A SEDIMENTARY ANALYSIS OF THE UPPER JURASSIC MORRISON FORMATION AS IT IS EXPOSED IN THE VICINITY OF CANON CITY, COLORADO

By

REBECCA GAIL SWEET

Bachelor of Science in Arts and Sciences

Oklahoma State University

Stillwater, Oklahoma

1981

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 1984

A SEDIMENTARY ANALYSIS OF THE UPPER JURASSIC MORRISON FORMATION AS IT IS EXPOSED IN THE VICINITY OF CANON CITY, COLORADO

Thesis Approved:

Thesis Adviser

Dean of the Graduate College

PREFACE

The purpose of this thesis is to describe and evaluate the sedimentary geology of the Jurassic Morrison Formation as it is exposed in the vicinity of Canon City, Colorado. This thesis includes field descriptions of the outcrops combined with petrographic microscope, x-ray, and SEM analysis of samples collected.

I would like to express my sincerest appreciation to my thesis adviser, R. Nowell Donovan, for his unlimited assistance, suggestions and friendship. I would also like to give my thanks to my committee members, Dr. Arthur Hounslow and Dr. Gary Stewart for their assistance and advice.

Thanks goes to Kelly Cloyd and Weldon Beauchamp for their help in the field. Also to Janet Cairns and Mary Rafalowski for expeditiously cutting rocks and preparing thin sections. I would like to thank Hal White for the many hours spent printing pictures for the text. My appreciation goes to all of the faculty and graduate students, especially Debbie Ragland and Kathy Bridges, who gave me useful advice and support during the preparation of this thesis. A special recognition goes to Carole Lojek, whose drafting skills and companionship made the work go easier.

Finally, I would like to express my deepest gratitude

to my parents, Kenneth and Gail Sweet, who gave me their unqualified support and assistance throughout my graduate work. I dedicate this thesis to them.

TABLE OF CONTENTS

Chapter Page

Chapter Page

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

CHAPTER I

INTRODUCTION

Statement of Purpose

This thesis describes the sedimentary geology of the Jurassic Morrison Formation as it is exposed in the vicinity of Canon City, Colorado. Emphasis is on 1) definition and analysis of the depositional environments, and 2) petrologic studies of the provenance, diagenesis, and paragenesis of the various lithologies within the formation.

Early work in the area defined some of the environments and identified aspects of the fauna. However, complete descriptions and measured sections of specific examples of various facies such as those related to stream channels, lake beds and deltas, have not been included in previous investigations. Therefore, this thesis endeavors to expand understanding of the fluvio-lacustrine environment.

Location of Study

The work was conducted in the Canon City Embayment. The embayment is a structural re-entrant in the eastern front of the Rocky Mountains (Frederickson et al., 1956). It is located on the southern end of the Front Range and east of the Wet Mountains (Figure 1). The _en echelon_

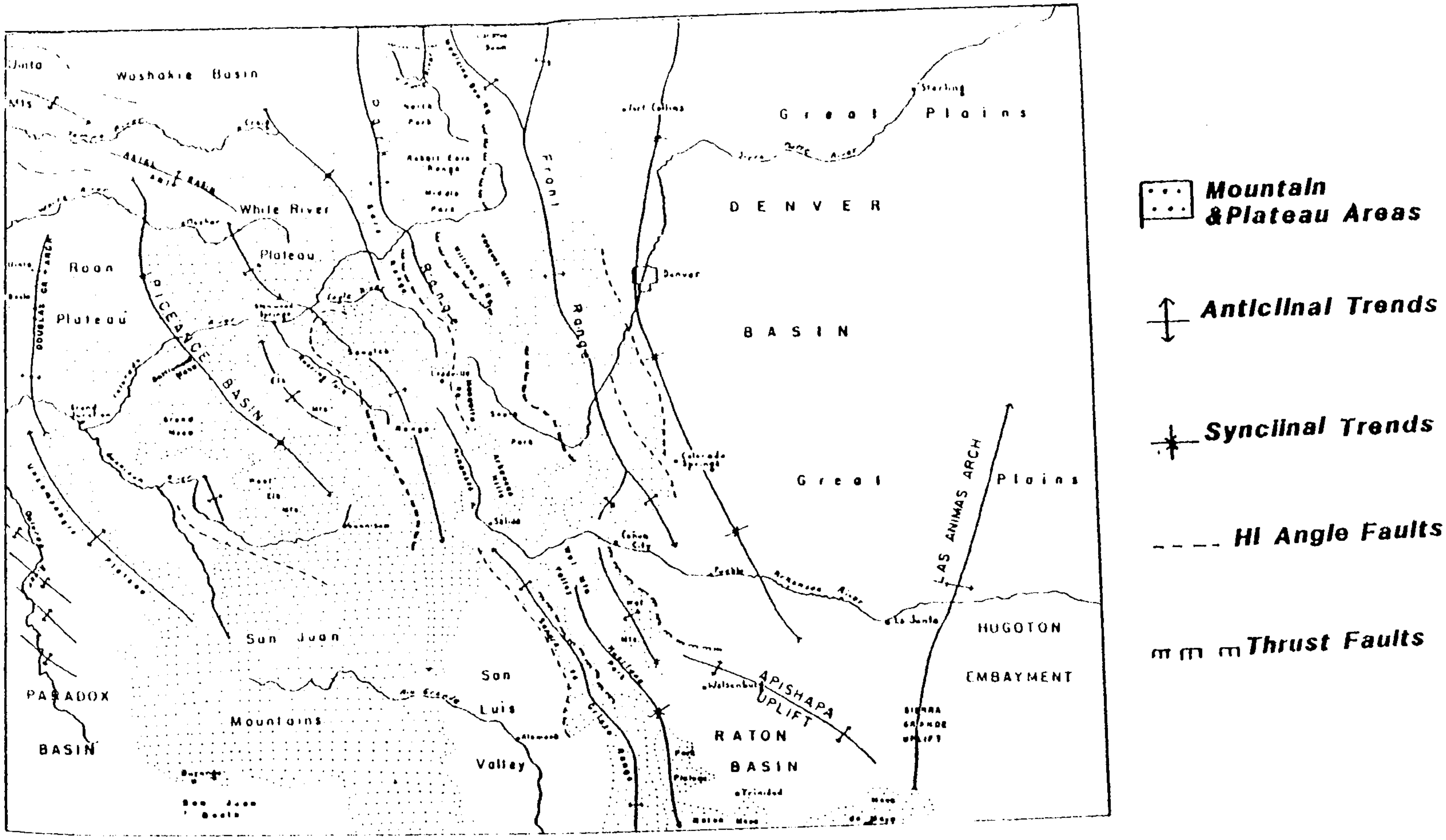


Figure 1. Major Physiographic and Structural Features of Colorado (after Curtis, 1958).

arrangement of the Wet Mountains and the Front Range form the embayment. A suite of sedimentary rocks ranging in age from Ordovician to Pliocene lies uncomformably on Precambrian basement in the area. The Morrison sediments are exposed in the embayment; sections measured are located in T17, 18S, R69, 70W (Figure 2). The study area lies approximately 85 miles south of the type section of the Morrison Formation, which is located near the town of Morrison, Colorado.

Procedure

The field work for this thesis was conducted during May and June of 1983 in the Canon City area. Six major and several auxilary sections were measured. Total footage in the sections ranged from 5 to 320 feet (Figure 3). Samples of most of the carbonates and sandstones were collected and representative samples of mudstones were chosen for their positioning and color gradations. Overall, more than 200 rocks were sampled.

Paleocurrent readings were taken on channel sandstones in the field for later environmental considerations.

Lab work included the slabbing and photographing of selected samples. Shale colors were classified according to the Rock Color Chart (Goddard et al., 1963). Nearly 150 thin sections were analyzed, and they yielded information concerning detrital composition, texture, maturity, cementation and paragenesis. Slides were stained with

Location Map Of Sections Measured In The Vicinity Of Canon City, Colorado

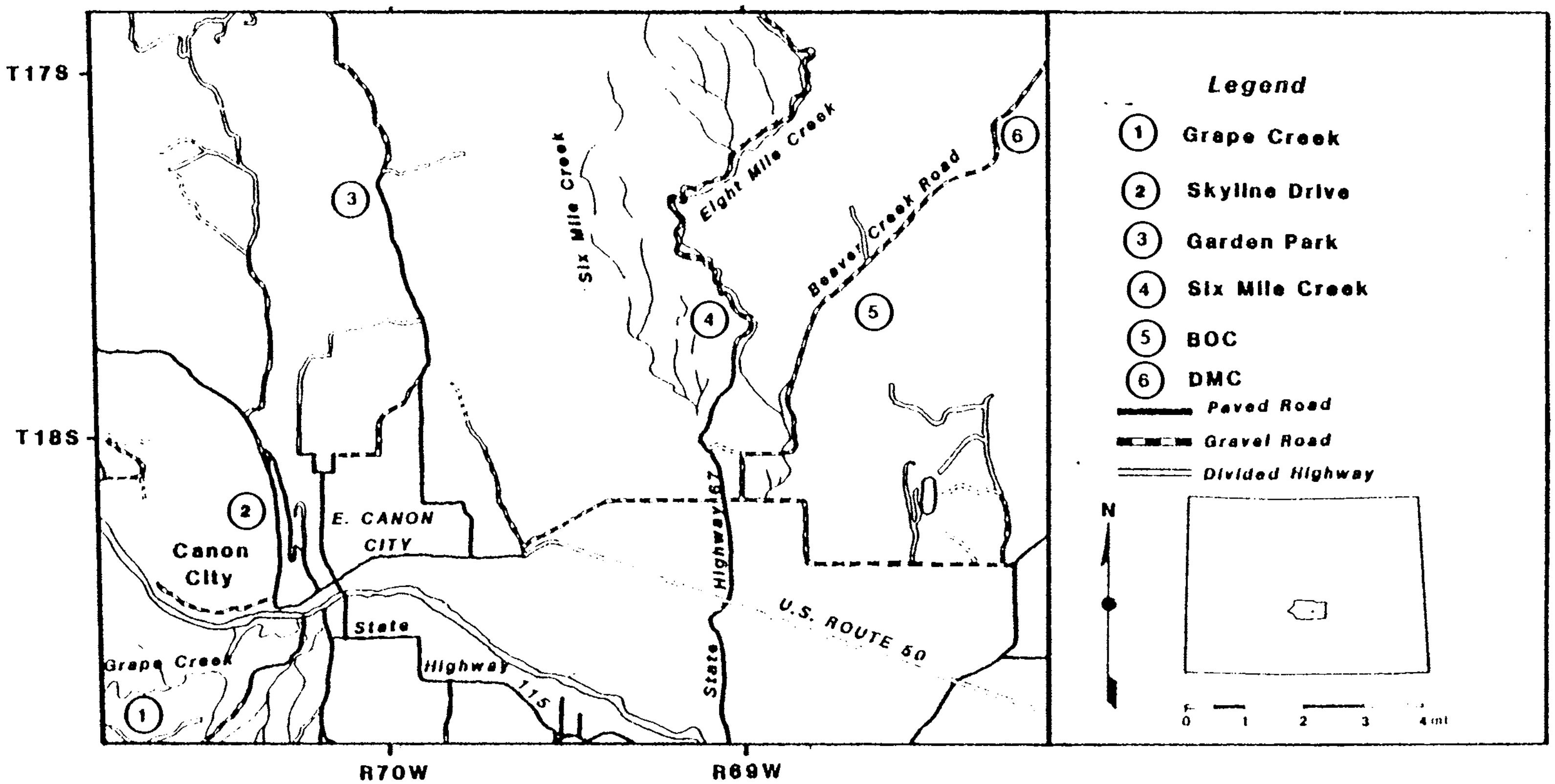


Figure 2. Location Map of Sections Measured in the Vicinity of Canon City, Colorado (after Fremont County General Highway Map, 1953)

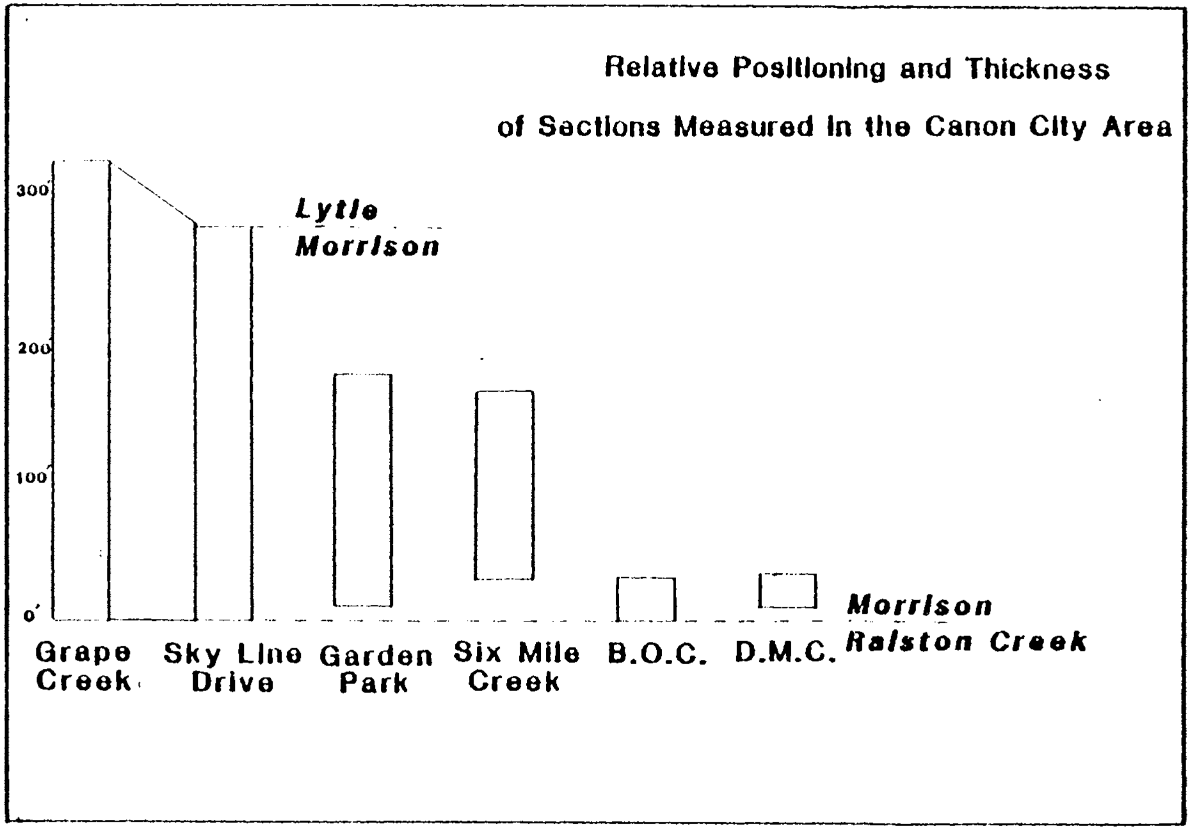


Figure 3. Relative Positioning and Thicknesses of Sections Measured in the Vicinity of Canon City.

alizarin red and potassium ferricyanide in order to differentiate ferroan calcite, nonferroan calcite and dolomite. Ninety samples were used in x-ray diffraction. X-ray parameters were set for each lithology and clay extractions of 25 sandstones and shales were done. Scanning Electron Microscopy coupled with an Energy Dispersive X-ray Analyzer were used on selected limestones and sandstones to identify cements and delineate authigenic and detrital clays.

