in arid environments where evaporation exceeds precipitation. They typically form on coastal or inland sabkhas where the evaporation of brines causes sediment pore fluids to become progressively concentrated with salts. As a result, gypsum crystals are precipitated displacively within the sediments. With increasing salinity, the gypsum crystals are replaced as pseudomorphs by fine grained anhydrite laths and granules defining an aphanitic texture (Leeder, 1982; Tucker, 1981). This takes place when sea water is concentrated by a factor of 7.5 (Tucker, 1981). The pseudomorphs may lose their original shape as a result of flowage (adjustment during compaction) and/or the continued growth of primary anhydrite (Kendall, 1979).

The continued precipitation of anhydrite results in a chicken-wire texture which is characterized by closely packed nodules with thin stringers of sediment in between. Beds or layers with enterolithic textures are typically precipitated in the more landward parts of the sabkhas

(Tucker, 1981).

Gypsum was the only evaporite mineral observed in the field. The conversion of anhydrite to secondary alabastrine gypsum was a late diagenetic event associated with uplift.

Hematite

Hematite occurs as localized patches of cement formed by the "in situ" disintegration of unstable detrital ferromagnesium minerals. It is also present in one of the dolomite beds where it occurs within the fenestrae as a pore lining cement.

Authigenic hematite was previously described in the section on diagenesis of sandstones and conglomerates.

Physical Processes

The only physical diagenetic process was compaction. This produced plastic flow in some of the gypsum beds. Plastic flow was previously described in the section on gypsum.

Other effects of compaction include: the reduction of pore space, fracturing, and stylotization.

Stylolites were observed in the white limestone bed. They form as a result of pressure solution (dissolution of limestone) along planes parallel to bedding.

Paragenesis

The paragenetic sequences were determined by thin section analysis of constituent relationships. The general orders of events are listed below.

White Limestone Bed

1) Precipitation of calcite as a pore filling cement.

2) Growth of secondary gypsum porphyroblasts.

3) Replacement of gypsum porphyroblasts by sparry calcite.

Laminated Dolomite and Gypsum Bed

1) Dolomitization of carbonate sediments.

2) Growth of large gypsum crystals within the carbonate sediments.

3) Conversion of gypsum crystals to anhydrite and the growth of a felted mass of anhydrite throughout the rock.

4) Conversion of anhydrite to secondary gypsum.

5) Precipitation of fibrous gypsum as a vein filling cement.

6) Growth of gypsum "selenite" crystals in a thin crust on top of the bed.

Dolomite Beds

1) Dolomitization of carbonate sediments.

2) Precipitation of hematite as a pore lining cement.

3) Precipitation of calcite and gypsum as pore filling cements.

Calcretes

1) Growth of micritic and finely crystalline calcite within the host sediment.

2) Partial dolomitization of micritic and finely crystalline calcite.

3) Replacement of micritic and finely crystalline calcite by sparry calcite.

4) Formation of dilation fractures.

5) Precipitation of sparry and/or fibrous calcite as a fracture filling cement.

Nodular and Bedded Gypsum

1) Growth of gypsum crystals within the host sediment.

2) Conversion of gypsum crystals to anhydrite and the continued growth of primary anhydrite.

3) Conversion of anhydrite to secondary gypsum.

CHAPTER VII

DEPOSITIONAL ENVIRONMENTS

During Pliensbachian to Middle Oxfordian time, the central and southern Rocky Mountains region occupied a paleolatitude range of 5° to 25° north (Kocurek and Dott, 1983). Outcrop evidence suggests a hot and arid paleoclimate. Four major marine transgressions have been recorded for the Jurassic of the Rocky Mountain area. The last and most extensive transgression began in the Callovian and reached its maximum limits during the Oxfordian. It is the opinion of this author that the southernmost extent of this transgression has not been satisfactorily determined.

Outcrops of the Ralston Creek Formation have been recognized in central-northern, central, and south-central Colorado. Ralston Creek sediments were derived from the Ancestral Rocky Mountains, the Ancestral Uncompahgre Highlands (both of which are Precambrian), and from the reworking of older neighboring sedimentary deposits such as the Fountain and Entrada Formations.

In the western part of the Canon City area, the Ralston Creek Formation is composed primarily of conglomerates and sandstones. These are a local feature associated with the Wet Mountain uplift area which was tectonically active at this time.

Eastward and north of the Canon City embayment, the lithology changes to one composed primarily of gypsum with interbedded sandstones and shales and minor carbonates. Previous authors have described these deposits as being of marine, marginal marine, restricted marine (Heaton, 1950; Imlay, 1952; Frederickson, DeLay, and Saylor, 1956; Cramer, 1962; Carter, 1984; Kocurek and Dott, 1983; Peterson, 1974) or nonmarine origin (Haun, 1960). This thesis proposes a nonmarine origin for these deposits.

Three depositional facies are found in the Ralston Creek Formation in the vicinity of Canon City, Colorado: an alluvial fan facies, a perennial saline lake facies, and an inland playa facies (Figure 39).

Alluvial Fans

Alluvial fans are cone shaped deposits of sediment which accumulate at the base of a mountain front or other upland area where there is an abrupt change to a flat or slightly sloping area and where sediment looses its confinement from a high-relief valley. They are particularly numerous in tectonic regions where long fault blocks have produced an extensive scarp. Where the mountain front is relatively straight, a series of adjacent and coalescing fans will form a bajada or piedmont slope.

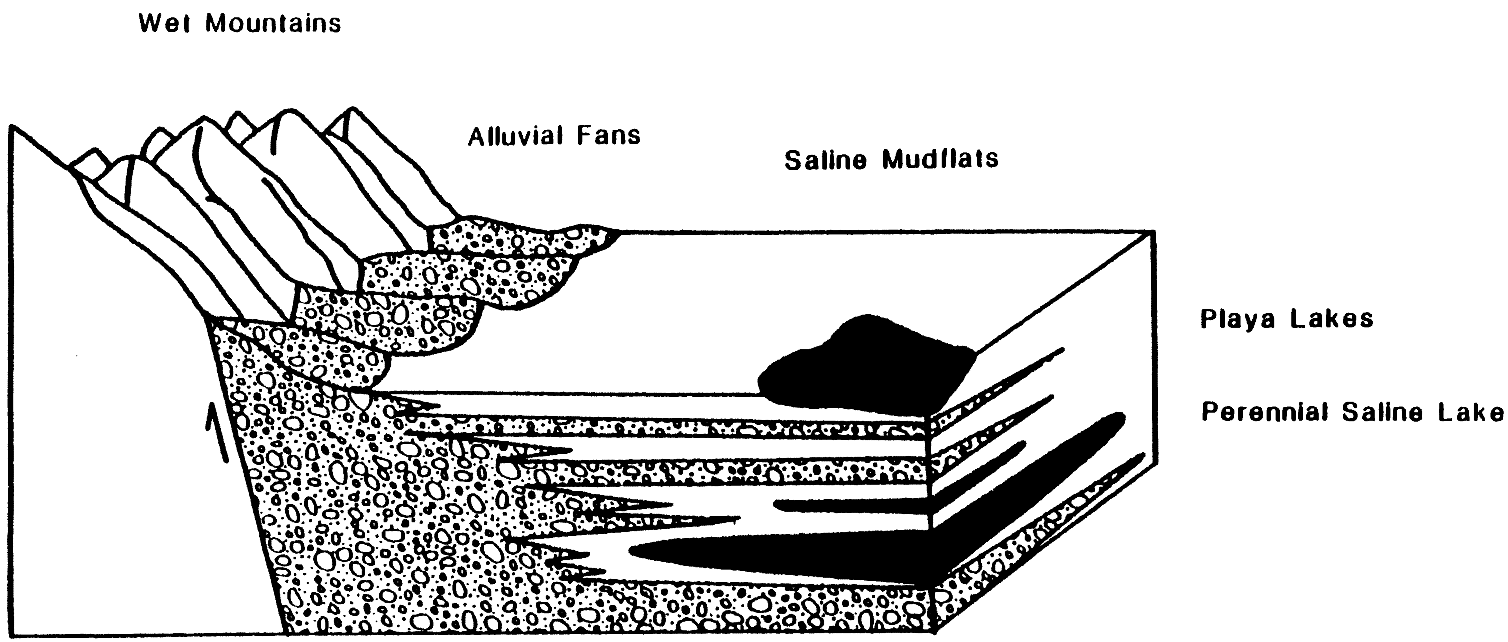


Figure 39. Block Diagram Showing the Alluvial Fan, Perennial Saline Lake, and Inland Playa Depositional Facies in the Ralston Creek Formation (after Smoot, 1978)

Geometry of Alluvial Fan Deposits

The sizes and shapes of alluvial fans are controlled by several factors. They include: the size of the drainage area, the amount of sediment carried by the feeding stream, and the relief and rate of tectonic uplift at the basin margin.

The size of alluvial fans can range from less than a hundred meters to more than 150 km in radius. They generally average less than 10 km. Thickness can range from a few meters to as much as 25,000 meters (Nilsen, 1982). In addition, hundreds of meters of relief may exist between the elevation of the apex and the valley floor.

The internal geometry of alluvial fans is closely related to the rate and style of tectonic uplift of the source area. Most fans prograde rapidly following uplift of source areas and establishment of drainage systems. Active fan progradation and outbuilding is indicated by thinner and finer grained sheetlike deposits which are overlain by thicker or coarser grained channelized deposits. These form an overall coarsening and thickening upward vertical sequence with more distal facies being overlain by more proximal facies. As the fan builds outward towards the basin, lateral shifting of channels gradually constructs a depositional body that exhibits: a characteristic fan shape in plan view, a convex upward cross fan profile, and a concave upward radial profile that consists of a series of merging lens shaped bodies in transverse cross section

(Figure 40). Lens shaped bodies are formed by: 1) the coalescing of adjacent fans, and 2) the process of entrenchment and abandonment due to shifting in the depositional areas of wash from the mountainous source which produces a fan complex composed of several fans or lobes (Figure 41). Fining and thinning upward sequences are indicative of relative inactivity or fan retrogradation.

Alluvial Fan Facies

Alluvial fans can be divided into proximal and distal facies. Proximal facies are characterized by coarse grained sediments which are deposited in the upper or inner parts of the fan, near the area of stream emergence from the upland area. Distal facies are characterized by finer grained sediments which are deposited in the lower or outer parts of the fan. Proximal facies can also be distinguished by highly channeled and lenticular beds; distal facies can be distinguished by less channelized sheetlike beds (Kerr et al., 1979).

Nilsen (1982) subdivided alluvial fan facies into four major facies associations: 1) inner-fan, which consists of a major channel complex that is connected to the feeding upland stream, 2) middle-fan, which consists of a series of radiating distributary channels that are characteristically braided and separated from each other by interchannel and levee deposits, 3) outer-fan, which consists of a generally smooth and gently sloping area where sheets of sediment are

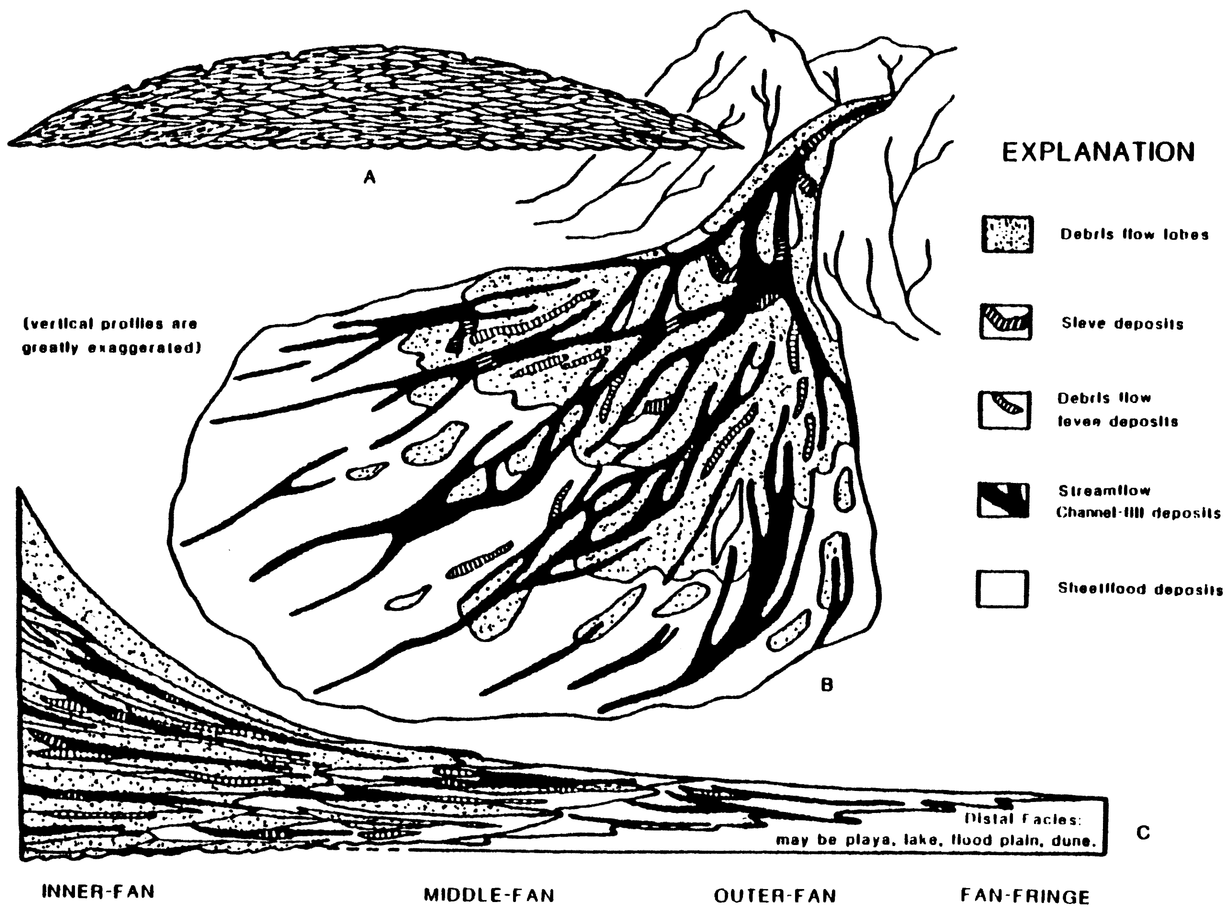


Figure 40. Generalized Model of Alluvial Fan Sedimentation Showing: A) the Characteristic Fan Shape in Plan View, B) the Convex Upward Cross Fan Profile, and C) the Concave Upward Radial Profile (after Spearing, 1974)