CHAPTER II

REVIEW OF OVERALL GEOLOGIC SETTING

Stratigraphic Relationships

The upper Jurassic Morrison Formation is an extensive, relatively thin blanket of continental sediments. The Morrison outcrops from south Canada to central New Mexico and Arizona and from central Utah and southeastern Idaho to Oklahoma and Kansas (Figure 4). After much debate the Morrison was accepted as Kimmerigdian-Portlandian in age (Figure 5). The formation is underlain by Oxfordian units including the Sundance Formation in Wyoming, the Ralston Creek Formation in Colorado, the Swift Formation in Montana, and the Curtis-Summerville Formation in Utah (Figure 6). The overlying Cretaceous units are the Cloverly Group of Wyoming and southern Montana, the Kootenai Formation of northern Montana, the Lytle-Purgatoire Formation of Colorado, and the Burro Canyon Formation of Utah (Figure 7).

Three possible sources of Morrison sediments have been postulated: 1) a western source in Idaho and Nevada; 2) a southwestern source in central and southwestern Arizona; and 3) a northeastern source from the transcontinental arch in Colorado (Dodson, 1980). The Morrison continental sediments, which are the final phase of the Jurassic, are

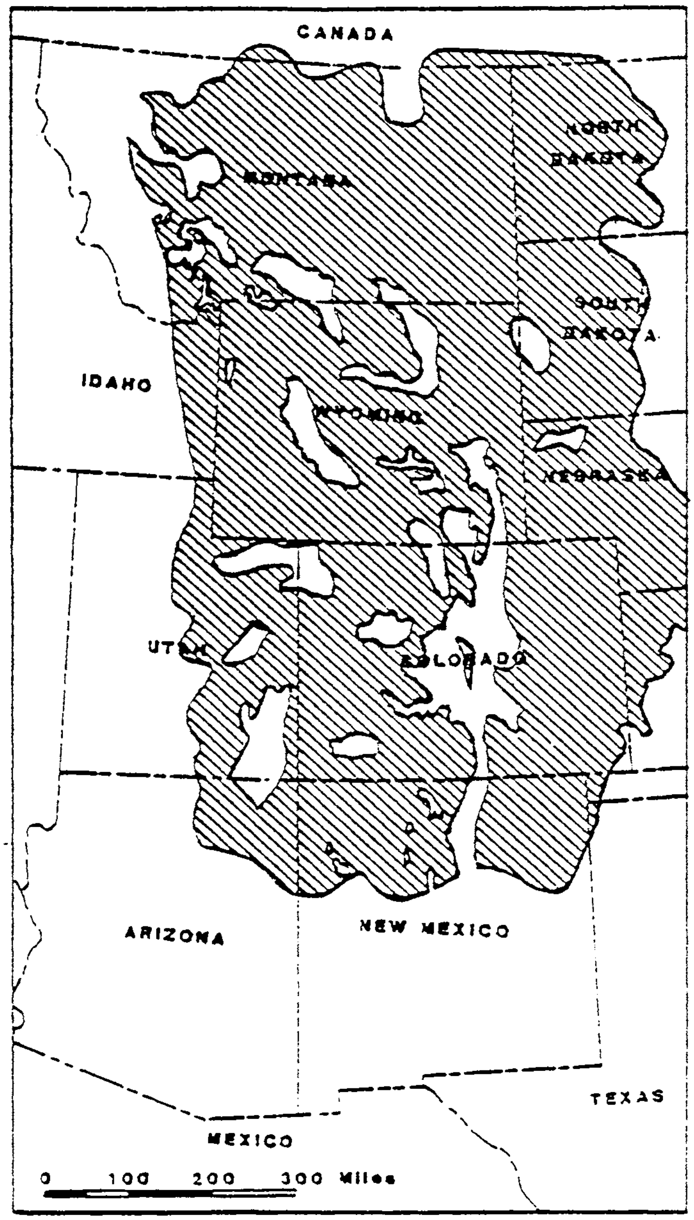


Figure 4. Map Showing the Extent of Morrison Rocks (after Peterson, 1972)

EPOCH	PERIOD	EUROPEAN STAGES	STRATIGRAPHIC UNIT
CRETACEOUS	LOWER CRETACEOUS	*Aptian*	*Lytle Sandstone*
		Neocomian	
JURASSIC	UPPER JURASSIC	*Portlandian*	*Morrison Formation*
		Kimeridgian	
		Oxfordian	*Ralston Creek Formation*
		Callovian	

Figure 5. Generalized Stratigraphic Section for Upper Jurassic and Lower Cretaceous Rocks.

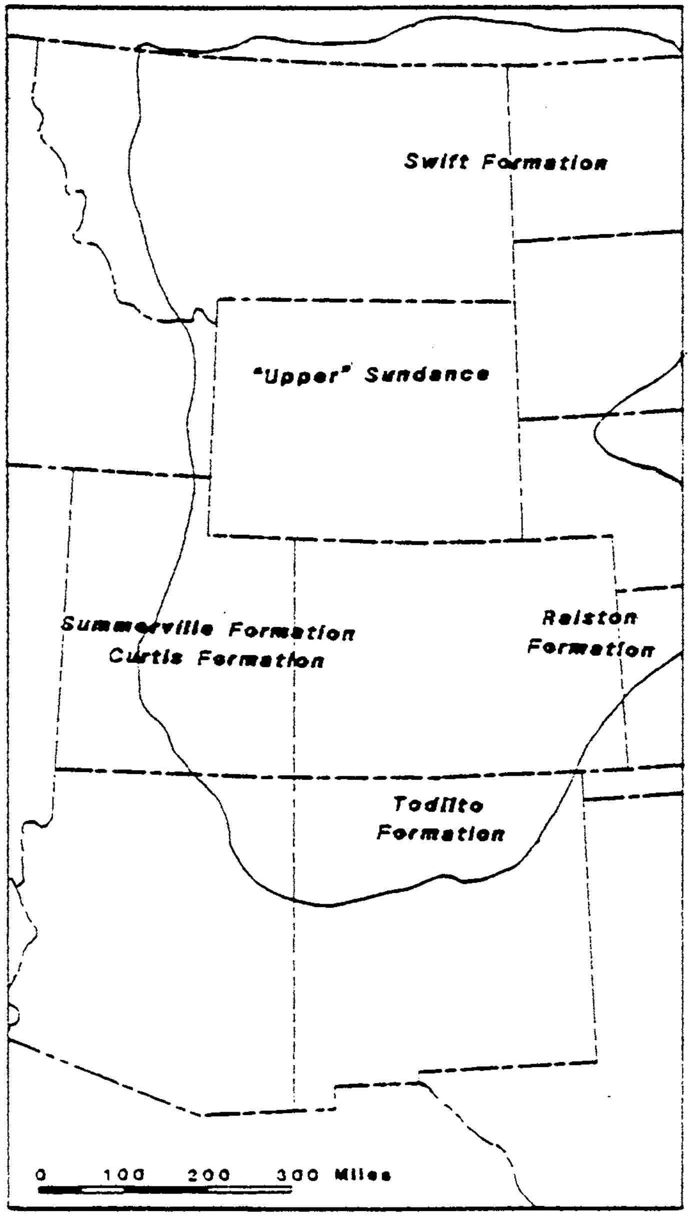


Figure 6. Nomenclature Map of Oxfordian Rocks (after Peterson, 1972)

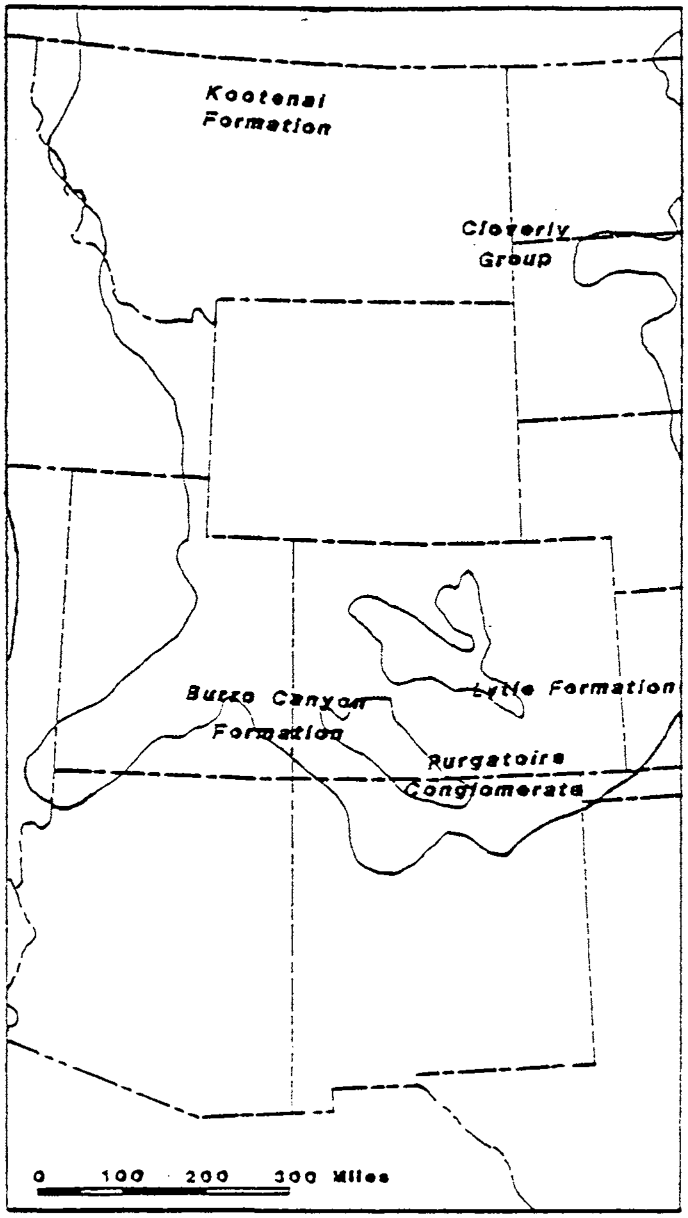


Figure 7. Nomenclature Map of Neocomian and Aptian Rocks (after McGookey, 1972)

underlain by sediments which record four episodes of Jurassic marine transgressions (Hallam, 1975).

Environmental Synopsis

In the most recent environmental interpretation, Dodson (1980) described the Morrison as a fluvio-lacustrine sequence developed on a broad flood plain, with a principle sediment source from the Ancestral Rocky Mountains. This environment was strongly affected by severe climatic changes. Moberly (1960) suggested a monsoon-like climate which had an overall high annual rainfall, but which was also characterized by dry seasons and droughts. Brady (1969) proposed that there had been an overall upward change from dry to humid conditions (his evidence was a change in clay mineralogy near the middle of the formation).

Development of Geological Thought Concerning the Morrison Formation

The sediments now known as the Morrison Formation were formally defined by Eldridge in 1896. Eldridge designated outcrops near the town of Morrison, Colorado as the type section. It was Cross (1894), however, who first published the name "Morrison," using it in a description of the Pike's Peak Quadrangle. Prior to this time the nomenclature of the Morrison had been confused. Terms used included: "Jurassic Beds" (Peak, 1877), "Dakota Beds" (Cope, 1877a, b), "Beulah Beds" (Jenny, 1899), "Atlantosaurus Beds" (Marsh, 1896), "Como Beds" (Scott, 1897), "Gunnison Formation" (Eldridge, 1894), "McElmo Formation" (Cross, 1894), and "Flaming Gorge Formation" (Powell, 1876; Mook, 1912; and Brady, 1957). Difficulties with boundaries plagued Eldridge's type section. In order to remove confusion, Waldschmidt and LeRoy (1944) recommended that the type section be resited in a road cut along the north side of the West Alameda Parkway, near Morrison, Colorado. This section has distinct upper and lower stratigraphic boundaries and is located near the original type section.

Through the years many authors have studied the area surrounding Canon City, including Simpson (1926), Baker and others (1936), Peck (1937), Stovall (1938), Stokes (1944), Craig and others (1955), Tank (1956), Moberly (1960), Mirsky (1962), Keller (1962), Wahlstrom (1966), and Derr (1974). However, the most detailed study of the Morrison has been in the type area and on the Colorado Plateau.

Synopsis of Previous Work in the Vicinity of Canon City

The Dinosaur Bonanza

Dinosaur remains first drew attention to the Morrison of Canon City area. In 1876, Professor O. C. Marsh opened the first dinosaur quarry 150 feet above the Ralston Creek Formation in the Garden Park area (Hatcher, 1901). Shortly afterwards, E. D. Cope started another quarry about 250 feet above Marsh's. Cope's quarry is located three quarters of a mile from the Garden Park entrance in the vicinity of a prominent hill named the "Nipple." Unlike Marsh, all of Cope's investigations were carried out in the upper horizons of the Morrison (Hatcher, 1901). Owing to labor costs, the quarries were closed in 1884, but they were later reopened in 1900 by J. B. Hatcher. Collectively these workers were responsible for the erection of several new dinosaur genera, including _Haplocanthosaurus_, _Camarasaurus_, _Apatosaurus_, _Diplodocus_, _Allosaurus_, and _Stegosaurus_ (Cope, 1877a, 1878; Marsh, 1877, 1878a, 1878b; Hatcher, 1901, 1903a, 1903b).

Local Stratigraphic and Sedimentologic Studies

The Canon City area was first mapped and described by Cross (1894). Mook (1916) conducted the first stratigraphic and sedimentological study of the Morrison. In it he measured 319 feet of section in the Garden Park area. In an unpublished master's thesis, Schulze (1954) also measured a section in Garden Park and described the Morrison of the northern half of the Canon City Embayment. Brady (1967, 1968) described the stratigraphy, petrology and depositional environment of the Morrison in the western half of the Canon City area. Cherts, which locally occur at the base of the section, have long been of interest. Ogden (1954) suggested that these beds be used as time-stratigraphic markers. King and Merrian (1969) hypothesized that the presence of chalcedony is related to devitrification of vitric tuffs.

CHAPTER III

LITHO-STRATIGRAPHY

Characteristics of Exposures

Within the Canon City area there are three types of exposure. Firstly, the Formation can be seen on the steeper scarps of prominent hogbacks, as in the exposures at Skyline Drive and the BOC sections. The eroded shaly Morrison is capped by the more resistant Dakota Group sandstones, which form the dip slopes of the hogbacks. The Morrison is also exposed along the sides of stream gullies, as in the section at Six Mile Creek. Thirdly, Canon City outcrops may occur in combinations of hogback and stream gully exposures. Such combinations are seen in in the Garden Park, DMC and Grape Creek sections.

Stratigraphic Relationships

To the west and northwest of Canon City, the Morrison Formation is nonconformable on the Precambrian Pike's Peak Granite and the Idaho Springs metamorphic complex. In this area conglomerates at the base of the formation contain pebbles of granite and metamorphic rock.

To the east, near the Canon City area, the Morrison lies with apparent conformity on the Jurassic Ralston Creek

Formation. In the most easterly part of the area studied, the Ralston Creek is bedded gypsum which lies beneath the welded cherts ("Beekite"), which are locally taken as the base of the Morrison. Further to the west, at Canon City itself, the Ralston Creek consists of interbedded arkoses and thin conglomerates containing fragments of granite and metamorphic rocks of Precambrian origin. The overlying Morrison in these areas is generally shaly with some interbedded shaly marls containing feldspar pebbles. The following factors usually differentiate the Morrison from the Ralson Creek: 1) the absence of gypsum in the Morrison; 2) the general increase of shale and concomitant decrease in the amount of arkosic fragments from the Ralston Creek; and 3) the presence of carbonates in the Morrison.

The Lower Cretaceous Lytle Sandstone, part of the Purgatoire Formation, overlies the Morrison. The disconformable contact between the two formations is generally denoted by conglomerate in the lower part of the Lytle. The ubiquitously crossbedded Lytle sandstones are generally coarser grained than those in the Morrison. Plant fossils, including tree stems, are found near the base of the Lytle. The Lytle sandstones usually form a topographic ledge above the more easily eroded Morrison. However, this ledge does not always coincide with the basal Lytle conglomerate, but may include some uppermost Morrison sandstones. In this study, the Morrison-Lytle boundary was always placed at the base of the incoming of conglomeration.

Thickness

The Morrison Formation exhibits a wide range of thicknesses. The greatest accumulation of sediments is in the Colorado Plateau area, where the Morrison is as thick as 900 feet (Brady, 1969). Along the Front Range in Colorado, the Formation ranges from 200 to 300 feet thick. The type section is 277 feet thick.

In the Canon City area, thicknesses of 350 feet have been recorded in Garden Park (Brady, 1967). However, this figure is suspect, for it is apparent that major Pleistocene landslides in the area may have increased the thickness. The most complete section measured in this study is found at Grape Creek, where 320 feet of section was measured (Figure 3). Faulting approximately parallel to strike has caused some authors to miss important parts of this section (Schultze, 1954; Brady, 1967). Similar faulting may have thinned other sections, such as Skyline Drive where only 290 feet of section is present. Due to Laramide tectonism, dips differ widely in the various sections measured.

Lithologies

Sandstones

Lenticular sandstones, with variable internal geometry and maximum individual thicknesses of up to 20 feet, are seen throughout the Formation, although they are particularly common in the upper portions. For example, at

Grape Creek, 21 percent of the total section consists of sandstones. However, only 2 percent of the lower 110 feet of section (which is dominated by green shale) consists of sandstones, whereas the upper 210 feet (dominated by red silts and shales) is 31 percent sandstones. A similar trend can be seen in the Skyline Drive section, where sandstone increases from 12 percent in the lower portion to 21 percent in the upper portion.

The upper and lower contacts of individual sand bodies generally are sharp, although there are some instances where they are shaly at the base or become shaly near the top. Many sand units have basal load structures and exhibit evidence of much dewatering. Some intraformational conglomerates occur. The conglomerates contain a variety of fragments, including cherts, granite, limestone, pelecypod shells and dinosaur bones.

Laterally, the sandstones pass into siltstones or shales. The thickest most laterally persistent sandstones are found at the top of the formation.

The color of the sandstones generally is related to their stratigraphic position. Thus, thin grey, green and occasionally buff sandstones are found in the lower part of the formation, whereas red, mottled red and green, purple, buff and white sandstones are found in the upper portion.

Carbonates

Fine grained, micritic limestones and dolomite-rich micrites are present in all sections measured. All carbonates examined contain at least a small percentage of siliciclastic grains, chiefly quartz.

Thicknesses of the carbonate units range from six inches to four feet. Many limestones are laminated or thinly bedded. Contacts are sharp and some upper surfaces show subaerial mudcracks. The units generally show birdseye (fenestral) textures; some are associated with dewatering and slump structures.

There are two limestones, informally referred to as the "white" and "black" limestones, which can be traced throughout the study area. The "white" limestone, which is up to four feet thick, contains vari-colored cherts in some locations. Gastropods are the principle body fossils. The "black" limestone is one foot thick and is best developed in the western and northern portions of the area. It is a laminated rock, which is kerogen-rich and has a distinctive bituminous smell from freshly fractured surfaces. It contains numerous fragments of fossil fish, principally fins and scales. This important horizon has gone unnoticed in previous studies (Shultze, 1954; Brady, 1967), perhaps due to the aforementioned strike-parallel faults and also because it is generally talus-covered.

Carbonates other than the above mentioned, are thinly bedded and less persistent laterally. They are located in various shales and are more abundant in the lower parts of the formation. At Grape Creek, however, there is a 1.5 foot thick, orange weathering, dolomitic limestone with conspicuous horizons of the green alga Chara.

In the eastern portion of this study area, close to the base of the Morrison, are some very thin limestones which alternate with thin bedded cherts. Overlying these beds are some dolomites with large pseudomorphs after evaporites, that alternate with limestones and shales.

Claystones and Shales

Variously-colored claystones and shales are the dominant lithology of the formation. Black, grey, green, red and purple are the five major colors of shale present. Some variegated beds are also recorded; altogether it is the various hues of shales which make the Morrison such a colorful formation at outcrop. Generally, black, grey and green are predominant in the lower portion, with red and purple found more commonly in the upper part.

The clays and shales contain varying amounts of silt and sand, principally in the form of distinct laminae. Many of the claystones are calcareous, especially although not entirely in the lower portion of the formation, as recognized by Brady (1967) and Mirsky (1962).

Calcareous shales grade into impure sandy limestones with increasing lime content. Beds of intermediate .pa composition (40 percent or greater CO_3) are conveniently classified as marlstones.

CHAPTER IV

SANDSTONES IN THE MORRISON FORMATION

Field Characteristics and Geometry

Sandstones are common in the Morrison in the vicinity of Canon City. They vary in thickness up to 20 feet, but are generally thickest at the top of the formation. Individual units are lenticular and grade laterally into siltstones and shales. Maximum width of sandstone bodies does not exceed 400 yards. Average width:thickness ratio seen in this study was 15:1. Channel morphologies are profuse.

Units commonly show scoured and eroded bases which may be modified by load structures (Figure 8). The base of many channeled units is marked by a conglomerate. Compositions of these conglomerates varies widely. Chert, granite and feldspathic fragments are common near the base of the formation, whereas limestone clasts are abundant in the middle. Near the top of the Formation the conglomerates are polymictic.

Primary Sedimentary Structures

Some of the sandstones appear to be massive. However, it is suspected that bedding characteristics may be masked

Figure 8. Channel Sandstone from Garden Park Exhibiting Load Structures with An Intraformational Conglomerate Developed at its Base

due to a heavy iron oxide weathering crust. This coating is a particular problem in the Skyline Drive area. Elsewhere, a full suite of primary bedding features is developed.

The most common structures seen are those associated with weak flow regime conditions. Parallel lamination, arising from changes in grain size between laminae, is developed in very fine grained sandstones and siltstones. Slightly coarser beds are characterized by small scale trough and planar cross bedding. This cross bedding can be related to ripple marked surfaces in some cases. Straight-crested (Figure 9) and linguoid ripple marks are developed on the exposed surfaces of some units. Both current and wind generated varieties of straight-crested ripple marks are present. The former grade into linguoid types whereas the latter are characterized by bifurcation points. Climbing ripple cross stratification and associated rib and furrow structures are common (Figure 10).

Medium scale trough cross bedding, with set thicknesses of up to 12 inches, is restricted to the thicker and coarser parts of channel sandstones. Current directions are unimodal with a large standard deviation.

Large scale cross bedding of the epsilon variety (Allen, 1965a) has been observed. An excellent example of these cross beds has been studied in detail at Garden Park (Figure 11). Here the epsilon cross beds show a dip direction at right angles to current directions indicated by associated medium scale trough cross bedding.

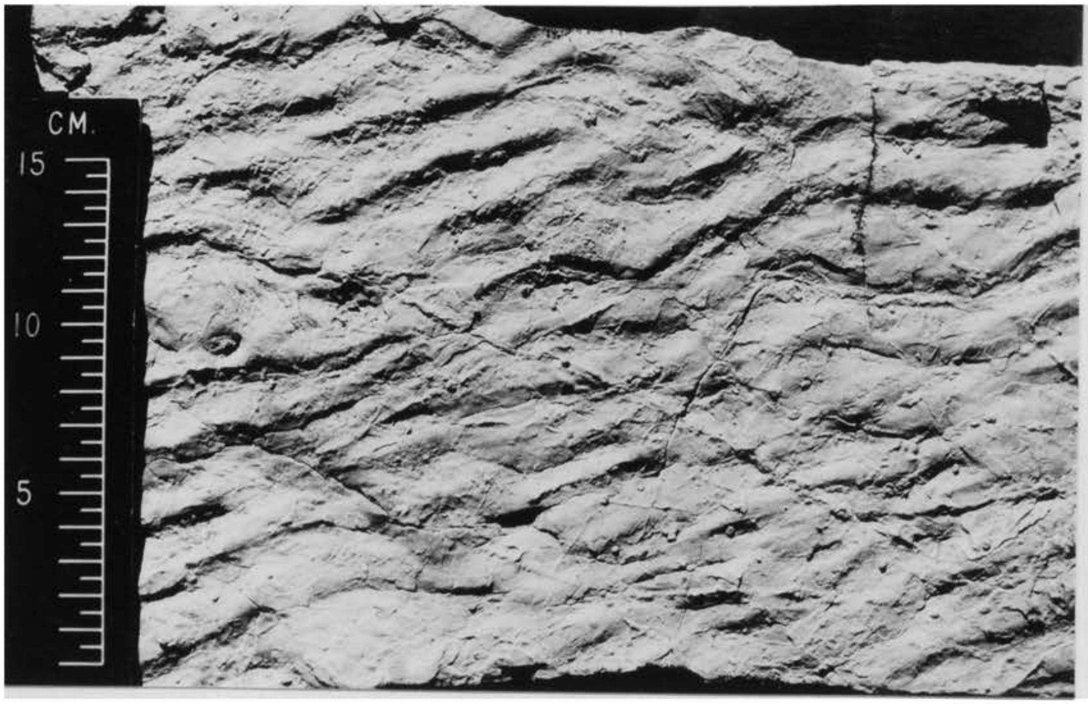


Figure 9. Straight-Crested Asymmetric Ripple Marks, Probably of Current Origin from Garden Park (Note: Crawling and Feeding Traces on the Surface)

Figure 10. Top Surface View of Ripple Cross Stratification Illustrating Development of Rib and Furrow