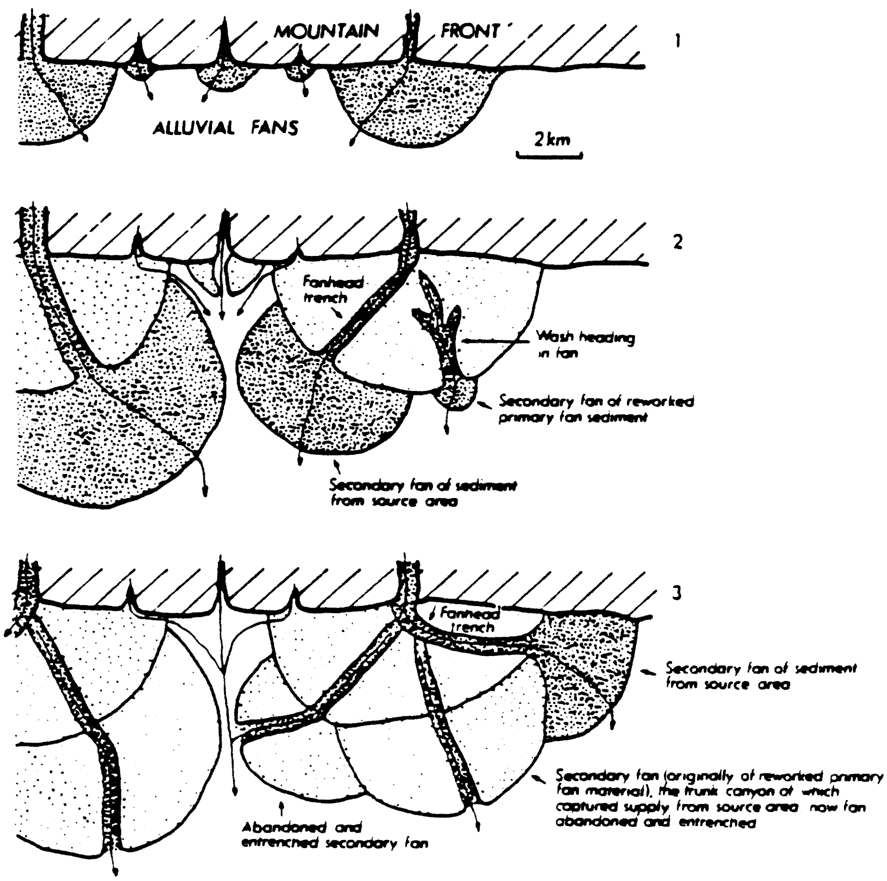


Figure 41. Diagram, Showing the Development of an Alluvial Fan Complex Along a Steep Fault Scarp (from Denney, 1967)

deposited by emerging flows from channels, and 4) fan-fringe, which consists of the smooth and flat fan margin where distal fan deposits intercalate with other facies such as alluvial plain, lacustrine, marine, playa, estuarine, deltaic, and eolian.

Depositional Processes

Fan sequences consist primarily of mixtures of streamflow deposits and debris flow and related deposits (Nilsen, 1982; Bull, 1972). Streamflow deposits result from the deposition of sediments carried in suspension, saltation, and traction by flowing water whether of channelized or nonchannelized flow. Debris flow and related deposits result from the deposition of sediments as viscous gravity flows. Sediment can also be transported by landsliding to the fan from inter-stream slope areas of the mountain front.

Streamflow deposits are generally well stratified, contain a variety of sedimentary structures indicative of different flow regimes, are clast-supported, contain clasts that are oriented relative to flow direction, and have small amounts of clay sized matrix. They include: 1) channel-fills, 2) channel-margin, levee, and interchannel deposits, 3) sheetflood deposits, and 4) sieve deposits.

Channel-fills are geometrically long and narrow. The basal surface is characteristically concave upward in transverse cross section. Contacts with flanking and underlying deposits are erosional. Inner-fan channel deposits typically fill straight and entrenched channels. Middle-fan and outer-fan channel deposits typically fill braided channels. Channel-fills are the most coarse grained and poorly sorted streamflow deposits; they are commonly conglomeratic. Channels become shallower and channel deposits finer grained downfan.

Channel-margin, levee, and interchannel deposits are characterized by beds which generally thin and fine away from the channel towards interchannel areas where thin, sheetlike beds are deposited by over-banking floods. They are poorly preserved in ancient fan sequences where channels gradually shifted across the fans and eroded the deposits. They are better preserved where new channels developed more abruptly by avulsion.

Sheetflood deposits most typically develop in the lower parts of fans. They may also develop in wide channels and in interchannel areas. They result from the spreading out of sediment-laden floodwater where it emerges from the channels. A decrease in flow velocity combined with the lower slopes present in lower fan areas results in the deposition of sheets of sediment. They typically occur as a series of low bars of sand or gravel that may be cut by small, shallow channels during waning flood stages. Sheetflood deposits are generally composed of sand with minor amounts of clay. They are fairly well sorted and well stratified and contain parallel and cross bedding.

Sieve deposits are a type of streamflow deposit generally present in proximal areas. They consist of permeable lobes of gravel that fine upslope and through which flood discharges completely infiltrate before reaching the fan fringe (Hooke, 1967). They are composed of well sorted gravel containing relatively angular and monomict clasts with well developed imbrication. The beds are massive and laterally extensive. Sieve deposits form on some arid fans where the source area supplies gravel sized sediment rather than sand, silt, or clay. Subsequent deposition and cementation eventually fill pore spaces with matrix. As a result, few sieve deposits have been reported from ancient fan deposits.

Debris flow and related deposits are generally poorly stratified, contain few sedimentary structures, are matrix-supported, contain clasts with little or no orientation relative to flow direction, and have large amounts of clay sized matrix.

Debris flow deposits are commonly intermixed with streamflow deposits. They may be confined to channels or may spread out laterally as sheets or lobes in interchannel or lower fan areas. They are most common in the upper fan or proximal areas (Hooke, 1967). Debris flows generate where the source area supplies abundant muddy material, where slopes are steep, vegetation is scarce, and rainfall is either seasonal or irregular. Sediment bodies are lobate and tabular in shape. They are characteristically poorly sorted, reverse graded in their basal parts, and form disorganized beds with isotropic fabrics. A determining factor in the internal organization of a debris flow is the amount of water in a flow. Relatively low strength flows may have graded bedding, show imbrication, and contain a smaller maximum clast size compared to high strength flows which may carry large boulders (Bull, 1972).

Mudflows are a type of debris flow that consist almost entirely of fine grained sediments, sand size and finer. They may be deposited either in channels or in nonchannelized areas of fans. Mudflow viscosities can vary widely. Therefore, the resulting deposits can range from thin widespread sheets to thick lobate bodies. When mudflows solidify, extensive mud cracks may form, particularly on the surface of flows, due to contracting clay-rich sediment.

Alluvial Fan Facies in the Ralston Creek Formation

The Ralston Creek Formation contains both proximal and distal fan facies. These can be subdivided into middle-fan, outer-fan, and fan-fringe facies.

The middle-fan facies is represented by the basal conglomerate member and the upper conglomeratic member. It is composed of conglomerates, sandstones, siltstones, and shales. They are interpreted as follows: the clast-supported and sandy matrix-supported conglomerates are channel-fill deposits, some of the sandstones are channel-fill deposits resulting from waning flow, the muddy sandy matrix-supported conglomerates are debris flow deposits, other sandstones, siltstones, and shales are channel-margin, levee, interchannel, and mudflow deposits.

The outer-fan facies is represented by the basal sandstone member and the upper sandstone member. It is composed of parallel laminated and parallel bedded sandstones that are interpreted as sheetflood deposits.

Fan-fringe facies are marginal fan deposits that intercalate with the inland playa facies. They are composed of conglomerates (minor), sandstones, siltstones, and shales.

Alluvial fan deposits are identified primarily by their physical rather than chemical and biological characteristics. Some of the major criteria for the recognition of alluvial fan deposits that were observed in the Ralston Creek Formation are listed below:

1) Alluvial fan deposits are commonly associated with fault bounded basins.

2) Sediments are deposited relatively close to the source area.

3) Clasts are poorly rounded, due to the short distance in transport.

4) Sediments may have a wide range in composition, depending on the types of rocks present in the source area.

5) Sediments are characterized by major changes in lateral and vertical facies.

6) Sediments are characterized by a general decrease in grain size from the apex to the distal portions of the fan.

7) Sediments are typically very poorly sorted and contain a wide range in grain size.

8) Sediments generally contain sedimentary structures such as medium scale cross bedding and planar stratification.

9) Sediments are generally oxidized.

10) Sediments generally do not contain large amounts of organic material.

11) Sediments generally do not contain many fossils.

12) Depositional bodies typically have a lenticular or wedge shaped geometry.

13) Depositional bodies consist of a mixture of unstratified debris flow deposits and better stratified stream flow deposits.

14) Depositional bodies are extensively channelized.

15) Depositional bodies contain distal fan deposits that intercalate with other facies.

16) Depositional bodies contain soil profiles.

17) Depositional bodies contain salts such as calcite or gypsum deposited interstitially within soils.

Perennial Saline Lakes

A saline lake is one which contains greater than 5000 ppm dissolved solids (Hardie et al., 1978). In order to achieve such salinities, certain conditions must be met:

1) the outflow of water must be restricted, as in a hydrologically closed basin, 2) evaporation must exceed inflow, and 3) inflow must be sufficient to sustain a standing body of water (Eugster and Hardie, 1978). While neither closed basins nor evaporative conditions are uncommon, the combination of both, coupled with a plentiful inflow of water (from springs, ground water or rivers) is uncommon. As a result, the occurrences of saline lakes are greatly limited.

The most favorable conditions for the formation of saline lakes are found in rain shadow basins. They provide the unique combination of mountains, acting as precipitation traps, and arid valley floors. During deposition of the Ralston Creek Formation, a partial rain shadow was formed by the Ancestral Rocky Mountains. The effectiveness of the mountains was limited, however, due to their low relief.

Lake water dynamics are controlled by: 1) climate, which controls water chemistry, water temperature, organic productivity, and shoreline fluctuations, 2) water depth, which controls lake stratification and current effectiveness, and 3) the nature and amount of clastic sediment and solute input from the lake drainage basin (Leeder, 1982).

There is a wide range in the composition of saline lakes. The brines are dominated by relatively few major solutes: SiO_2, Ca^{++}, Mg^{++}, Na^+, K^+, HCO_3^-, $CO_3^=$, $SO_4^=$ and Cl^-. Although sodium is by far the most concentrated cation, anion abundance varies markedly (Eugster and Hardie, 1978). The most important factor contributing to the composition of saline lakes is the composition of the bedrock in the drainage basin.

Stratified perennial saline lakes are formed by the following mechanism: 1) evaporation causes the concentration of surface brine and eventual nucleation of minerals, 2) mineral precipitation causes the brine to sink due to increased density; less dense runoff floats on the surface, and 3) low concentration surface water eventually increases in density due to evaporation and the process is repeated. Although the minerals that precipitate will vary widely, this basic mechanism prevails (Hardie et al., 1978). The concentration of the brines, and therefore the minerals that will precipitate tend to be determined by the relative rates of evaporation and inflow in the lake.

The sequence of minerals that precipitate with increasing brine concentration is: carbonates, co-precipitation of carbonates and gypsum, and halite. At this stage of maturity, in shallow lakes, the brine commonly dries up and the lake becomes ephemeral or dry. Only if the lake is hundreds of meters deep will it remain a perennial saline lake (Hardie et al., 1978). It will eventually dry up or become ephemeral, but not until very thick accumulations of evaporites have precipitated.

Although few sedimentary structures develop in saline lakes, stratification is common. Layers of terrigenous clastic particles interbedded with evaporites and organic material have been interpreted as varves or annual cycles of sedimentation representing seasonal accumulations (Anderson and Kirkland, 1960). They have also been interpreted as irregular, representing longer durations, with continuous year-round deposition of evaporite layers and the periodic introduction of terrigenous particles by storm-floods (Neev and Emery, 1967).

Saline Lake Facies in the Ralston Creek Formation

The saline lake facies in the Ralston Creek Formation is represented by the laminated dolomite and gypsum member and the white limestone member (Figure 42). Four distinct laminae are present in the laminated dolomite and gypsum bed: dolomite, organic material, clastic grains, and gypsum. Three laminae are present in the white limestone bed: limestone, organic material, and clastic grains. The laminae are interpreted according to the model described by Anderson and Kirkland (1960). Although not all constituent relationships described by Anderson and Kirkland were actually observed in thin section, it is probable that their model of deposition can be applied to the Ralston Creek Formation.

Environmental factors believed to have had an influence in controlling the seasonal deposition of the carbonate laminae include: temperature, evaporation, inflow of water

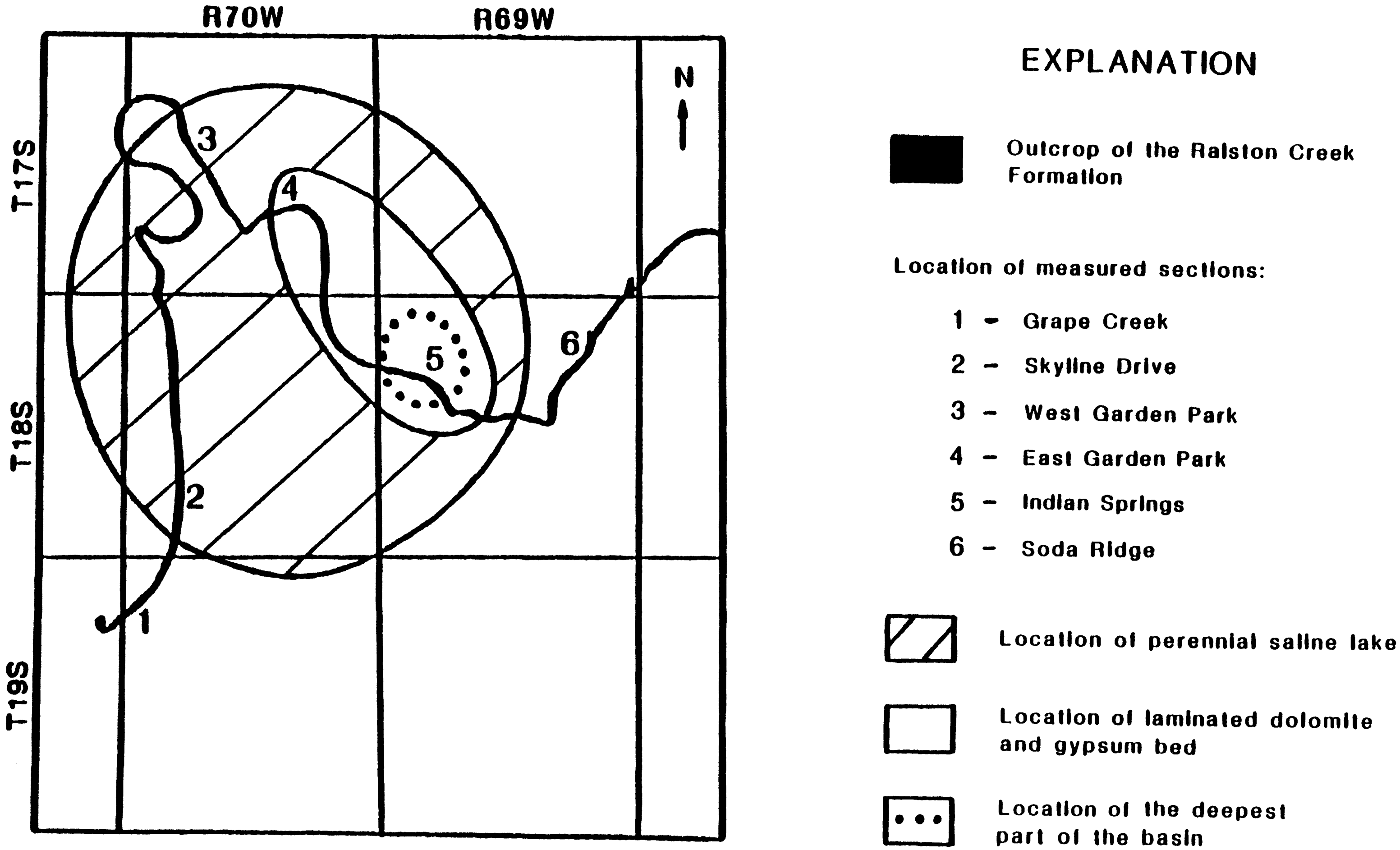


Figure 42. Diagram Showing the Estimated Location of the Perennial Saline Lake Facies in the Canon City Area

into the basin, and photosynthesis. Temperature was probably the most important factor. Calcium carbonate was precipitated during the summer months as a result of increased water temperatures which reduced the amount of carbon dioxide in solution and the capacity of the water to hold calcium bicarbonate in solution. Increasing evaporation with increasing temperature also contributed to calcium carbonate precipitation. Another factor was the seasonal inflow of water into the basin. If the concentration of calcium bicarbonate in the inflowing water was less than that in the basin, the concentration in the basin would be reduced and calcium carbonate precipitation would either stop or be decreased. Also important during the summer months is the process of photosynthesis. Phytoplankton remove carbon dioxide from the system which reduces the acidity of the water and the solubility of calcium carbonate.

Variations in laminae thickness may be the result of seasonal weather changes. Cooler and/or wetter years are indicated by annual cycles in which carbonate laminae are thin or absent. Warmer and/or drier years are indicated by thicker carbonate laminae.

The organic laminae are composed of sapropel. At the time of deposition, the sapropel was an ooze composed primarily of phytoplankton and water. The original thickness of the laminae has probably been reduced considerably by compaction. The growth of plankton and the formation of calcium carbonate crystals probably reached their peak at about the same time, at maximum annual temperatures during the summer. The carbonate particles settled to the bottom; the plankton remained in suspension until they were killed by decreasing temperatures in autumn or early winter. The lag between the growth of organisms and their fall as sedimentary particles explains the stratification of the carbonate and organic laminae.

Layers of clastic particles lie between the carbonate and organic laminae. Their position indicates that the particles were brought into the basin during the winter and spring, when sedimentation was slowest and the grains had more time to accumulate.

There is an inverse relationship between the thickness of the clastic and carbonate laminae. Generally, as the number of clastic grains increases, the thickness of the overlying carbonate lamina decreases. There are two explanations for this. If the clastic grains were wind-born, a thick clastic layer and a thin carbonate layer would be the result of years of high average wind intensity accompanied by abnormally low average summer temperature. If they were stream-born, the number of clastic grains would be indicative of the volume of inflow into the basin. High rainfall and inflow would result in an increase in the number of clastic grains and an increase in the ability of the basin water to hold calcium carbonate in solution. The result would be a thin carbonate layer.

It is likely that the grains were transported by both wind and streams. The distribution of suspended sediments more or less uniformly over the basin could be the result of fresher water from streams, which would have floated on top of the more saline water and eolian transport, which is expected in a desert basin.

Gypsum deposition seems to have directly followed carbonate deposition. The factor that determines which will precipitate is the solubility ratio. Seasonal changes caused the concentration of carbonate and sulfate ions to fluctuate about the solubility ratio. During the summer, increased temperature, salinity, and photosynthesis decreased the amount of carbon dioxide in the water and caused the precipitation of calcium carbonate. During cooler seasons, decreased temperatures, reduced salinity, and the inactivity of plankton allowed more carbon dioxide to be held in solution. This caused calcium carbonate to go into the more soluble calcium bicarbonate and resulted in the precipitation of calcium sulfate.

The sizes of the gypsum laminae indicate that the rate of deposition of gypsum was considerably greater than that of the carbonate. The number of clastic grains decreases proportionately and can no longer be seen in discrete layers. Organic laminae also decrease and eventually disappear.

Conditions favorable to the preservation of the microstratigraphy of the beds and the preservation of sapropelic sediments include:

1) Deposition below the zone of agitation.

2) Lack of strong or moderate currents at depth.

3) Lack of overturn or exchange of bottom and surface water.

4) Temperature decrease with depth.

5) Thermal and chemical stratification.

6) Bottom waters which were probably charged with hydrogen sulfide and held relatively large amounts of calcium carbonate in solution. The toxic bottom environment probably accounts for the absence of fossils in the beds.

Thin section analysis of the laminated dolomite and gypsum bed indicates that deposition began with a 2 fold cycle of clastics and organic material (oil shale) and progressed through a sequence of increasing and decreasing varve complexity. The 2 fold cycle was followed by a 3 fold cycle which included carbonates. Apparently, planktonic blooms began soon after the basin was filled with water and seasonal deposition was established. Carbonates were precipitated later, as a result of the evaporative concentration of brines. This was followed by a 4 fold cycle which included gypsum. The eventual disappearance of organic laminae resulted in a 3 fold cycle of carbonates, clastics, and gypsum. Following this, the lake dried up and became ephemeral. The top of the bed is composed of massive gypsum with traces of scattered clastic grains. A diagramatic illustration of the varved sequences is shown in

Figure 43.

Assuming that the varved sequences represent annual cycles of sedimentation, an estimation of the amount of time required for each phase of deposition can be calculated. A summary of these calculations is shown in Table IV. Note that it is not possible to distinguish exactly where in the section the disappearance of organic laminae takes place. Therefore, the 3 fold cycle of carbonates, clastics, and gypsum is combined with the 4 fold cycle of carbonates, organic material, clastics, and gypsum. The perennial saline lake depositional facies in the Ralston Creek Formation appears to have lasted approximately 5,000 years.

Deposition of the white limestone bed occurred as a 3 fold cycle of limestone, organic material, and clastic grains. Apparently deposition of the other cycles of sedimentation was confined to the deepest parts of the basin. The white limestone bed was probably deposited in the shallower parts of the basin.

Inland Playas

A playa is the central basin of a desert plain in which water accumulates and is evaporated. It is characterized by an almost horizontal surface that is largely vegetation-free and composed of fine grained sediments. Playas range in size from a few hundred square meters to 8000 km^2 (the size of Lake Eyre in Australia) (Twidale, 1972).