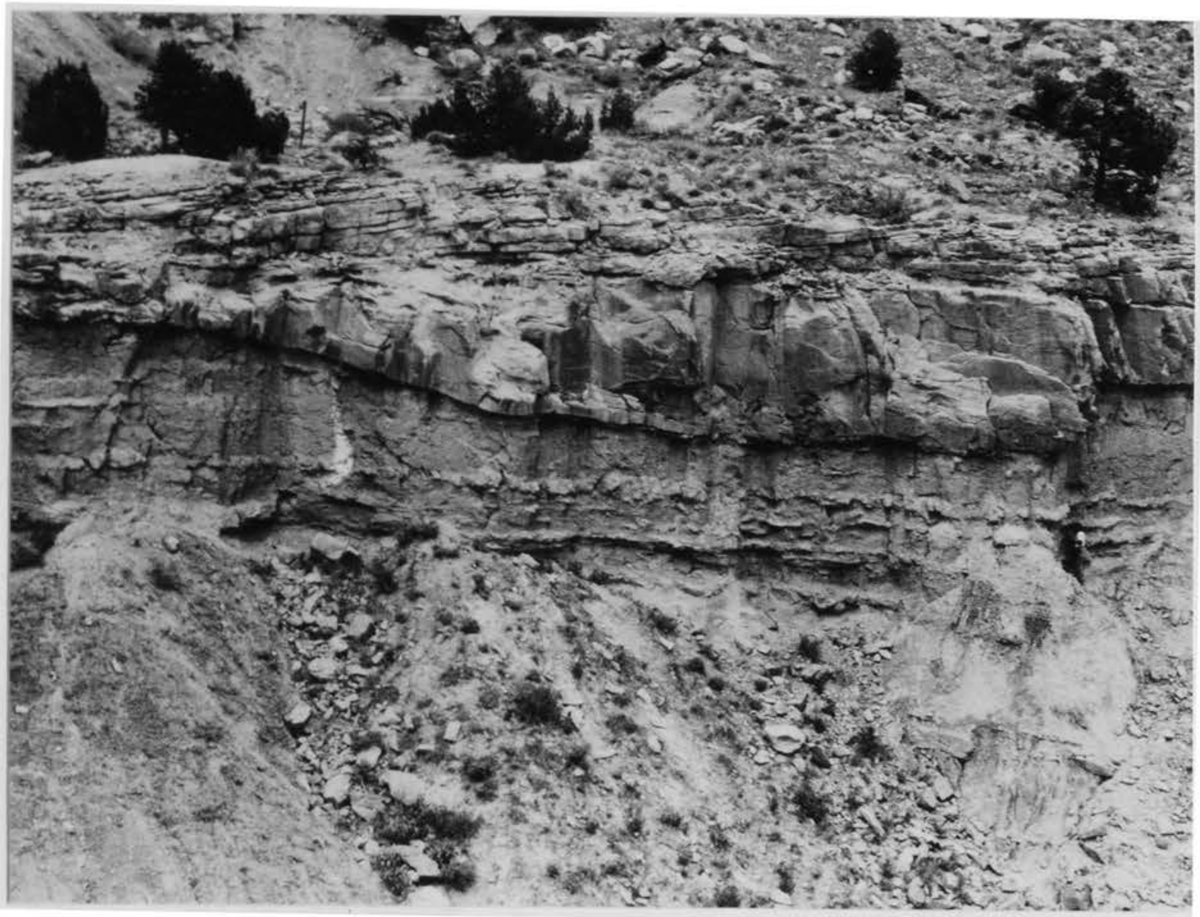


Figure 11. Point Bar with Large Scale Epsilon Crossbedding (Dipping to the Left) Developed Near the Top. Prominent Channel is Incised into Green Mudstones Interbedded with their Carbonates. Point Bar is Located at Garden Park 140 ft. Above the Base of the Section

Trace Fossils

Evidence of biogenic activity is seen on many of the ripple covered sandstone surfaces. Crawling traces are the most obvious (Figure 9). Browsing traces made by organisms feeding on the sediment surface are also present (Figure 9). Few vertical burrows have been observed. Little is known about freshwater trace fossils and no attempt has been made to classify those observed in this study (Donovan, personal communication).

Penecontemporaneous Sedimentary Structures

Soft sediment deformation structures of varying types and magnitudes (from 1 inch to 2.5 feet in diameter) are common. Dewatering structures (buttock folds) are perhaps the most common structure, although convolute bedding has affected many cross bedded sequences and presumably records sand wave drag or collapse. As noted, the bases of many sandstone units are characterized by load structures where the sand has foundered into underlying mudstone.

Sandstone Petrography

Method of Study

Nearly 150 thin sections were examined for textural and mineralogical parameters; percentage estimates were made on their constituents. These values were plotted on a ternary diagram with quartz, rock fragments and feldspars at the apices (Figure 12). This diagram was modeled on Folk's classification (1974). Thin sections were stained to determine carbonate species. Clays were determined by standard x-ray diffraction and SEM techniques.

Fabrics of Sandstones

Grain size varies from silt to coarse sand, with very fine to fine sand being predominant. Most of the grains are subrounded to subangular (Powers, 1953). Sphericity is medium to low (Powers, 1953). Sorting is generally poor; overall the rocks are texturally submature. Two grain size populations usually arise within one sandstone. The fine to medium grains are more well rounded and spherical than the angular and less spherical silt-size grains.

Mineralogy of the Sandstones

The average percentage of composition of detrital constituents in all the outcrops studied is shown in Figure 13. Averages for each major measured section are given in Figures 14, 15 and 16.

Quartz. Quartz is the major detrital constituent (Figure 17), composing 91 percent of all samples examined (maximum 97%, minimum 83%). Microcrystalline quartz is predominant, although some polycrystalline quartz is present. Quartz grains exhibit both parallel and undulose extinction.

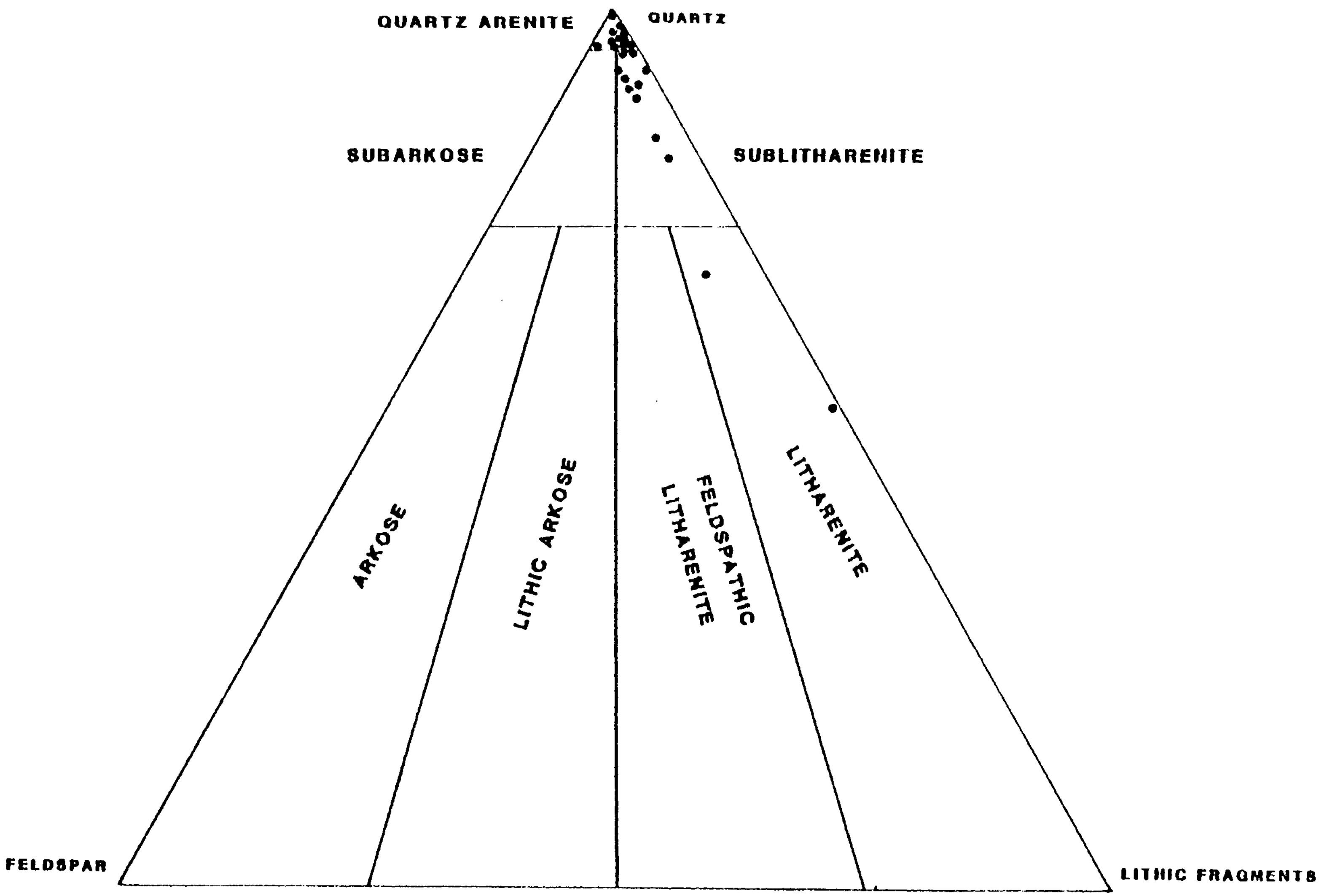


Figure 12. Ternary Diagram of Morrison Sandstones Taken from the Canon City Area (Classification Follows Folk, 1974)

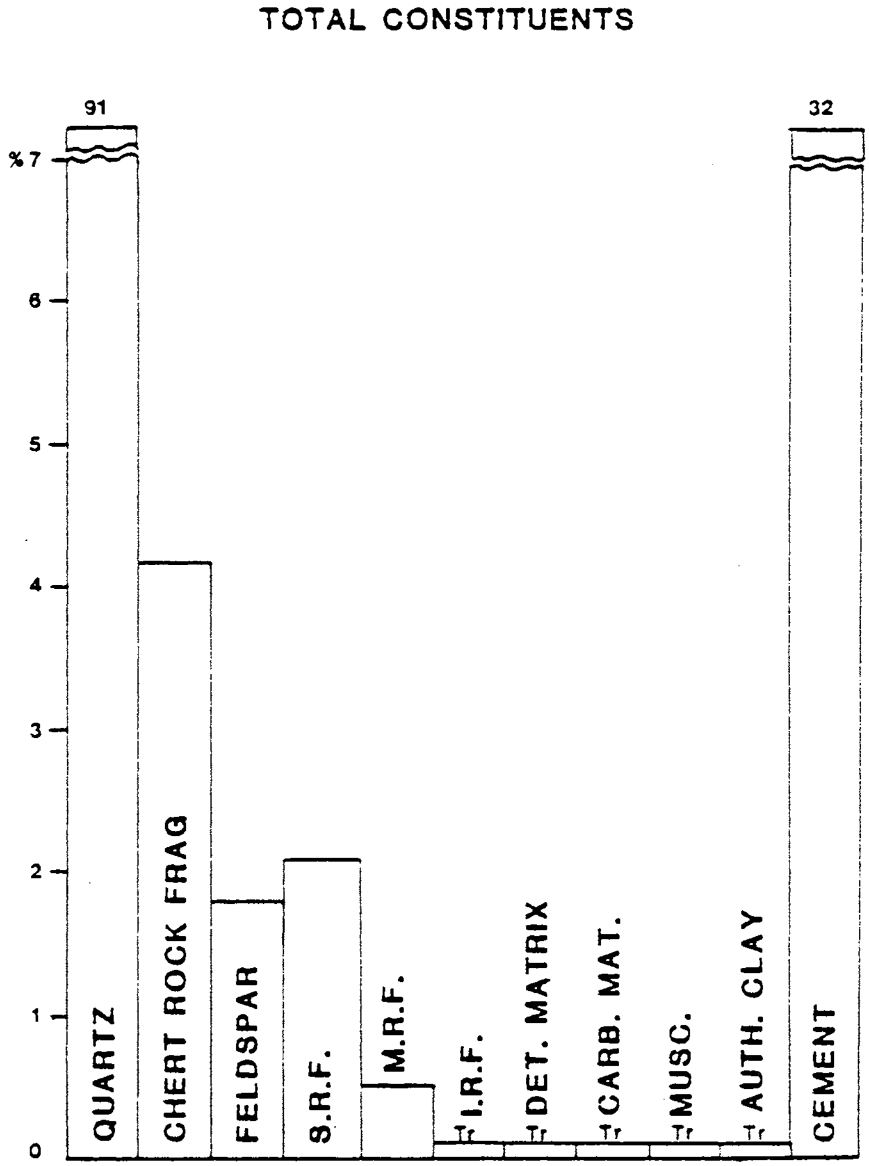


Figure 13. Average Percentage of Total Constituents in Morrison Sandstones Sampled in the Area Abbreviated as Follows: Sedimentary Rock Fragment (SRF); Metamorphic Rock Fragment (MRF), Igneous Rock Fragment (IRF), Detrital Matrix (Det. Matrix), Carbonacous Material (Carb. Mat.), Miscellaneous (Misc.), Authigenic Clay (Auth. Clay)