Terrigenous sediments are not abundant on playas

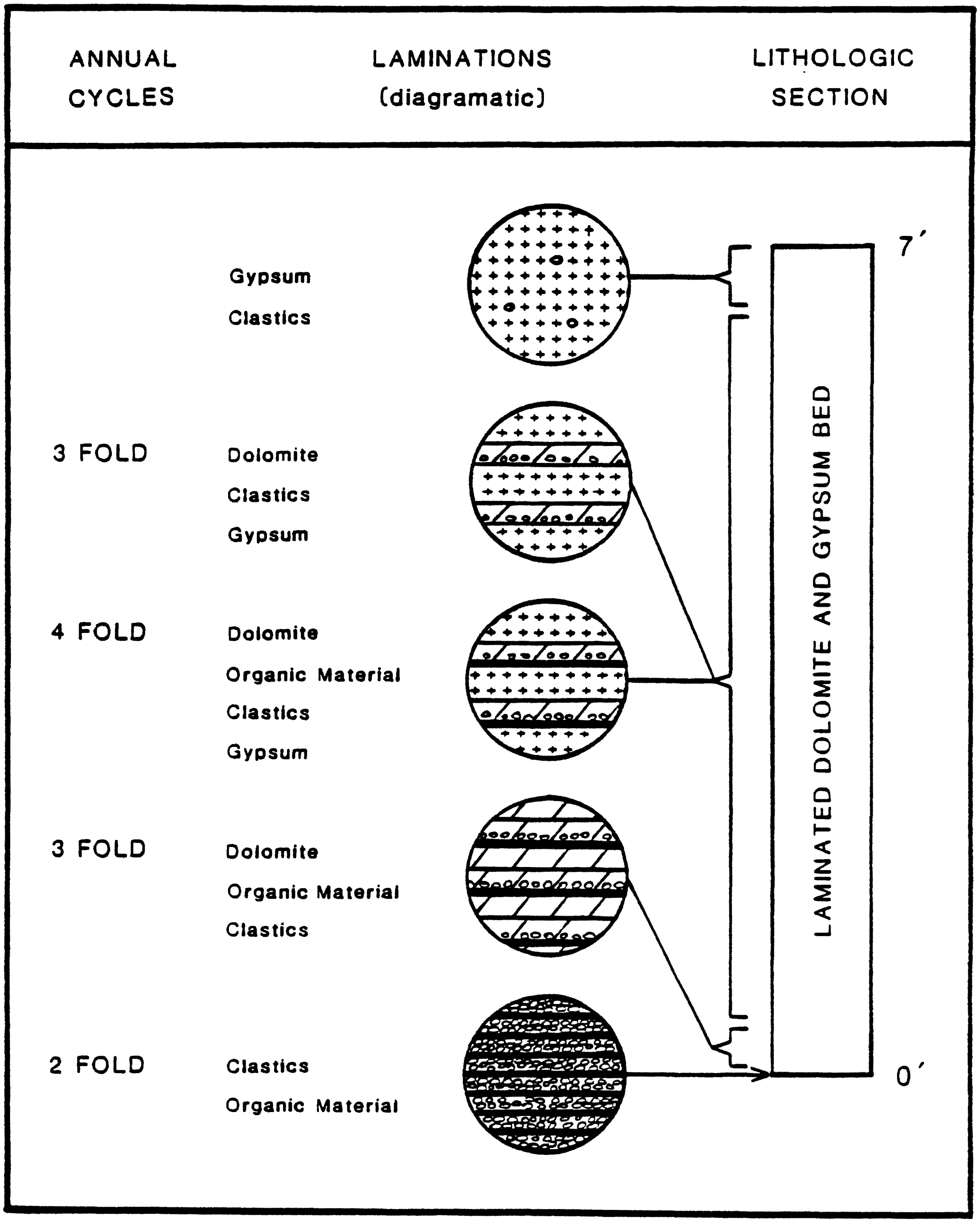


Figure 43. Diagrammatic Illustration of the Varved Sequences in the Laminated Dolomite and Gypsum Bed (after Anderson and Kirkland, 1960)

TABLE IV

ESTIMATED TIME REQUIRED FOR EACH PHASE OF DEPOSITION IN THE PERENNIAL SALINE LAKES FACIES OF THE RALSTON CREEK FORMATION

Annual Cycle	Composition	Average Varve Size (mm)	Thickness of Section (cm)	Time (Years)
	Gypsum		15	?
3 Fold	Carbonates	4	146	365
	Clastics	3	15	50
	Gypsum	2	19	95
		0.5	6.5	130
4 Fold	Carbonates			640
	Organic Material			
	Clastics			
	Gypsum			
3 Fold	Carbonates	0.01	1.2	1,200
	Organic Material	0.05	10.1	2,020
	Clastics			3,220
2 Fold	Clastics	0.01	1.2	1,200
	Organic Material			
			Total:	5,060

because of the general absence of weathering in arid environments. Playas are affected primarily by processes involving evaporation and chemical precipitants form the primary component of this environment. The size and character of a playa may remain constant or change significantly over just a few months. Where flash flooding is prominent, large quantities of water are commonly received and may persist for months. As the playa lake and marginal mud flats dry up, evaporite precipitation takes place. Evaporites are either precipitated from playa lakes or emplaced within desiccated sediments. Extreme evaporation and therefore reduction in the area of ponded water is necessary in order to achieve the salinities required to precipitate salts. As a result, evaporites may only be present in a small portion of the playa, usually in the lowest areas of the basin (Kendall, 1979; Eugster and Hardie, 1978). Couplets, composed of terrigenous mud layers and evaporites may be repeated to accumulate tens or hundreds of meters of sediment (Hardie et al, 1978).

Inland playa environments are affected primarily by catastrophic deluges of water associated with rain showers and flash flooding. Alluvial fans at basin edges trap most of the coarse sediment so that only mud and fine sand is carried into the basin. Aside from the surface flow which takes place during storms, water circulation in playas is generally confined to the subsurface. Most evaporites accumulate in playas where the water table is close enough to the surface for ground water discharge to occur. This may be indirect: caused by evaporative pumping, capillary rise or evapotranspiration, or direct: from the water table or from springs. Evaporation and the concomitant concentration of pore fluids results in the formation of brines. The type of mineral that will precipitate from these brines is dependent on the chemical composition of the ground water supply.

Continued evaporation results in a ground water concentration gradient towards the center of the basin and therefore a mineral zonation. More soluble minerals are precipitated in the most distal parts of the ground water flow; less soluble minerals are precipitated in the basin center. For example: 1) calcite cement and calcrete layers are precipitated in alluvial fans, 2) Mg-calcite and protodolomite occur in playa fringes, 3) travertines and pisolitic calcretes are found associated with peripheral springs, 4) carbonate muds are precipitated on playa flats, and 5) calcium sulfate and halite are found towards the basin center (Kendall, 1979).

Carbonate muds, together with any detrital sediments are transported towards the center of the basin by storm sheetflood. This imparts a laminated or cross-laminated structure to the sediment. The laminated structure is continuously disrupted by further ground water discharge and by the growth and dissolution of evaporite crystals and crusts. Surfical drying of the playa may also cause sediment deflation and extensive and multiple mud-cracking. Gypsum crystals precipitated displacively within sediments are concentrated as lag deposits. They may be swept together to form gypsum dunes or may dehydrate to bassanite or anhydrite. In some inland playas, calcium sulfate is emplaced within sediments directly as nodular anhydrite and appears identical to that observed in coastal playa environments (Kendall, 1979).

The evaporation of ponded storm waters or ground water discharge results in the formation of efflorescent crusts of saline minerals on the playa surface. These crusts may be 30 or more centimeters in thickness. Continued growth of salt crystals caused great increases in volume and the formation of salt-thrust polygons or highly irregular surfaces with up to several meters of relief. Evaporite crusts are composed of metastable and highly soluble salts that are dissolved by rain and storm waters to form concentrated brines which ultimately reach the basin center. Salts that initially survive dissolution by rain or storm waters and become buried will eventually be dissolved if the underlying ground waters are undersaturated. The upward movement of the less saline ground water dissolves the salt and reprecipitates it at the surface. Ground water becomes increasingly saline towards the basin center where calcium sulfate and even halite may become stable in the sediment (Kendall, 1979).

Playa lakes may lie at the termination of ground water flow paths. They are fed by ground water seepage, springs or by accumulation of storm water. As the ponded brines continue to evaporate, saline minerals are precipitated. Playa lakes last only as long as precipitation and inflow are greater than the amount of water lost by evaporation. Factors which determine the amount of water lost by evaporation are climate, water salinity, and the geometry of the water body (Kendall, 1979).

Playa Facies in the Ralston Creek Formation

The inland playa facies in the Ralston Creek Formation is represented by the upper gypsiferous member. It is composed primarily of bedded "chicken-wire" gypsum interbedded with shales and/or nodular gypsum within shales. These are interpreted as playa mudflat deposits. Also of significance are the two thin dolomite beds at Indian Springs. These are interpreted as playa lake deposits.

The basin center appears to have been located at Indian Springs. Evidence for this is as follows:

1) The deepest part of the basin in the perennial saline lake facies previously described was represented by the laminated dolomite and gypsum member. This bed is thickest at Indian Springs. The perennial saline lake eventually dried up and became ephemeral.

2) The two dolomite beds that are interpreted as ephemeral playa lake deposits are located at Indian Springs.

Playa lakes generally occupy central depressions caused by deflation or tectonic setting.

3) Playa mudflat deposits of interbedded gypsum and shale are thickest at Indian Springs. They comprise 94 feet of the upper gypsiferous member. Playa mudflat deposits to the east at Soda Ridge are only 35 feet thick.

The section at East Garden Park represents the westernmost portion of the playa. It is composed primarily of interbedded sandstone and shale. Present within the shales are varying amounts of gypsum nodules. The amount of gypsum present is far less than that described at Indian Springs or Soda Ridge.

Clastic sediments were derived from the alluvial fans to the west. Alluvial fan-fringe deposits intercalate with the inland playa deposits. These sediments decrease in abundance in an eastern direction.

Depositional History of the Ralston Creek Formation

The Wet Mountain uplift area in the western part of the Canon City area was tectonically active during the deposition of the Ralston Creek Formation. The first episode of tectonic activity resulted in the deposition of alluvial fan sediments that reached as far east as Indian Springs. It appears that the relief of the Wet Mountain uplift area was not very great at this time. Alluvial fan deposits only reach 7 feet in thickness.

A relatively long period of geomorphic stability followed. During this time, a perennial saline lake developed. It is estimated that the lake was in existence for approximately 5,000 years. Further evidence for a period of geomorphic stability is the presence of a thin, stratigraphically equivalent, Type 4 calcrete layer at Grape Creek. The perennial saline lake eventually dried up and became ephemeral. An episode of playa lake formation followed which resulted in the deposition of a thin dolomite bed at the basin center at Indian Springs.

A second episode of tectonic activity resulted in the deposition of a relatively thick sequence of alluvial fan sediments. These sediments reach 138 feet in thickness at Skyline Drive. Evidence for the progradation of alluvial fans is seen in the vertical sequences in the western part of the study area. They are characterized by an overall coarsening up megasequence in which distal facies are overlain by more proximal facies. The eventual cessation of tectonic activity and fan retrogration is evidenced at West Garden Park, where the top of the section contains a fining upward sequence.

As fan activity diminished, a second episode of playa lake formation occurred at Indian Springs and an inland playa environment developed that covered the area from East Garden Park to Soda Ridge. Nodular and bedded chicken-wire gypsum grew displacively within deposited clastic sediments. Playa deposits reach 94 feet in thickness at the basin center at Indian Springs. The inland playa depositional facies represents the final stage of development of the Ralston Creek Formation (Figure 44).

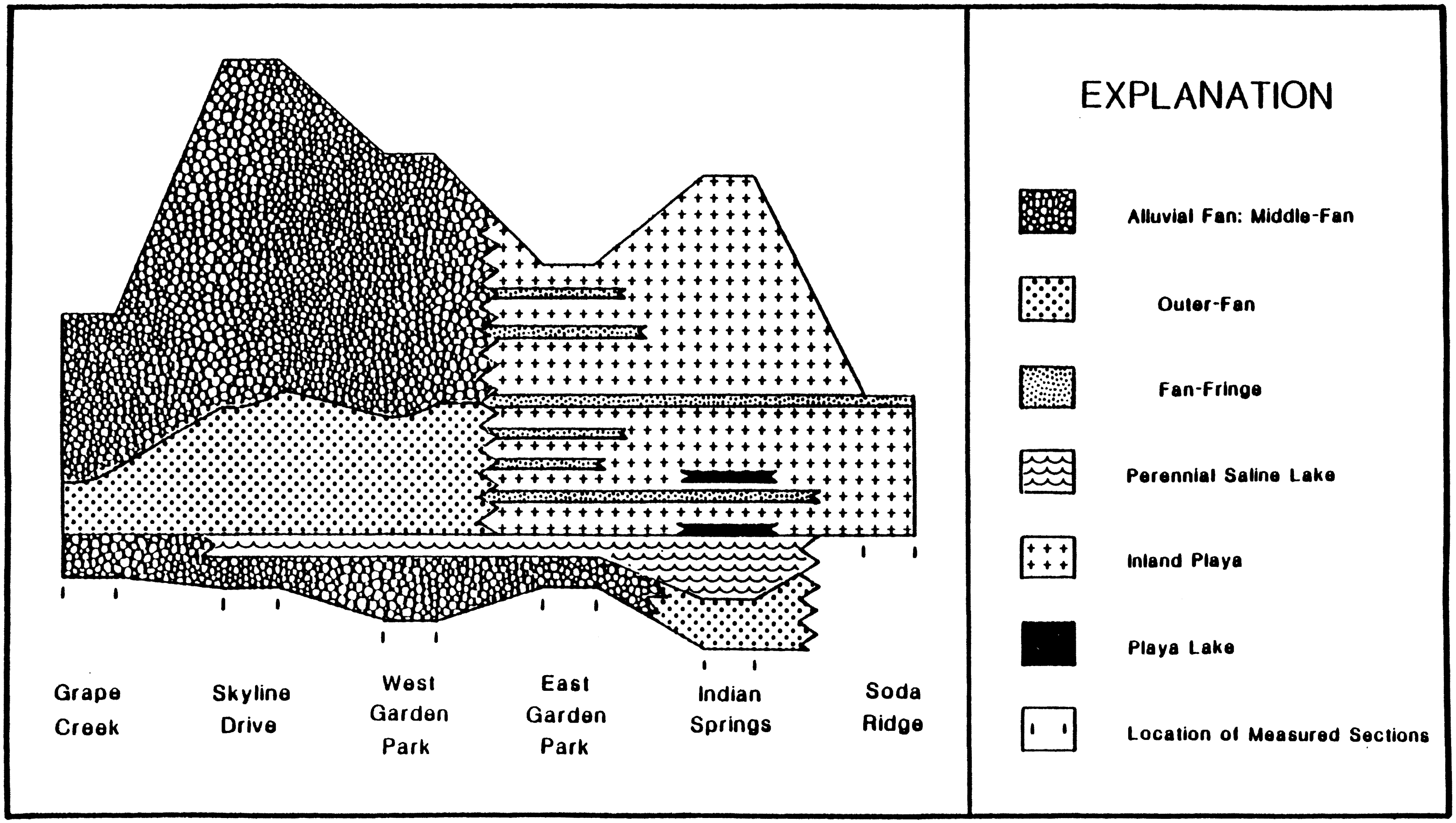


Figure 44. Diagram Showing the Depositional Facies in the Ralston Creek Formation in the Vicinity of Canon City, Colorado

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The purpose of this thesis is to describe and interpret the sedimentary geology of the Jurassic Ralston Creek Formation as it is exposed in the vicinity of Canon City, Colorado. Primary objectives were: 1) to redefine the lithofacies, 2) to describe the lithologies, 3) to analyze the petrography and diagenesis of the various lithologies, and 4) to interpret the depositional environments.

Analysis of the lithofacies resulted in the identification, description, and correlation of seven <u>ad</u> <u>hoc</u> "members" which are locally persistant. These members have not been previously described. Petrographic analysis resulted in the classification of rock types, detailed descriptions of the detrital and authigenic constituents, and descriptions of the diagenetic histories of the lithologies. Analysis of the depositional facies resulted in a new interpretation of the depositional environments. In particular, this study proposes a nonmarine origin for the evaporite deposits. The following conclusions have been made.

Lithofacies

1) Two major lithofacies are present in the Canon City

area: a western conglomeratic facies and an eastern gypsiferous facies.

2) The western conglomeratic facies includes: a basal conglomerate member, a white limestone member, an upper sandstone member, and an upper conglomeratic member.

3) The eastern gypsiferous facies includes: a basal sandstone member, a laminated dolomite and gypsum member, and an upper gypsiferous member.

4) The upper conglomeratic member is composed of conglomerates, sandstones, siltstones, shales, and limestone.

5) The upper gypsiferous member is composed of gypsum, sandstones, siltstones, shales, limestones, and dolomite.

Lithologic, Petrographic, and Diagenetic Characteristics of the Lithologies

1) Sandstones: The sandstones are either massive or contain the following sedimentary structures: parallel laminations, graded parallel bedding, small scale planar and trough cross bedding, and ripple marks. In some areas, slump structures and dewatering structures have disrupted the bedding planes.

Grain size ranges from very fine sand to medium pebble gravel. Types of sorting include bimodal, moderately, and poorly sorted grains. The majority of grains are subangular to subrounded with low sphericity. Rounded to well rounded grains with medium to high sphericity are present in some samples. Overall the sandstones are texturally submature.

The sandstones can be classified as subarkoses. Detrital constituents include quartz, feldspar, chert, volcanic, and shale rock fragments, muscovite, biotite, chlorite, zircon, and opaque minerals. Authigenic constituents include calcite, illite, gypsum, and hematite. The only physical diagenetic process was compaction.

2) Conglomerates: There are three different types of conglomerates: clast-supported conglomerates, sandy matrix-supported conglomerates, and muddy sandy matrix-supported conglomerates. In the clast-supported conglomerates and sandy matrix-supported conglomerates, bed geometry is mostly lenticular and consists of single to multistoried erosive based channel deposits. Medium scale trough cross bedding is abundant. The muddy sandy matrix-supported conglomerates occur as single deposits, they are generally massive and very friable, the basal contacts are not erosive, and the sediments are commonly stained red by hematite.

Grain size ranges from fine sand to cobble gravel. The average size of the gravel is granule to medium pebble. The sorting is bimodal. The grains are angular to subrounded with low sphericity. Overall, the conglomerates are texturally submature or immature.

The conglomerates can be classified as arkoses or subarkoses. The clasts are composed of: large angular feldspars, rounded quartz grains, some frosted quartz grains, granitic fragments, volcanic, chert, and shale rock fragments, gneisses, schists, various types of carbonates, and just west of the study area, dinosaur bones. Detrital constituents include quartz, feldspar, rock fragments, muscovite, biotite, chlorite, zircon, and opaque minerals. Authigenic constituents include calcite and hematite.

3) Siltstones and shales: Siltstones and shales are found throughout the study area interbedded with the other lithologies.

4) Limestones: There are two different types of limestones: the white limestone bed and calcretes.

The white limestone can be classified as a micrite. The dominant texture consists of thin horizontal laminations. The laminae are composed of micritic calcite and clastic grains. Muscovite, biotite, and stringers and flakes of brown organic material are present in trace amounts. Finely crystalline calcite occurs as a pore filling cement in small fractures and associated with some layers of clastic grains. Sparry calcite cement occurs as a replacement of salt pseudomorphs. The only physical diagenetic process was compaction. This resulted in the reduction of pore space, minor fracturing, and stylotization.

Calcretes occur either as nodules within sandstones, siltstones, and shales, or as thin continuous layers. They are composed of micritic and finely crystalline calcite and varying amounts of clastic grains. The massive fabric is sometimes replaced by sparry calcite and crossed by irregular dilation fractures which have been filled with sparry and/or fibrous calcite cement. In one thin section, the calcite has been partially dolomitized. Calcretes form as an early diagenetic phase within ancient soil horizons.

5) Dolomites: The dolomite beds are thin and massive. The dolomites can be classified as dolomicrites or dolodismicrites. They are primarily composed of varying amounts of micritic dolomite and clastic grains. One of the beds analyzed in thin section contains numerous fenestrae which have been filled with pore lining hematite cement and pore filling calcite and gypsum cement.

6) Gypsum: Gypsum occurs in association with dolomite or as nodular or bedded gypsum.

The dominant texture of the laminated dolomite and gypsum bed consists of horizontal laminations that increase in size progressively up section. Small internal folds and localized disruption of the laminae were produced by soft sediment deformation. Disruption of the laminae also results from the displacive diagenetic growth of gypsum. The original texture of the bed is almost completely obliterated at the top.

The bed is composed of: dolomite, clastic grains, organic material, and gypsum. Gypsum types include alabastrine, porphyroblastic, and fibrous. Gypsum increases in abundance progressively up section.

Chemical diagenetic processes that have affected the laminated dolomite and gypsum bed include: cementation, recrystallization, replacement, solution, dehydration, and rehydration. Gypsum is converted to anhydrite at depth. Uplift results in the hydration of anhydrite to secondary gypsum. The most applicable model for dolomitization is penecontemporaneous hypersaline dolomitization. The only physical diagenetic process was compaction. This produced plastic flow in some of the gypsum beds.

Gypsum also occurs as small discrete nodules within clastic sediments and bedded gypsum. The bedded gypsum has a chicken-wire texture. Some of the beds or layers have enterolithic textures. Nodular and bedded gypsum form as an early diagenetic phase within deposited clastic sediments.

Depositional Environments

1) It is suggested that three depositional facies can be found in the Ralston Creek Formation in the vicinity of Canon City, Colorado: an alluvial fan facies, a perennial saline lake facies, and an inland playa facies.

2) Alluvial fan facies: The Ralston Creek Formation contains both proximal and distal fan facies. These can be subdivided into middle-fan, outer-fan, and fan-fringe facies.

The middle-fan facies is represented by the basal conglomerate member and the upper conglomeratic member. It is composed of conglomerates, sandstones, siltstones, and shales. They are interpreted as follows: the clast-supported and sandy matrix-supported conglomerates are channel-fill deposits, some of the sandstones are channel-fill deposits resulting from waning flow, the muddy sandy matrix-supported conglomerates are debris flow deposits, other sandstones, siltstones, and shales are channel-margin, levee, interchannel, and mudflow deposits.

The outer-fan facies is represented by the basal sandstone member and the upper sandstone member. It is composed of parallel laminated and parallel bedded sandstones that are interpreted as sheetflow deposits.

Fan-fringe facies are marginal fan deposits that intercalate with the inland playa facies. They are composed of conglomerates (minor), sandstones, siltstones, and shales.

3) Perennial saline lake facies: The saline lake facies is represented by the laminated dolomite and gypsum member and the white limestone member.

Four distinct laminae are present in the laminated dolomite and gypsum bed: dolomite, organic material, clastic grains, and gypsum. The laminae are interpreted as varves or annual cycles of sedimentation representing seasonal accumulations. Calculations of the estimated amount of time required for each phase of deposition were made based on this assumption. Deposition began with a 2 fold cycle of clastics and organic material which lasted approximately 1,200 years. The 2 fold cycle was followed by a 3 fold cycle which included carbonates. This phase of deposition lasted approximately 3,220 years. This was followed by a 4 fold cycle which included gypsum. The eventual disappearance of organic material resulted in a 3 fold cycle of carbonates, clastics, and gypsum. The time required for the deposition of the 4 fold cycle and the 3 fold cycle was approximately 640 years. It appears based on these estimates that the perennial saline lake facies in the Ralston Creek Formation lasted approximately 5,000 years. Following this, the lake dried up and became ephemeral. The top of the bed is composed of massive gypsum with traces of scattered clastic grains.

Deposition of the white limestone bed occurred as a 3 fold cycle of: limestone, organic material, and clastic grains. Apparently deposition of the other cycles of sedimentation was confined to the deepest parts of the basin. The white limestone bed was probably deposited in the shallower parts of the basin.

4) Inland playa facies: The inland playa facies is represented by the upper gypsiferous member. It is composed primarily of bedded "chicken-wire" gypsum interbedded with shales and/or nodular gypsum within shales. These are interpreted as playa mudflat deposits. The two thin dolomite beds at Indian Springs are interpreted as playa lake deposits.

The basin center appears to have been located at Indian Springs. The section at East Garden Park represents the westernmost portion of the playa.

5) Depositional History: The Wet Mountain uplift area

in the western part of the Canon City area was tectonically active during the deposition of the Ralston Creek Formation. The first episode of tectonic activity resulted in the deposition of alluvial fan sediments that reached as far east as Indian Springs.

A relatively long period of geomorphic stability followed. During this time, a perennial saline lake developed. It is estimated that the lake was in existence for approximately 5,000 years. The perennial saline lake eventually dried up and became ephemeral. An episode of playa lake formation followed which resulted in the deposition of a thin dolomite bed at the basin center at Indian Springs.

A second episode of tectonic activity resulted in the deposition of a relatively thick sequence of alluvial fan sediments.

As fan activity diminished, a second episode of playa lake formation occurred at Indian Springs and an inland playa environment developed that covered the area from East Garden Park to Soda Ridge. The inland playa depositional facies represents the final stage of development of the Ralston Creek Formation.