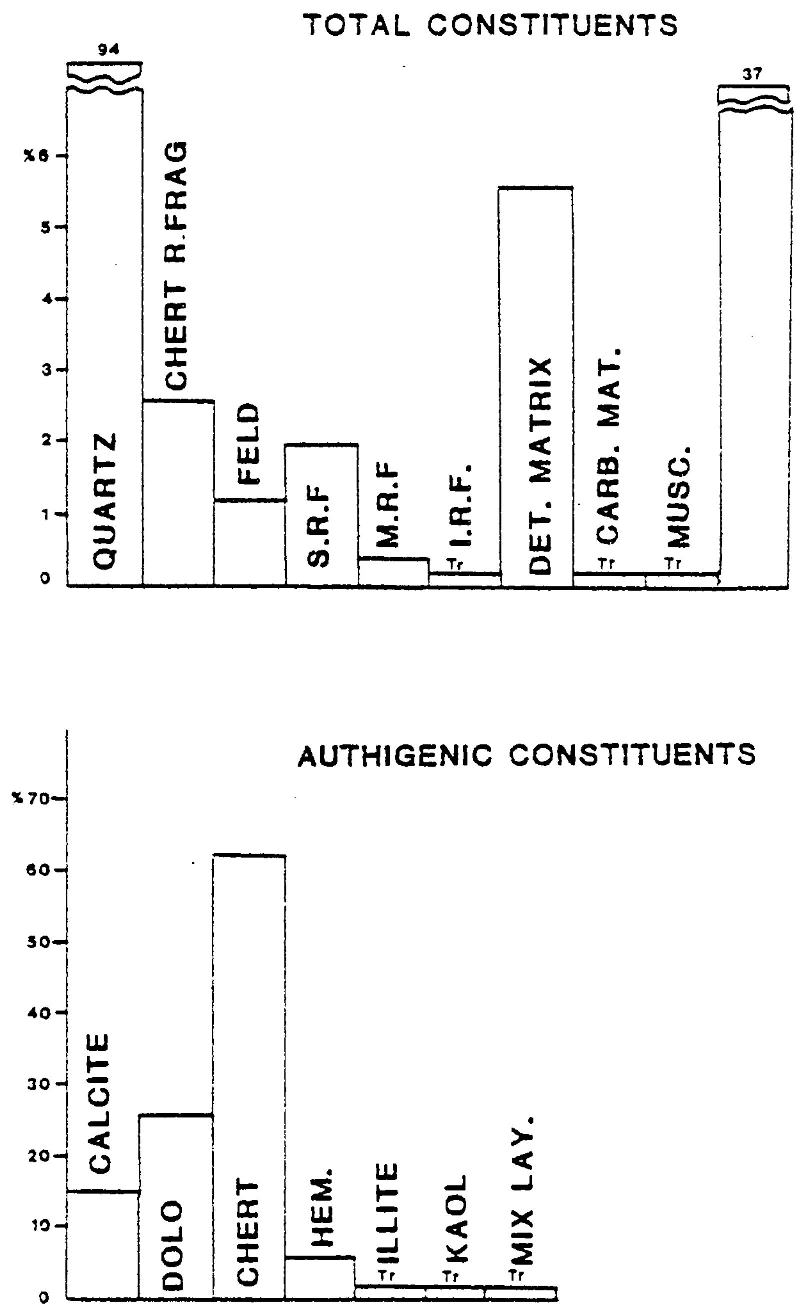


Figure 14. Average Composition of Detrital and Authigenic Constituents Found in Sandstones at Grape Creek. (Abbreviations same as Figure 13 with the addition of: Dolomite (Dolo), Hematite (Hem), Kaolinite (Kaol), Mixed Layer (Mix. Lay.)).

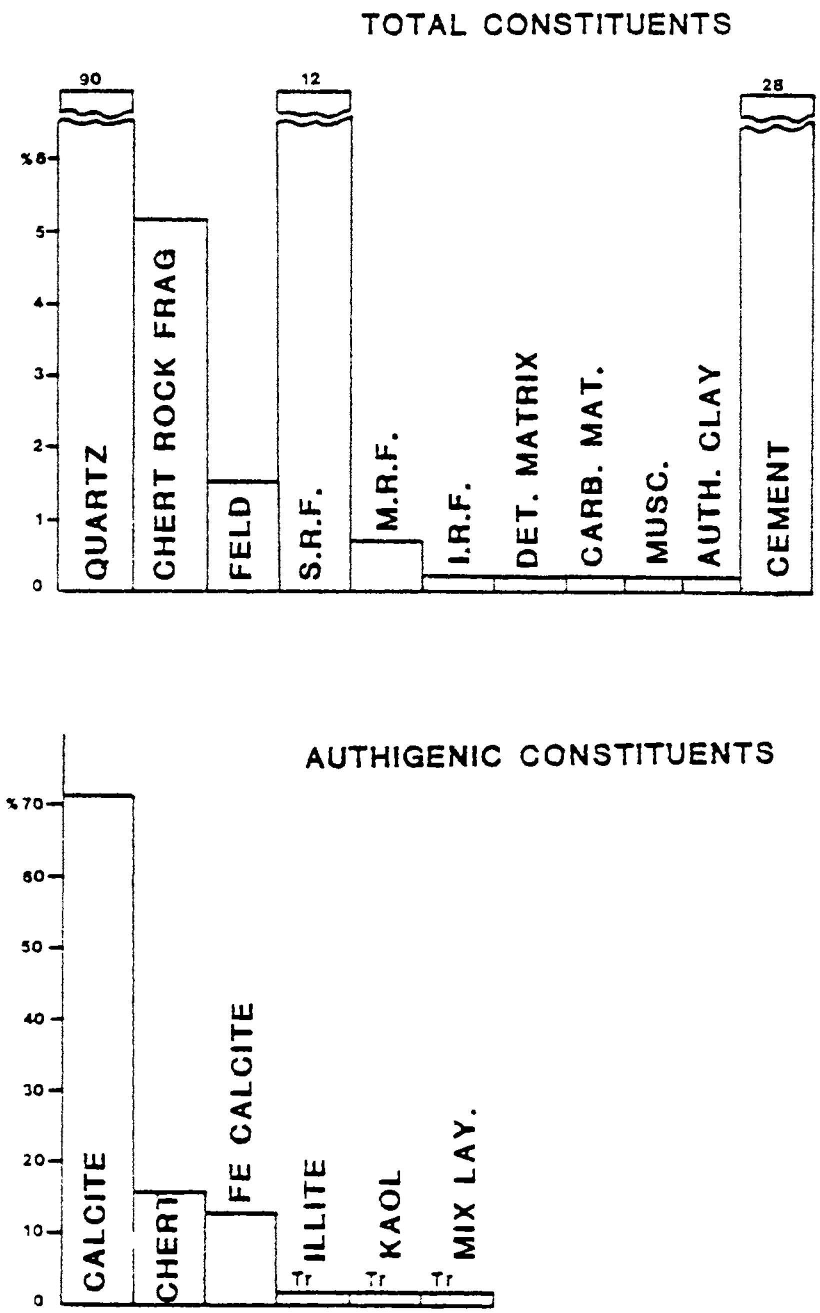


Figure 15. Average Composition of Detrital and Authigenic Constituents Found in Sandstones at Skyline Drive. (Abbreviations same as Figure 14).

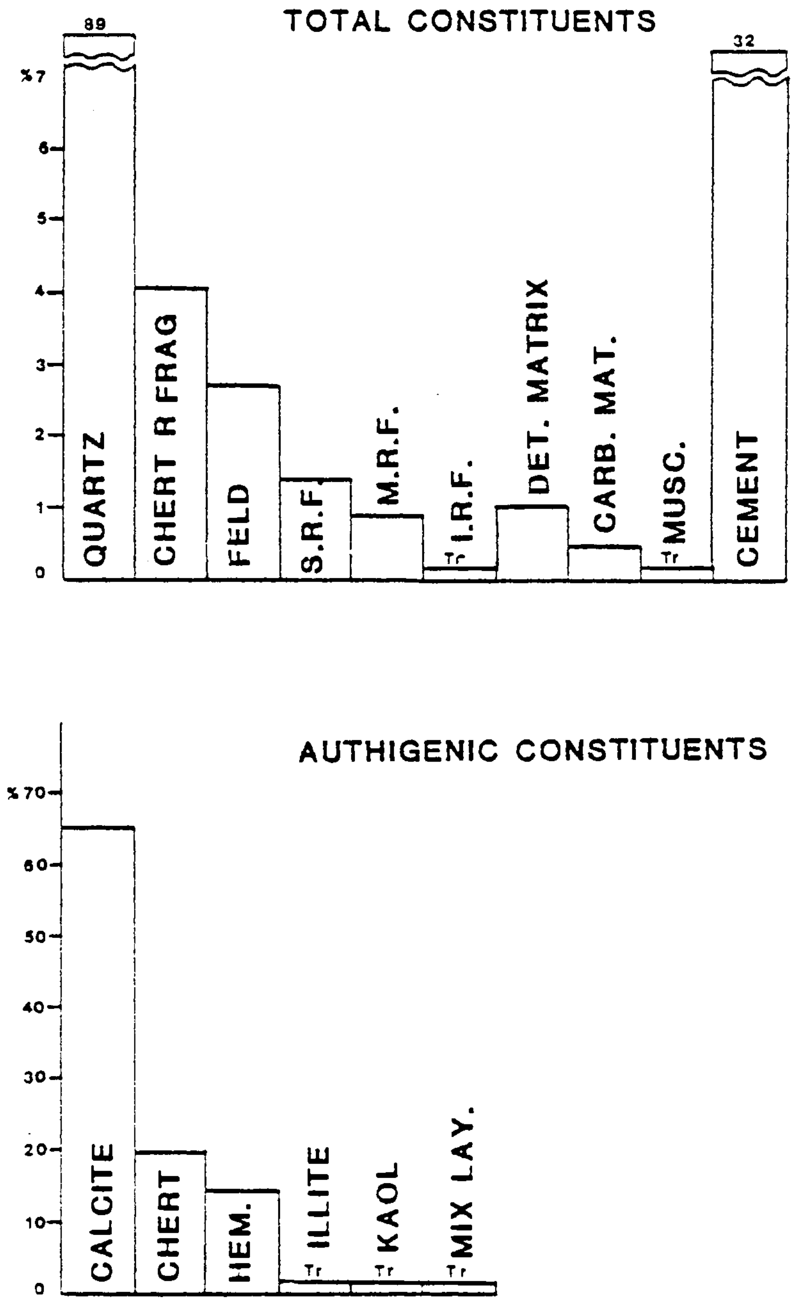


Figure 16. Average Composition of Detrital and Authigenic Constituents Found in Sandstones at Garden Park. (Abbreviations same as Figure 14).

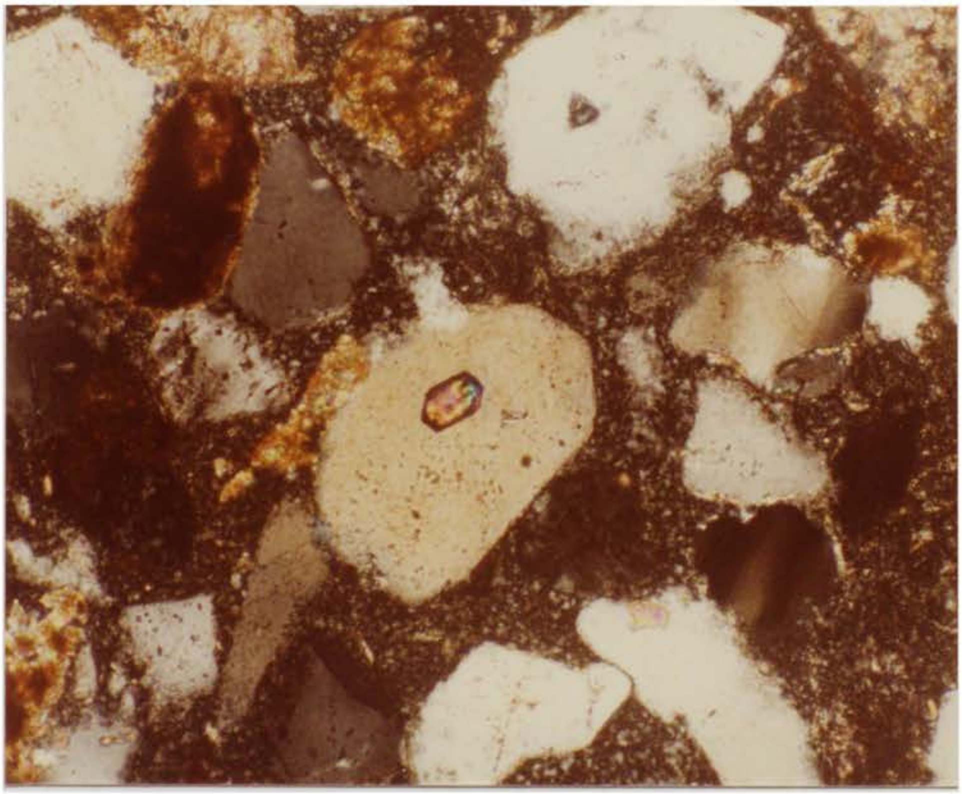


Figure 17. Photomicrograph of a Fine Grained Sandstone from Grape Creek with Detrital Quartz Displaying Embayed Edges, Quartz Grain in Center Contains an Euhedral Zircon Crystal (X20, Crossed Nicols)

The grains are usually highly vaculated and contain numerous inclusions (Figure 17). Recognizable included minerals include zircon, garnets rutile and tourmaline. Corroded and embayed edges are common.

Chert Rock Fragments. Chert rock fragments are the second most abundant constituent. Garden Park is the locality with the largest percentage (5.1%). This is not surprising, since the lower levels of Garden Park have a higher amount of chert than is present in any other major section. The average amount of chert is 4.2 percent.

In thin sections, microquartz is the dominant texture; microquartz or chert is predominant. Some chert textures are ultra-fine, while others show signs of grain growth (Figure 18). In addition, chalcedony fragments, including both lutecite and chalcedonite varieties, are present. Spherulites similar to those found in sites near the top of the Ralston Creek Formation are also present. Chert fragments are commonly well rounded and larger than the monocrystalline quartz grains.