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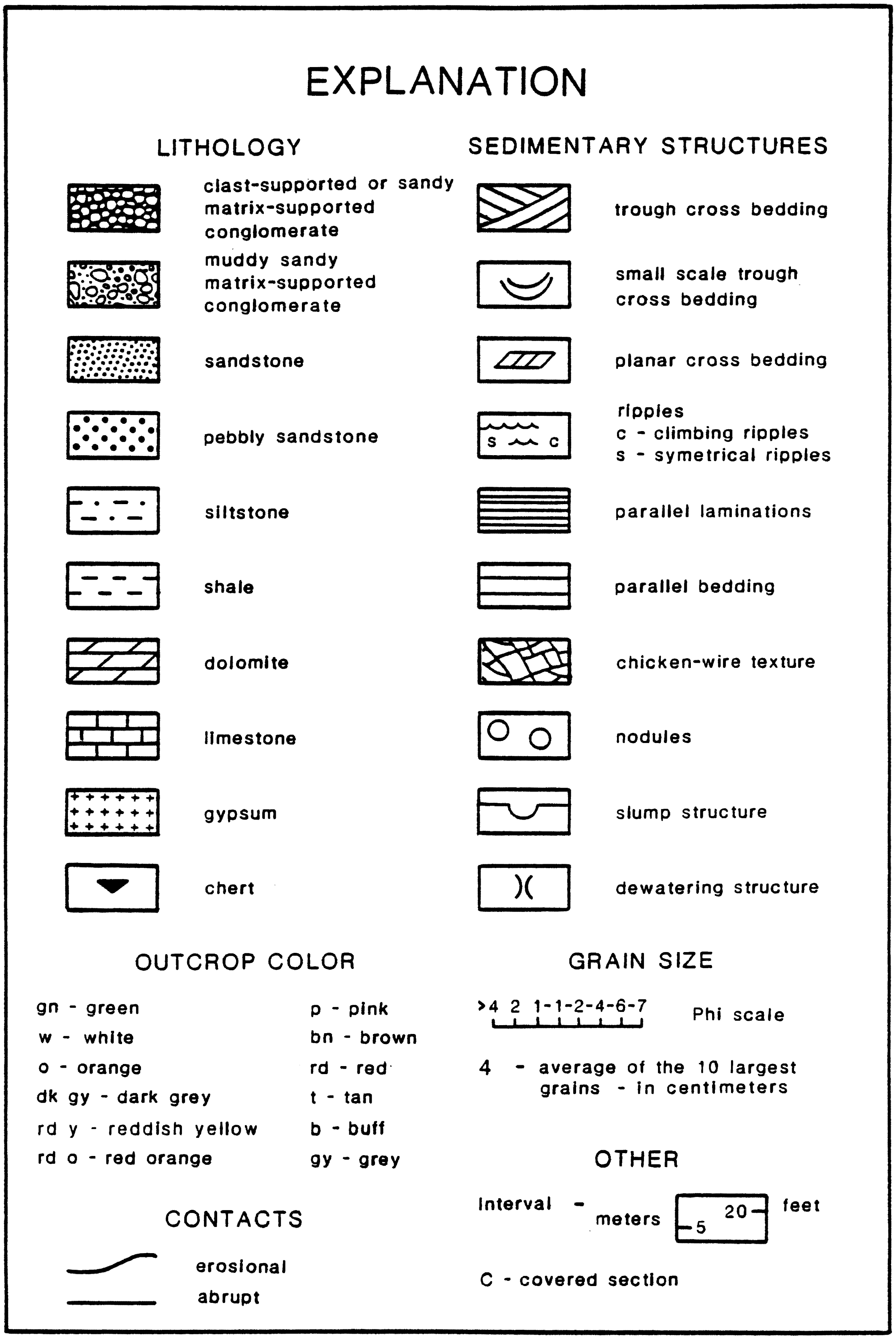
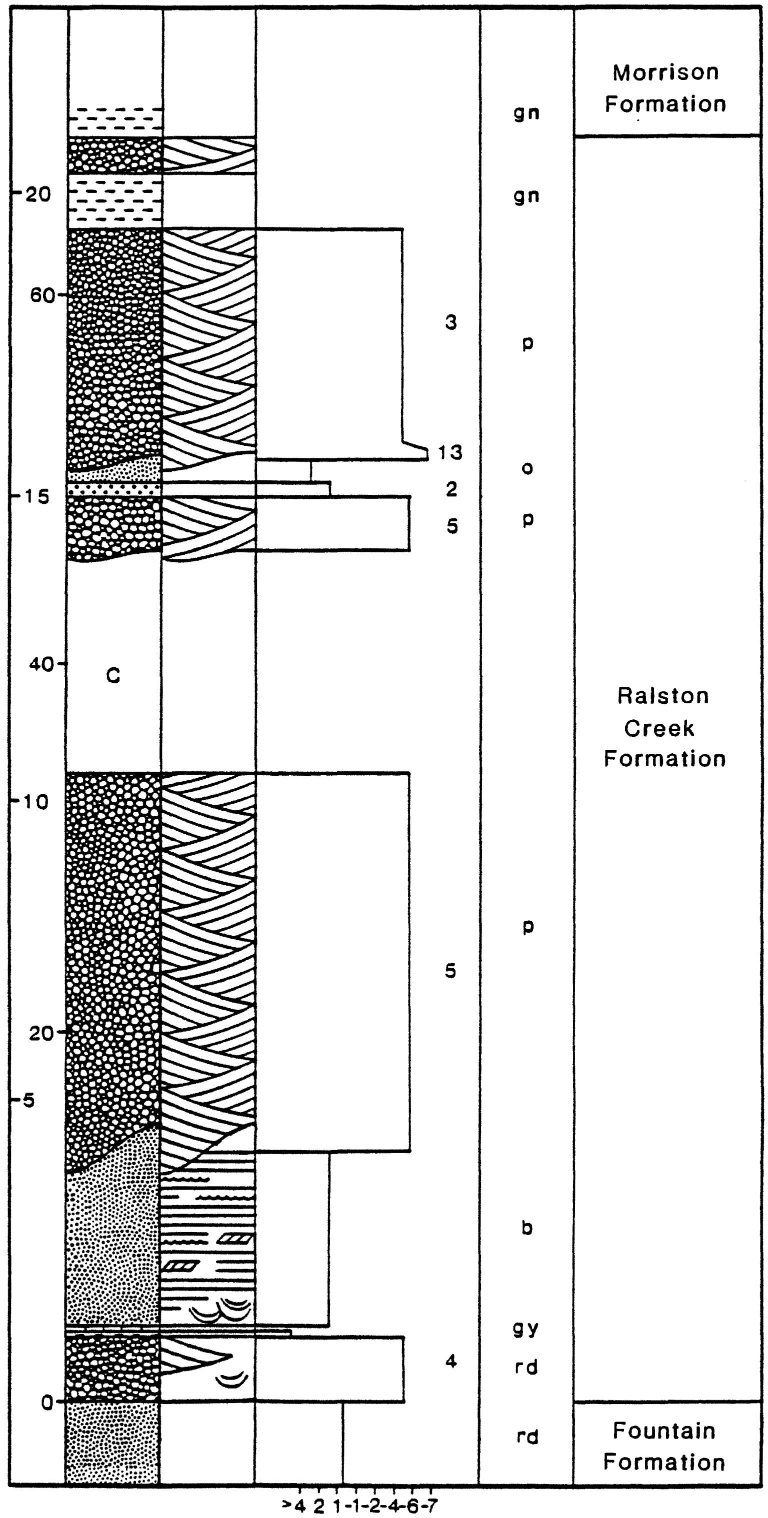
APPENDIX

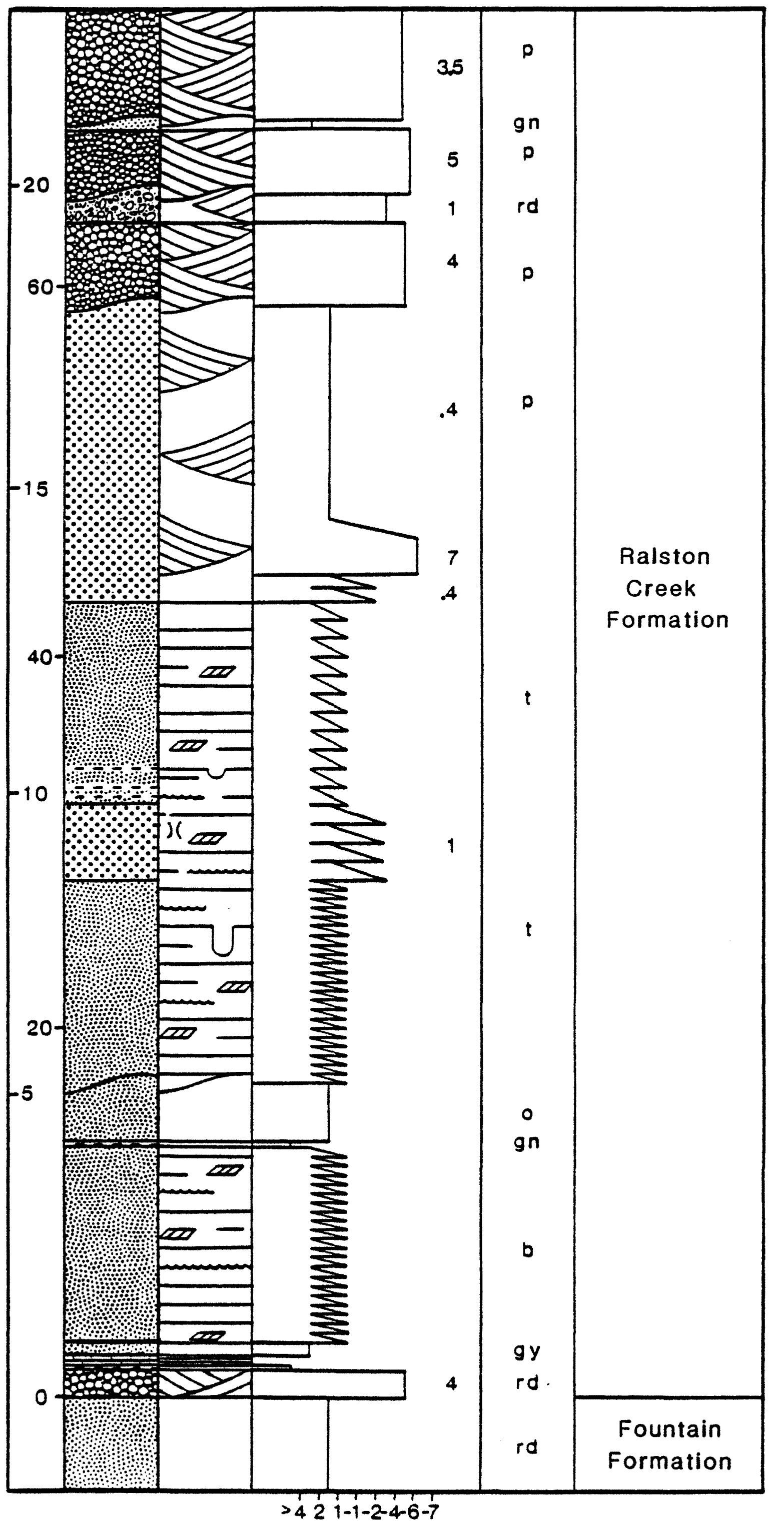
SEDIMENTARY LOGS OF THE RALSTON CREEK FORMATION AS MEASURED IN THE VICINITY OF CANON CITY, COLORADO


EXPLANATION
LITHOLOGY
clast-supported or sandy matrix-supported conglomerate
muddy sandy matrix-supported conglomerate
sandstone
pebbly sandstone
siltstone
shale
dolomite
limestone
gypsum
chert
SEDIMENTARY STRUCTURES
trough cross bedding
small scale trough cross bedding
planar cross bedding
ripples
c - climbing ripples
s - symetrical ripples
parallel laminations
parallel bedding
chicken-wire texture
nodules
slump structure
dewatering structure
OUTCROP COLOR
gn - green
w - white
o - orange
dk gy - dark grey
rd y - reddish yellow
rd o - red orange
p - pink
bn - brown
rd - red
t - tan
b - buff
gy - grey
GRAIN SIZE
>4 2 1-1-2-4-6-7
Phi scale
4 - average of the 10 largest grains - in centimeters
OTHER
Interval - meters 5 20 feet
C - covered section
CONTACTS
erosional
abrupt

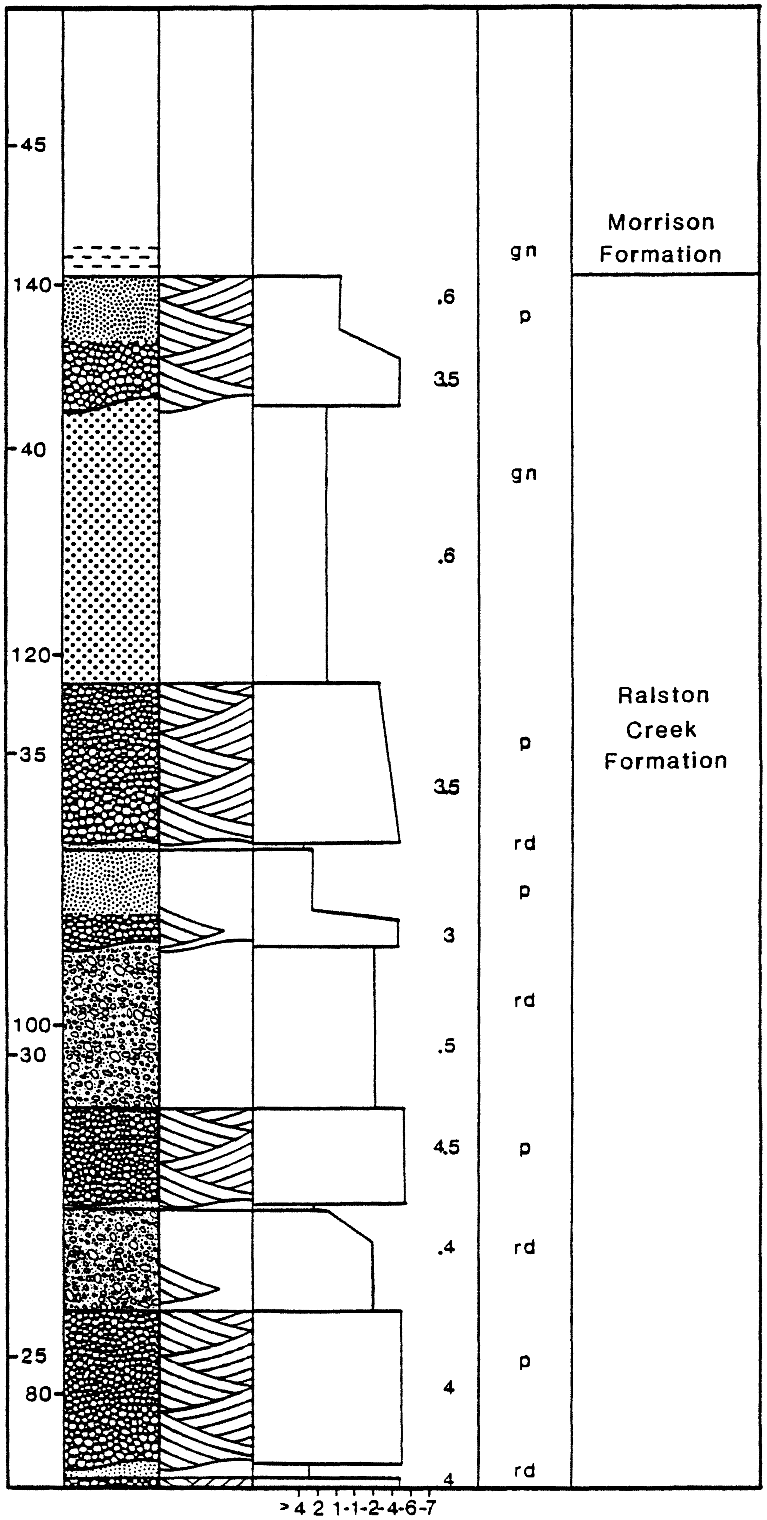
GRAPE CREEK


Morrison Formation
gn
gn
20
60
3
p
13
o
15
2
5
p
40
C
Ralston Creek Formation
10
p
5
20
5
b
gy
4
rd
0
rd
Fountain Formation
>4 2 1 -1 -2 -4 -6 -7