Feldspar. Feldspars are common throughout the formation, but never constitute a high percentage, averaging only 1.8%. Plagioclase feldspars which are more abundant than microcline, show varying degrees of honeycomb dissolution. Microcline is generally fresher with fewer dissolution fabrics developed. Perthite is present in very small amounts.

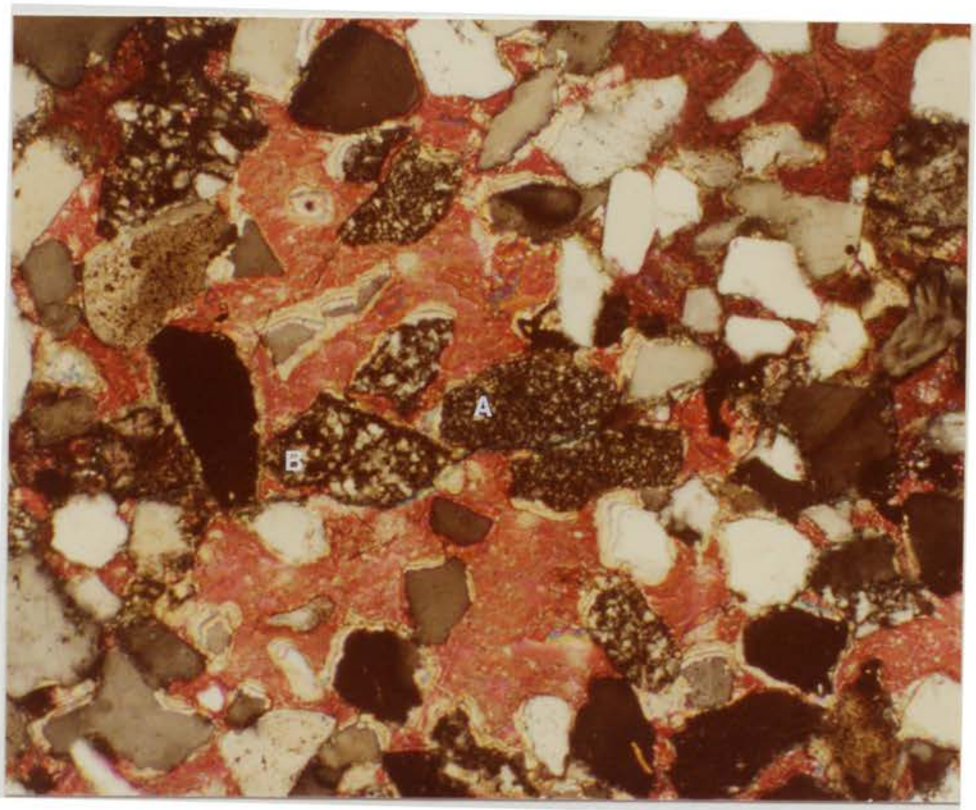


Figure 18. Photomicrograph of Chert Rock Fragment Texture: a) Microquartz, b) Showing Grain Growth, the Fine Grained Sandstone is Cemented by Poikilitic-Calcite (X10, Crossed Nicols)

Lithic Fragments Other than Chert. Apart from chert, sedimentary rock fragments (SRF's) include various types of carbonates (micrites, biomicrites and pelmicrites), shale fragments (which can be quite large) and small particles of sandstones (quartz arenite). Metamorphic rock fragments (MRF's) are schists and metaquartzites. Feldspathic-rich igneous rock fragments (IRF's) are present in only trace amounts.

Miscellaneous Trace Minerals. Morrison rocks in the study area contain a variety of heavy minerals. Zircons are ubiquitous in thin sections and tourmaline is common. Other trace minerals include hornblende, muscovite, biotite, detrital chlorite, hematite, phosphate, pyrite and allogenic glauconite. Grain size of the accessory minerals is .025 mm; rarely are they larger.

Matrix

Syndepositional detrital matrix that is compacted and mechanically injected between grains is present in small amounts in many thin sections. The average only equals trace amounts, although the percentage increases in marlstones. The shaly material is either dispersed throughout pore spaces or found forming laminae.

Carbonaceous material is found in some sandstones. Usually, only trace amounts are recorded; however, one Garden Park sample contained 4% organic material.

Authigenic Constituents

Figures 14, 15 and 16 show the authigenic constituents for thin sections taken from the three major measured sections. Cement percentages were equated to 100%.

Cement

Calcium Carbonate. Calcite is the most common cement; percentages range from 15 to 72 percent of total authigenic constituents. This cement may comprise up to 40 percent of marlstones. Cement textures include equant anhedral sparite and poikilitic crystals up to 2 mm in diameter (Figure 19). Some calcite is ferroan. It is patchy and seems to indicate an influx of iron after the precipitation of calcite.

Dolomite. Fine grained dolomite cements some of the sandstones. It is not found in all areas, but is prominent in the Grape Creek measured section. Minor amounts of the dolomite are ferroan.

Quartz. Two forms of quartz cement occur: microcrystalline quartz and syntaxial quartz overgrowths. Microcrystalline quartz is the second most common cementing material (Figure 17) and is found throughout the area. Distribution of syntaxial quartz overgrowths are patchy (Figures, 20, 21). Most of these overgrowths have clay dust-rims which surround the original grain. Some of the quartz grains have quartz overgrowths on them that are detrital. These quartz grains were eroded and transported

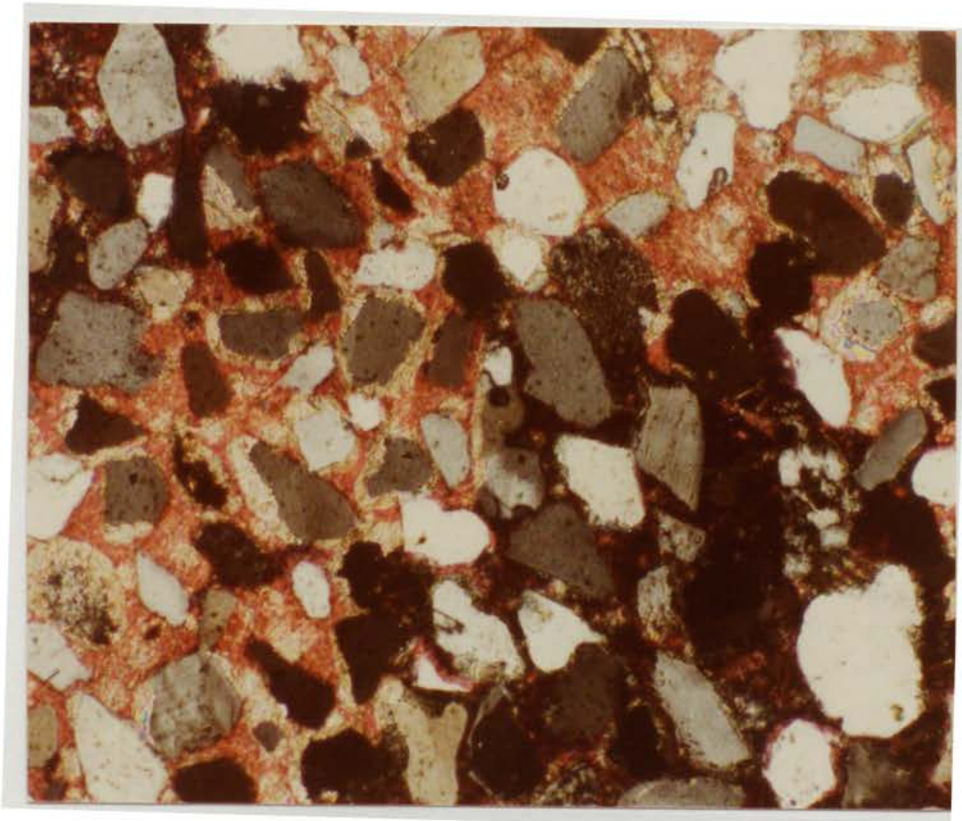


Figure 19. Photomicrograph of Poikilitic Non-ferroan Calcite Cementing a Fine Grained Sandstone from Garden Park (Stained with Alizarin Red, X10, Crossed Nicols)

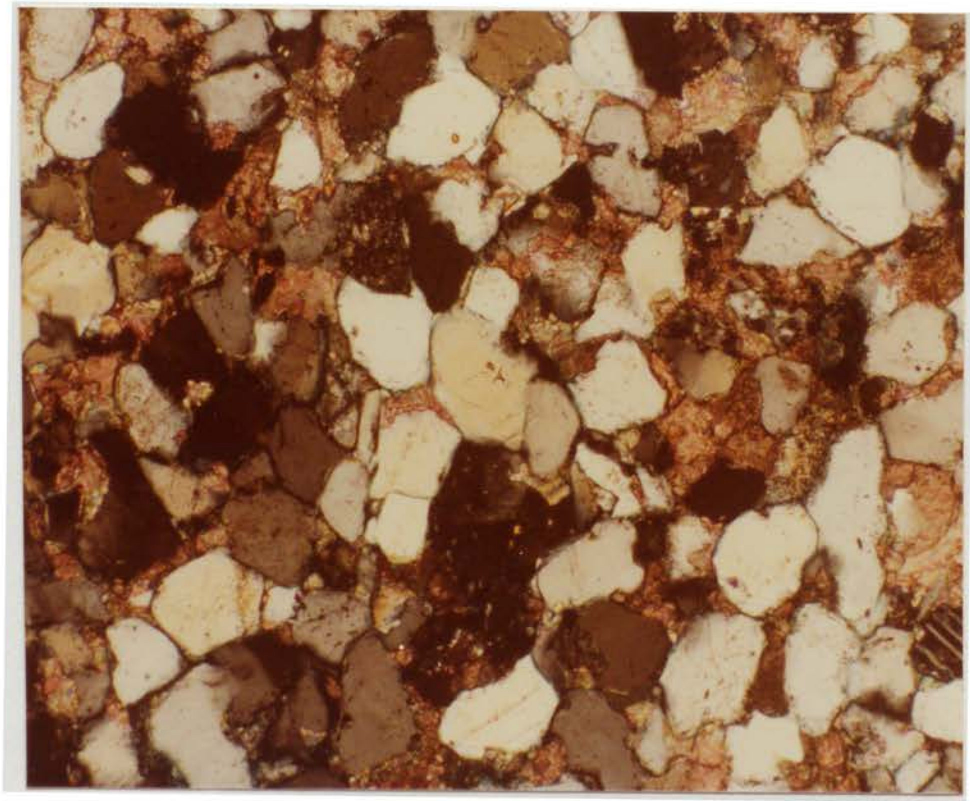


Figure 20. Photomicrograph of a DMC Sandstone Cemented by Syntaxial Quartz Overgrowths and Calcite (Stained by Alizarin Red, X10, Crossed Nicols)

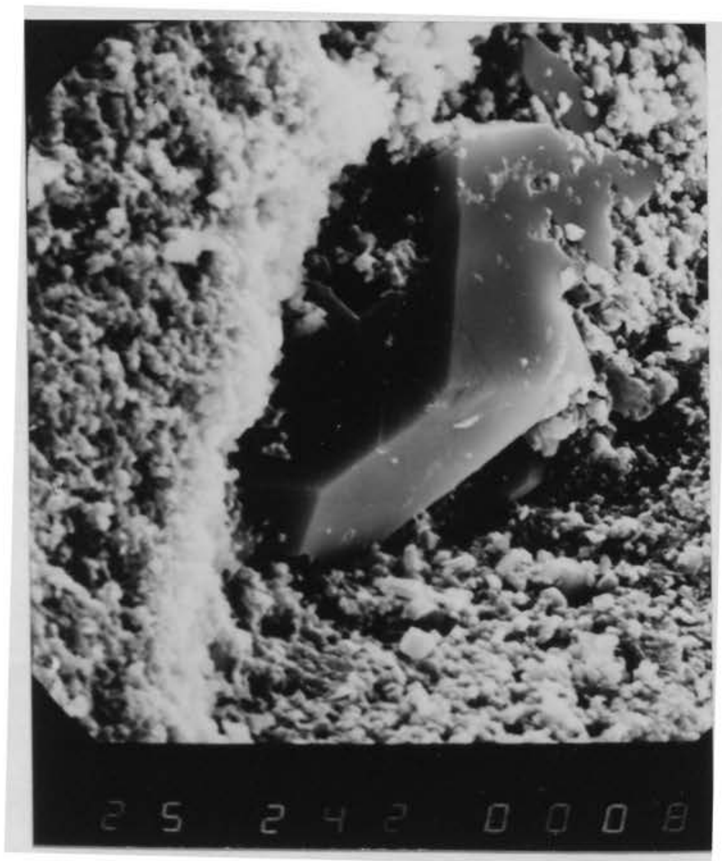


Figure 21. SEM Photograph of a Sandstone from the DMC Section Showing a) Syntaxial Quartz Overgrowth Surrounded by b) Grain Coating and Pore Filling Hematite (X2400).

after the growth of syntaxial overgrowths.

Hematite. Hematite is present as grain-coating and pore-filling cement (Figure 21). Hematite can cause problems with the identification of clay minerals, as it may obliterate everything but the framework constituents.

Clay Minerals. Four major clays are present: illite, smectite, kaolinite and mixed layer clays.

Kaolinite is well seen in some thin sections (Figure 22). Although it appears (as do all the clays) throughout the column, it is exceptionally well developed near the top of the formation. Kaolinite occurs in stacked pseudo-hexagonal plates (Figure 23), which form a pore-filling and pore-bridging morphology (Figure 22) in the Morrison. Hematite often corrodes, infiltrates and disrupts the stacking order (Figure 23).

Illite is difficult to identify in thin sections. When distinguishable, it has high birefringence and a fine crystalline appearance. In SEM, it is characterized by lath-like projections. Due to surface weathering the laths seen in this study are not as well defined as they are in samples from subsurface studies.