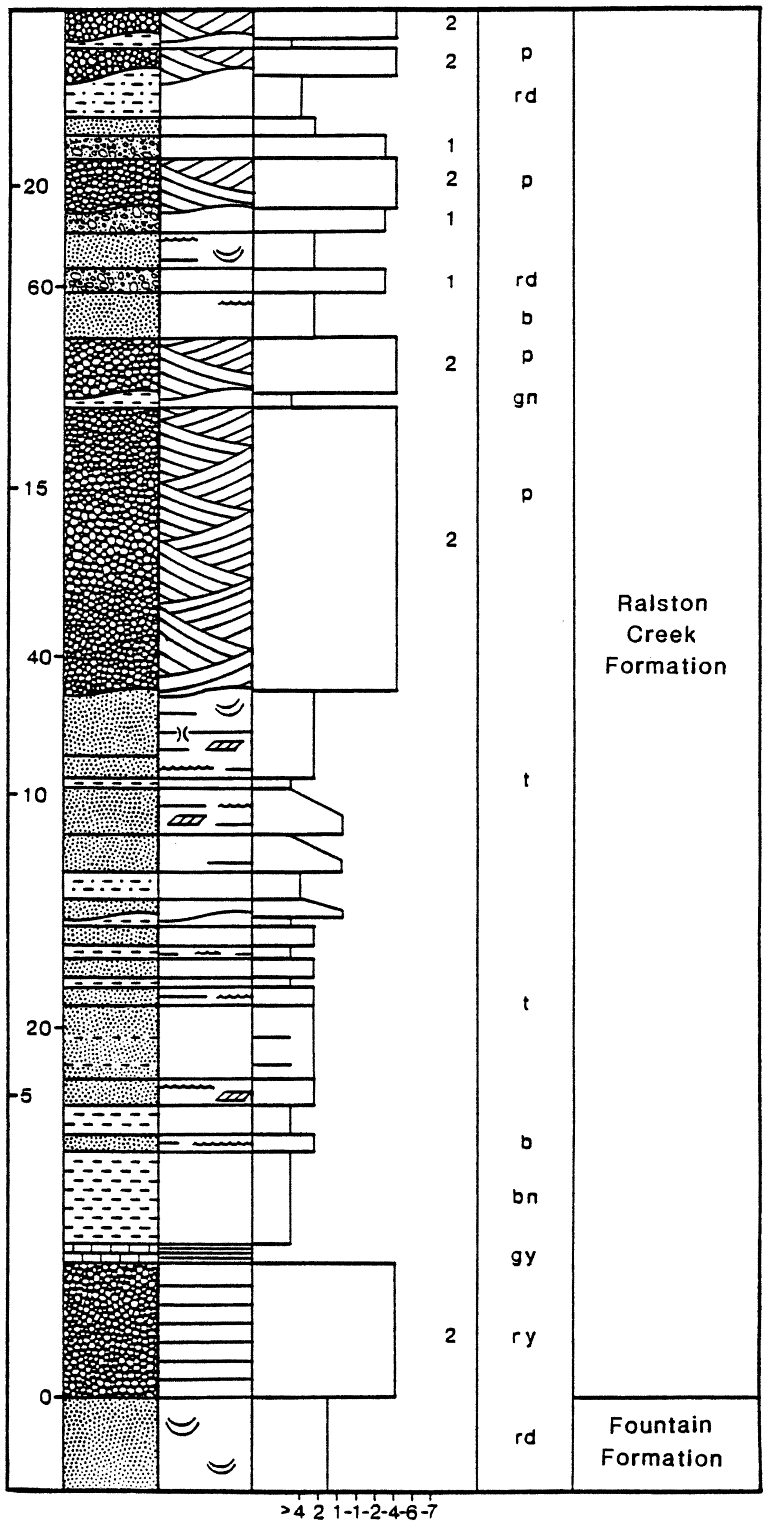
SKYLINE DRIVE



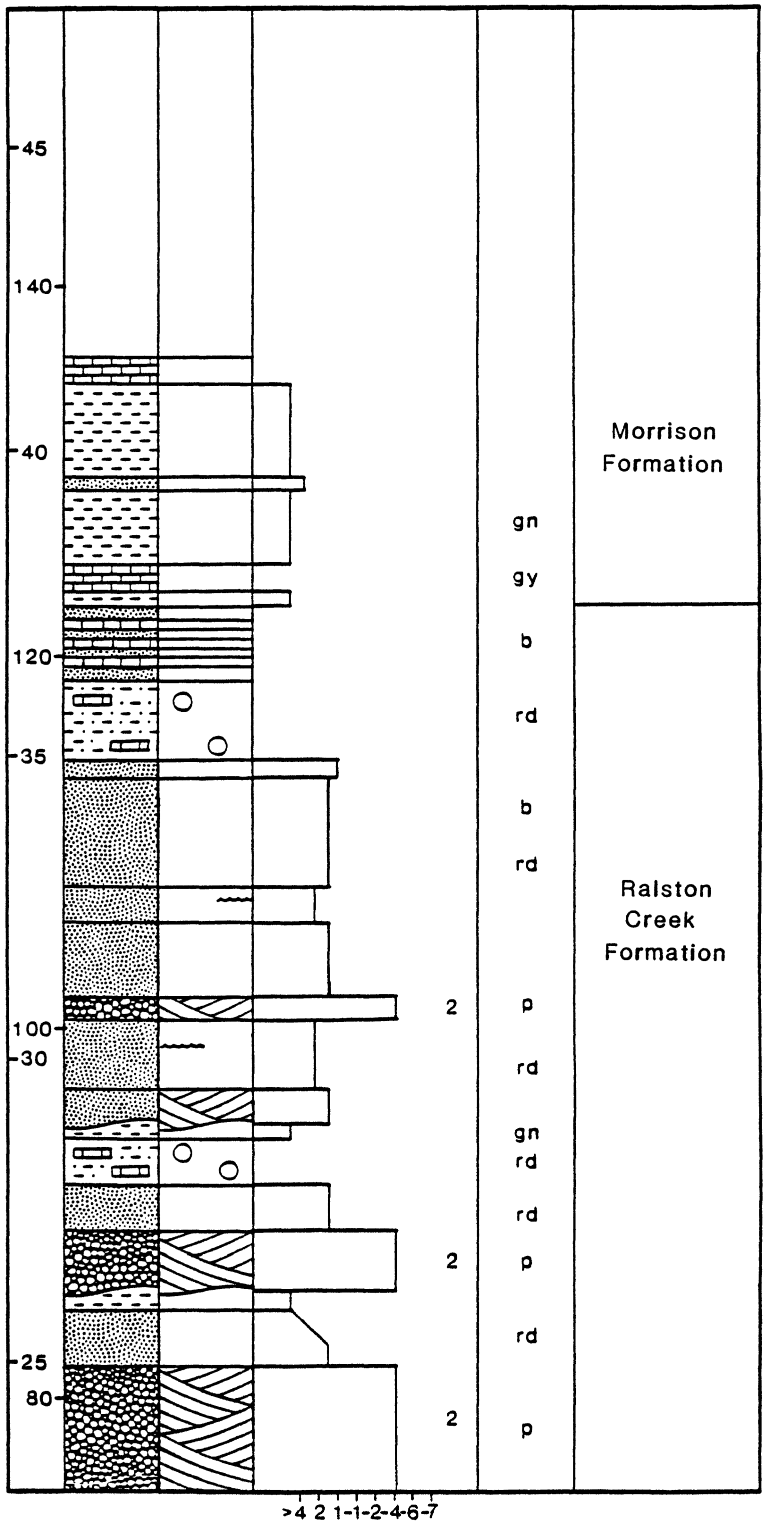
SKYLINE DRIVE



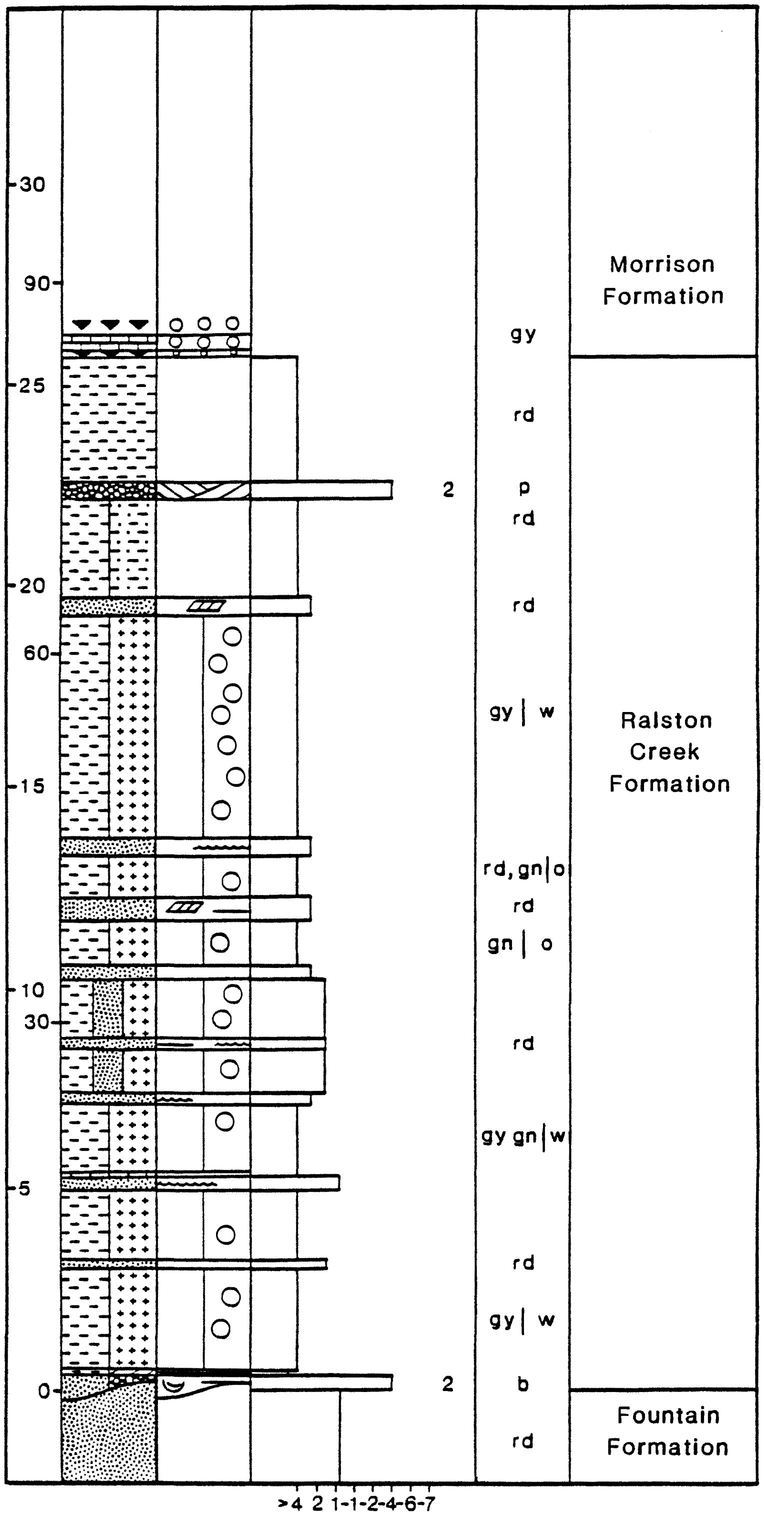
WEST GARDEN PARK



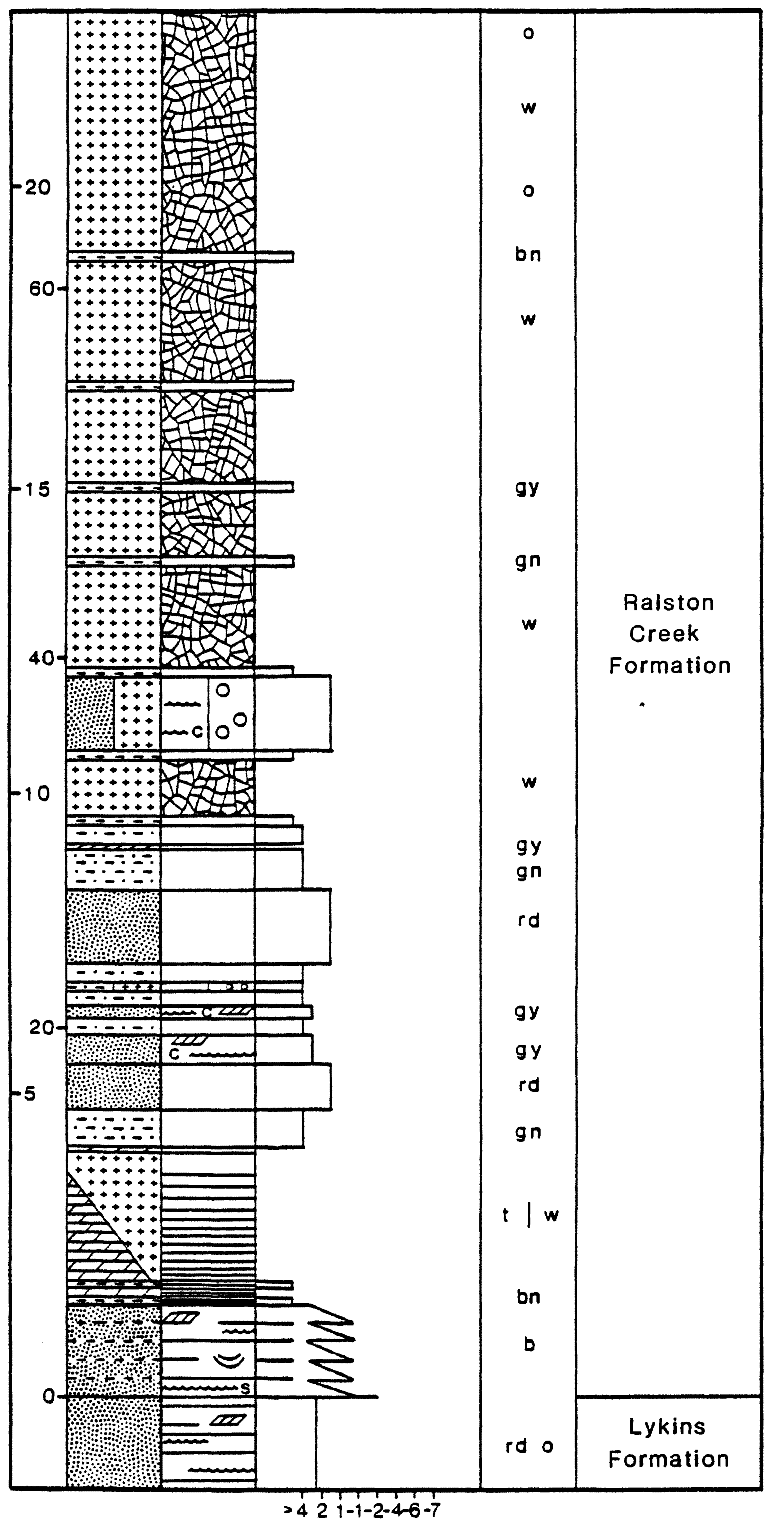
WEST GARDEN PARK



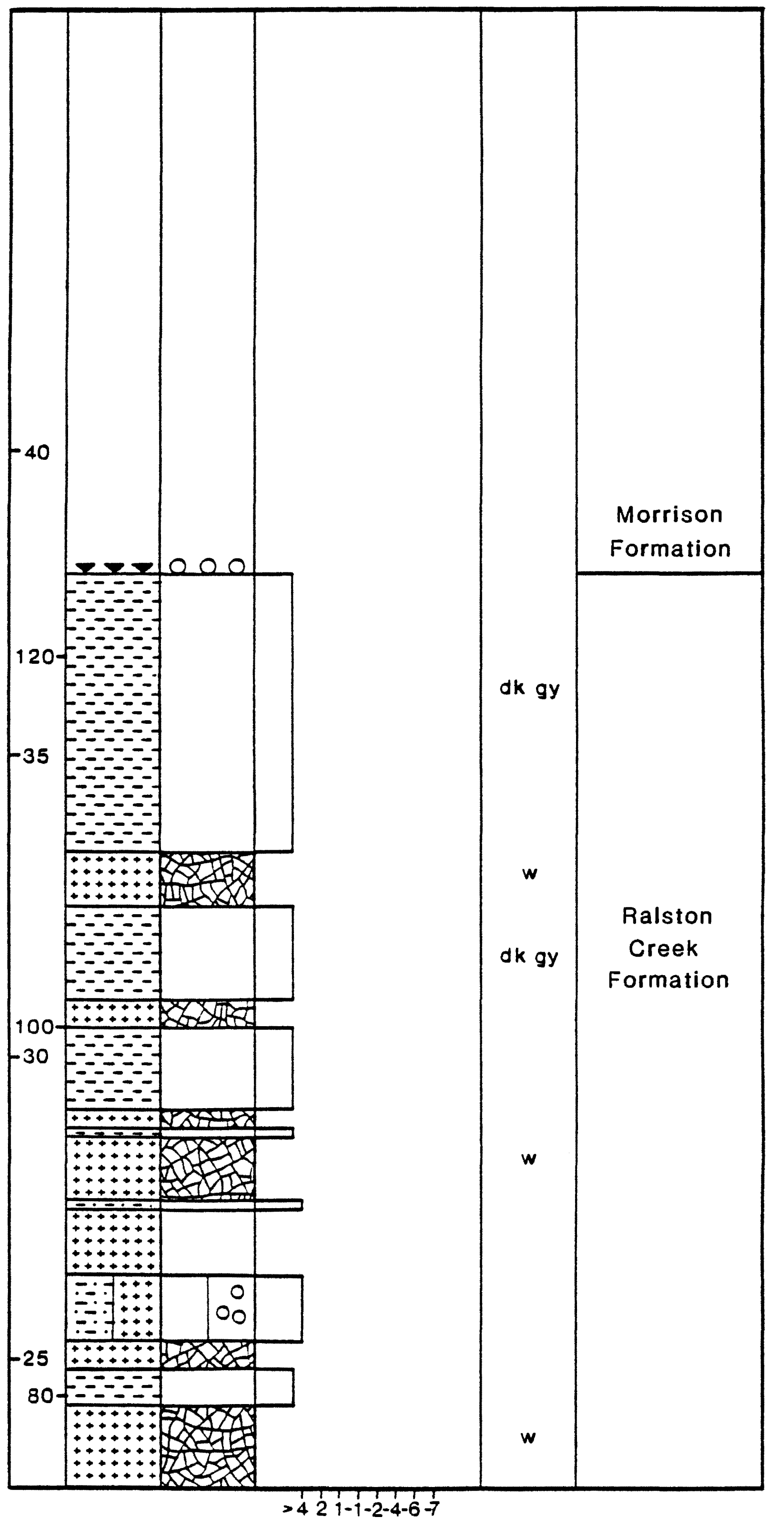
EAST GARDEN PARK



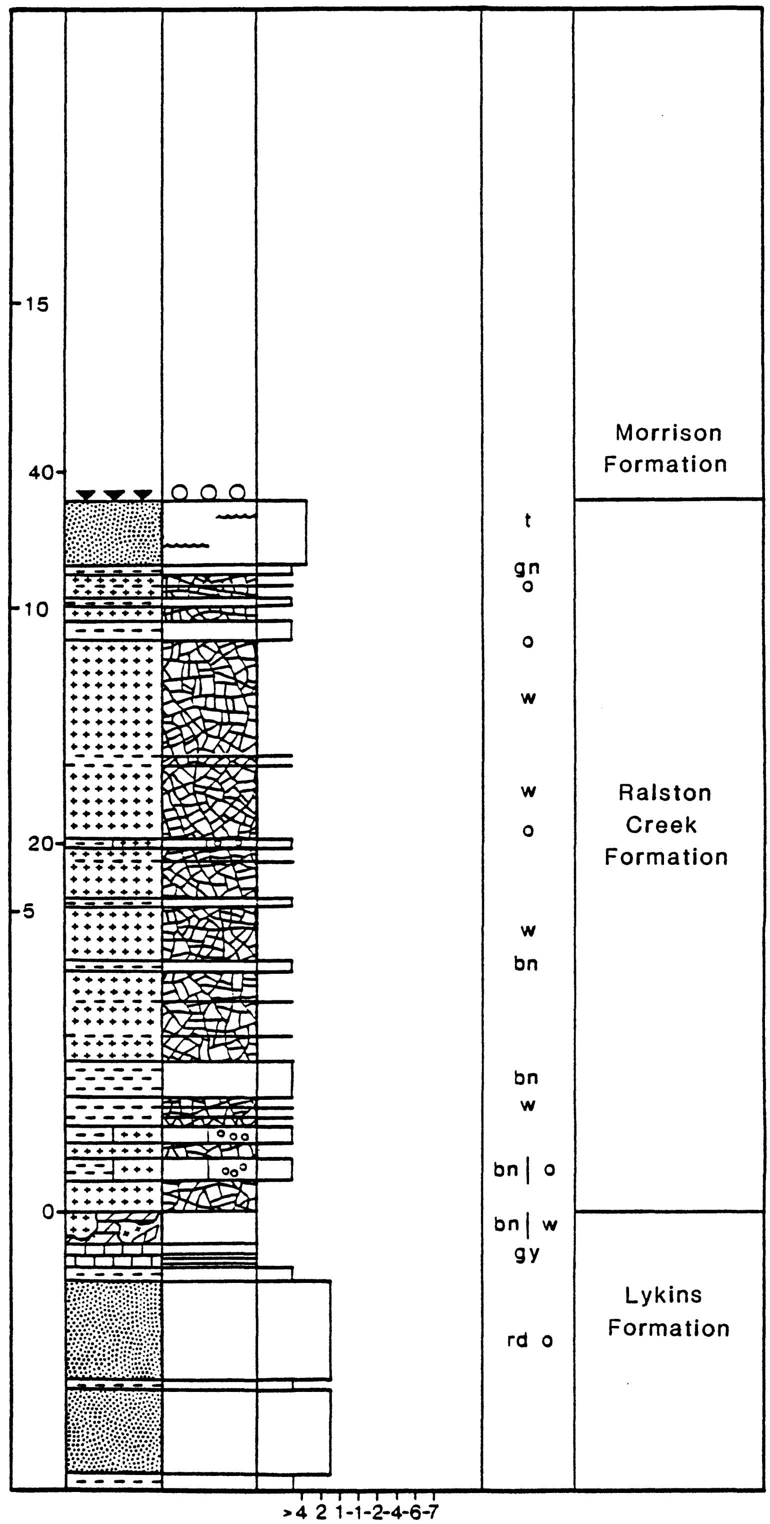
INDIAN SPRINGS



INDIAN SPRINGS



SODA RIDGE


15
40
10
20
5
0
t
gn
o
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bn
bn
w
bn | o
bn | w
gy
rd o
Morrison Formation
Ralston Creek Formation
Lykins Formation
>4 2 1 -1 -2 -4 -6 -7

VITA

Jennifer Lynn Richardson

Candidate for the Degree of

Master of Science

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