Smectite has lower birefringence than illite in thin sections. It is present as crenulated and crinkly grain coats, which at times display a honeycomb-like appearance, sometimes mistaken for chlorite (Figure 24).

The mixed-layer clays have medium-high birefringence.

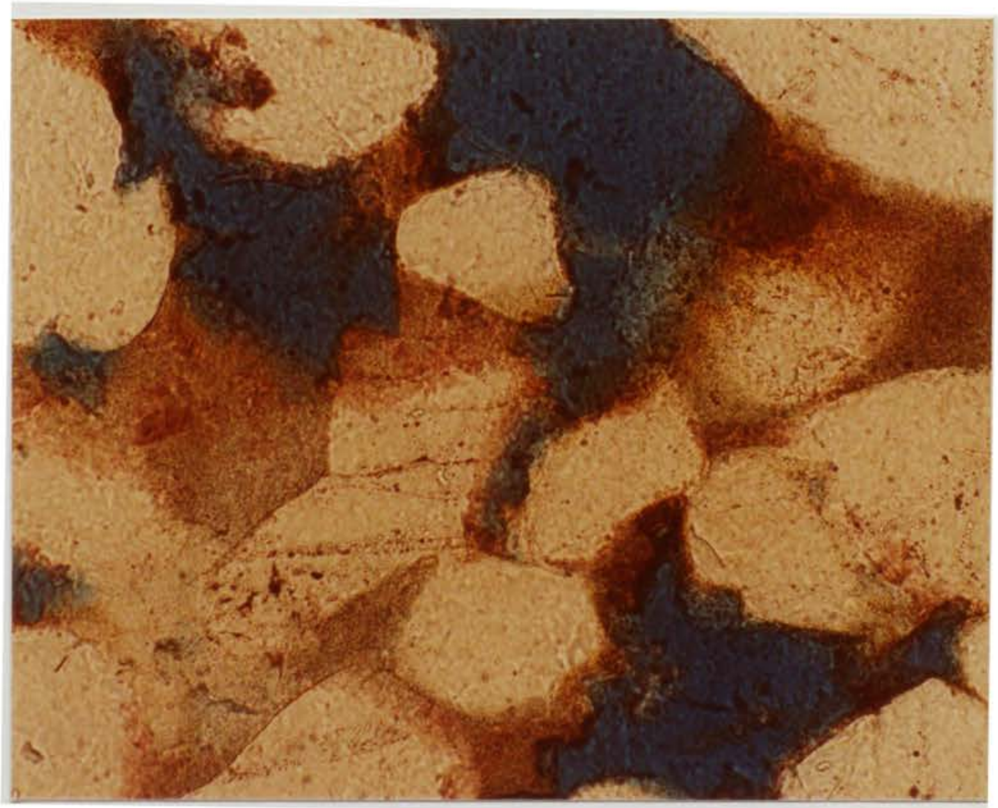


Figure 22. Photomicrograph of a Sandstone from Near the Top of the Grape Creek Measured Section Showing Pore Filling and Pore Bridging Kaolinite (Porosity Stained Blue, X10, Ordinary Light)

Figure 23. SEM Photograph of Stacked Pseudo-hexagonal Plates of Kaolinite Disrupted by Hematite in a Grape Creek Sandstone (X2000)

Figure 24. SEM Photograph of Smectite Forming Crenulated Grain Coats (X3000)

SEM indicates these clays have characteristics of both illite and smectite. Thus the crinkly form of smectite along with small illitic lath-like projections can be observed.

Petrology and Provenance of Intraformational Conglomerates

Intraformational conglomerates are found at various levels in the Morrison Formation. A suite of thin sections was examined in order to attempt to determine the provenance of the formation.

Textures

Because they are a mixture of rolled and saltated grain populations, the conglomerates have a bimodal grain size distribution, ranging from fine to medium grained sand to pebble sized grains. Most of the grains are subrounded to well rounded, and sphericity is high in some samples.

Mineralogy

Most of the conglomerates are polymictic (Figure 25) with only a few being oligomictic. Quartz and chert pebble conglomerates are predominant; however, limestone and shale-rich conglomerates are present.

Quartz. The quartz is usually subrounded to well rounded. While most grains show some corrosion the amount is not as great as it occurs in the sandstones. The quartz

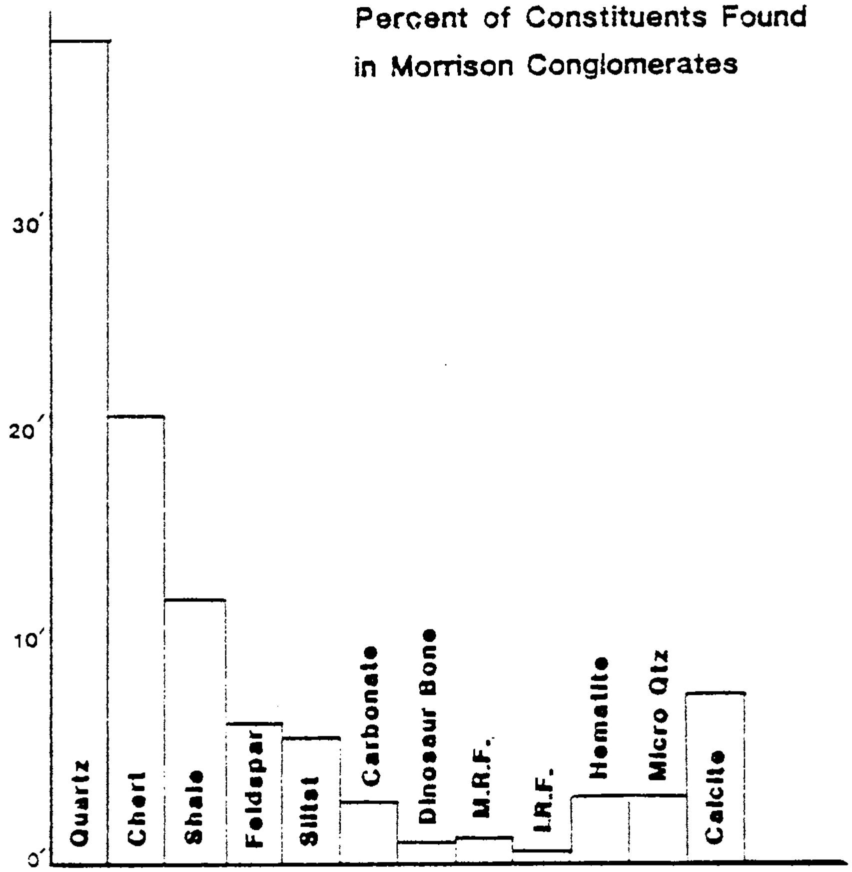


Figure 25. Average Percentage of Total Constituents in Morrison Conglomerates (Abbreviations Same as Figure 13).

is generally monocrystalline; grains show parallel and undulose extinction. However, a greater number of polycrystalline quartz grains are found in the conglomerates than in the finer grained sediments.

Chert. Chert is an abundant constituent in the conglomerates, second only to monocrystalline quartz. Morphologies differ greatly. Some of the pebbles are extremely fine grained microquartz (Figure 26). Others are not as fine and may have microquartz developed in them. Silt-sized quartz grains are present in some instances, indicating a sandstone origin. Lutecite and chalcedonite textures are seen, but are not abundant.

Feldspar. Feldspars form a higher percentage of grains in the conglomerates than in the sandstones. An assortment of both K-feldspars and plagioclases is present, many exhibiting various stages of alteration. Figure 27 shows feldspars associated with igneous rock fragments; however, this association is not common. Generally, the feldspars are disaggregated and scattered throughout the grain population.

Sedimentary Rock Fragments. Shale, siltstone and carbonates are important components of conglomerates. Siltstone and shale pebbles can be quite large, and appear to be rip-up clasts in some samples (Figure 28). Carbonates generally are micrites or dolomicrites; some have a scattering of silt in them. Fossils are rare, although

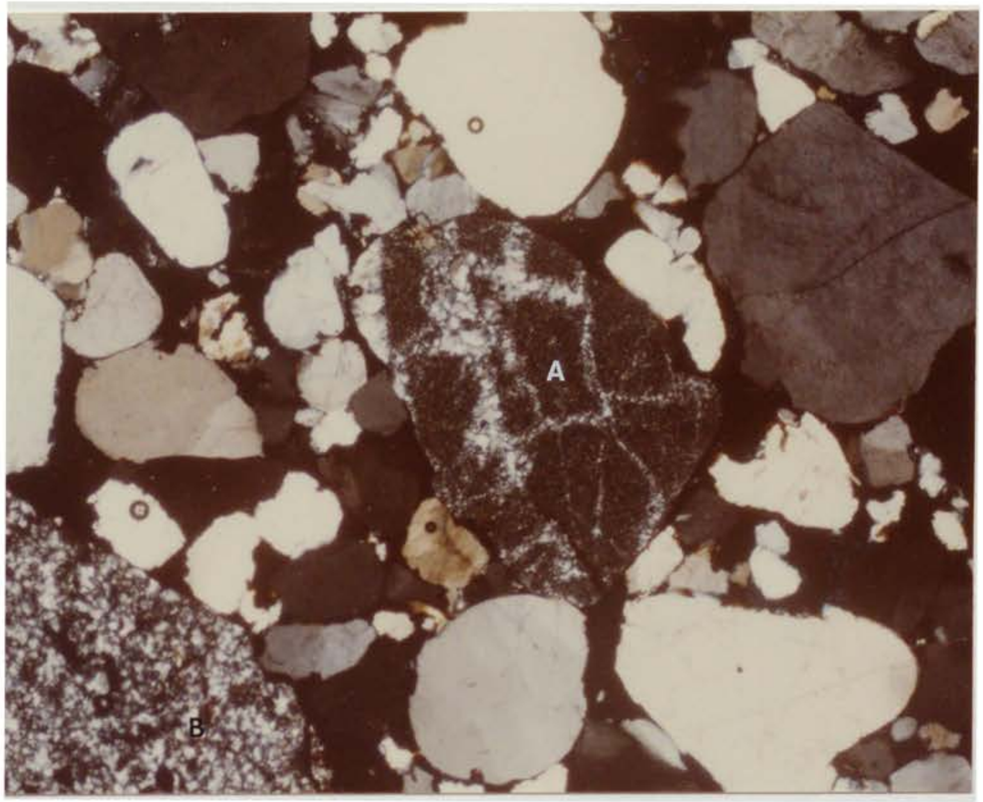


Figure 26. Photomicrograph of a Garden Park Conglomerate with Two Types of Chert Rock Fragments: a) Microquartz with Veins Filled with Megaquartz, b) Microquartz Showing Grain Growth, the Chert and Quartz Pebbles are Cemented by Hematite (X4, Crossed Nicols)

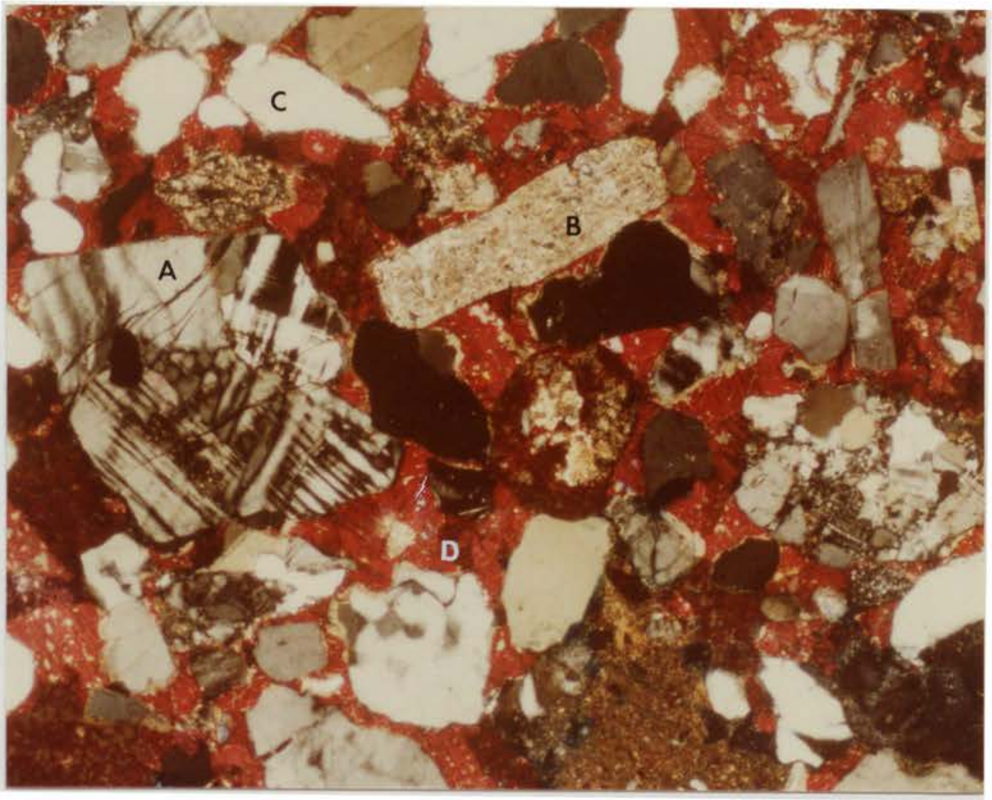


Figure 27. Photomicrograph of an Intraformational Conglomerate from Garden Park Showing: a) Feldspar-rich Granite Fragments; b) SRF's (Sedimentary Rock Fragments); c) with Quartz; d) Poikilitic Calcite (Stained by Alizarin Red, X4, Crossed Nicols)

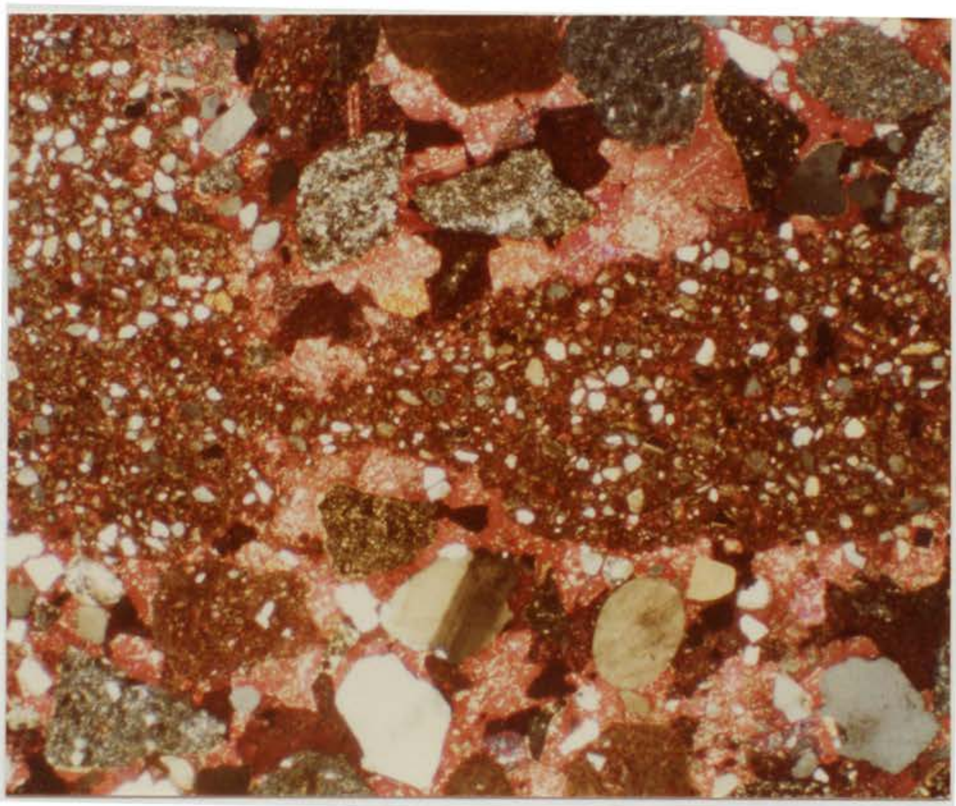


Figure 28. Photomicrograph of Siltstone Rip-up Clasts in an Intraformational Conglomerate from Garden Park, Chert Rock Fragments and Quartz Pebbles are also Present, Calcite Cement is Stained by Alizarin Red (X4, Crossed Nicols)

phosphatic dinosaur bone fragments are seen in a few thin sections (Figure 29).

Metamorphic and Igneous Rock Fragments. As mentioned before, igneous rock fragments, although uncommon, are usually present as aggregations of feldspars. Generally, metamorphic fragments are large polycrystalline metaquartzite grains, with a definite fabric developed in them. Chlorite schist pebbles are also present.

Cements. Microcrystalline quartz, hematite and non-ferroan calcite are the principle cements. The conglomerates have undergone essentially the same diagenesis and paragenesis as the sandstones. The cementing history involved hematite formation followed by calcite, microquartz and a final phase of hematite precipitation. Calcite is the dominant cement (Figures 27, 28 and 29).

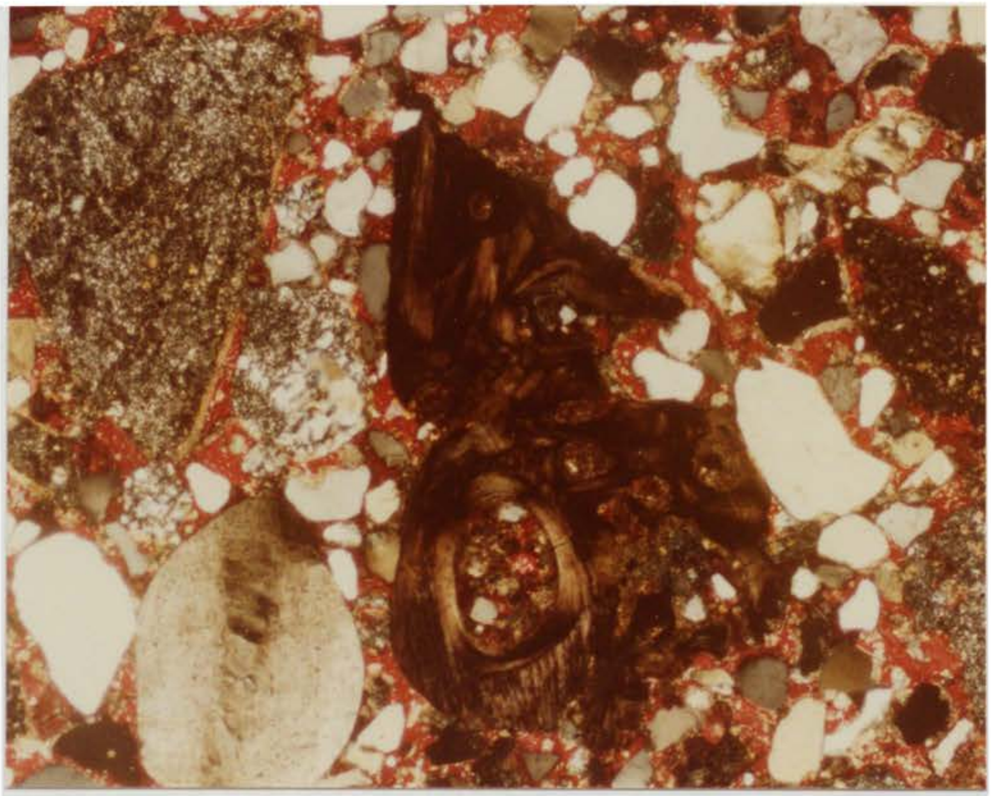


Figure 29. Photomicrograph of a Garden Park Intraformational Conglomerate Containing a Dinosaur Bone Fragment, Quartz Sand and Pebbles, and Chert Rock Fragment, Calcite Cement Stained by Alizarin Red (X4, Crossed Nicols)

CHAPTER V

CLAYSTONES AND SHALES

Multicolored claystones and shales constitute a large percentage of the Morrison Formation. Various combinations of black, grey, green, red and purple shales and claystones make the Morrison colorful at outcrop.

In addition to clay minerals, the claystones and shales contain differing amounts of silt, sand, carbonate, hematite and organic material. Some are fossiliferous (*Unio* and plant fragments). Two fabrics have been observed. In the first fabric, silt and sand grains are concentrated in layers to give a laminated fabric. Otherwise, the argillaceous rocks are essentially structureless. Laminated beds are particularly common in the lacustrine sequences found in the lower portions of the formation.

Gradational contacts are common, especially between claystones and sandstones or impure sandy limestones (marlstones). The latter, generally associated with calcareous claystones and shales, are located mostly in the lower portions of the formation, as recognized by Mirsky (1962) and Brady (1967).

Colors

Several authors have noted the ease at which the Morrison argillaceous rocks can be divided into color zones (Waldschmidt and LeRoy, 1944; Keller, 1953; Mirsky, 1962; Brady, 1967). Waldschmidt and LeRoy (1944) divided the redesignated type section into six units:

I. Basal Sandstone Unit

II. Grey and Red Shale Unit

III. Grey Clay and Limestone Unit

IV. Grey Shale and Sandstone Unit

V. Red Shale Unit

VI. Variegated Sandstone and Shale Unit

Similar trends can be seen in the Canon City area. In the lower portions of the formation, grey and green are the predominant hues; black shales are restricted to the lacustrine sequences. In the middle portions of the formation, green is the common color. At higher levels there is a very distinct change to red. Purple hues are common near the top of the Morrison, particularly at Skyline Drive.

Clays

Clay minerals in argillaceous sediments were distinguished by x-ray diffraction. Kaolinite, illite, smectite and illite-smectite mixed-layer clays were identified. Chlorite and vermiculite clays were not seen in the samples studied.

Keller (1953) divided the Morrison at the revised type section on the basis of clay mineral abundance. He noted that kaolinite and illite were common in the upper two zones (V, VI) of Waldschmidt and LeRoy's subdivision, illite and smectite were in zones III and IV, whereas illite and kaolinite were present in the lowest unit (I).

At Canon City (Figure 30), kaolinite is also in the upper portion of the formation, with illite and mixed-layer clays. Illite percentages increase downsection. There is a smectite-rich zone near the middle of the formation, although it appears to be thinner than the one observed by Keller (1953). In the lower portions the Morrison contains illite, smectite, mixed-layer clays and trace amounts of kaolinite. The appearance of smectite near the base is the only deviation from the findings of Keller (1953) and Brady (1967).

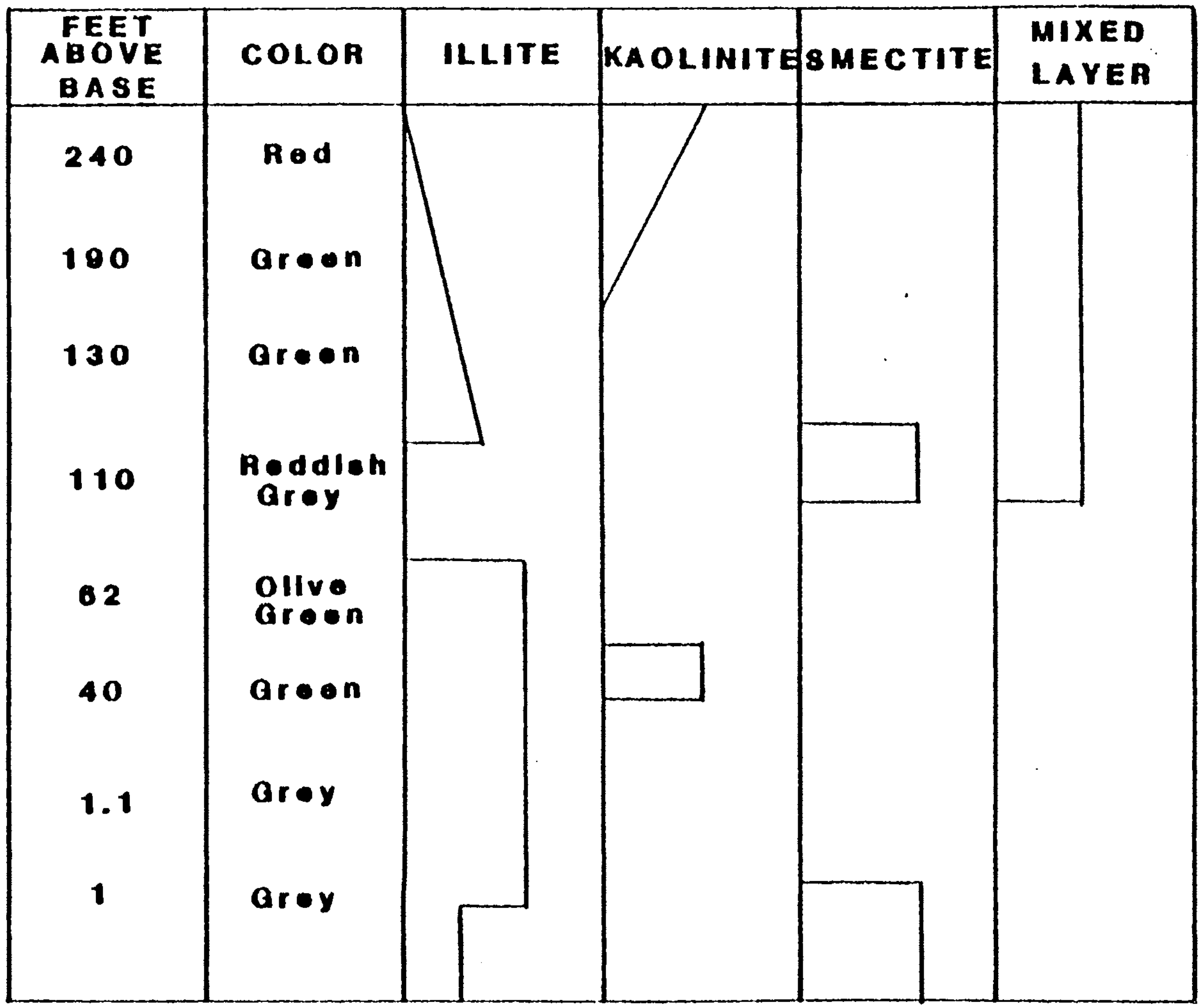


Figure 30. Shale Diagram Relating Color and Clay Mineralogy to Their Position in the Formation.

CHAPTER VI

CARBONATES IN THE MORRISON FORMATION

Field Characteristics and Geometry

Carbonates are found in the Morrison Formation throughout the Canon City Embayment. Carbonate lithotypes include micritic limestones, dolomite-rich micrites and a few finely crystalline limestones. Individual units range from 6 inches to 4 feet in thickness, and although they are common, most are of limited lateral extent. The exceptions to this statement are two units, informally referred to as the "white" and "black" limestones, which will be discussed in detail in the following text.

Generally, most carbonates are light grey on fresh and weathered surfaces. However, because of high iron content some carbonates are weathered orange.

Contacts shown by these relatively thin carbonates are sharp. Some of the upper surfaces are cut by subaerial mudcracks. Many of the carbonates are both thinly bedded and laminated; some are massive. Birds-eye (fenestrae) structures are common. A noticeable feature shown by many carbonates is penecontemporaneous (soft-sediment) deformation by dewatering, e.g., convolute bedding and buttock folding. This deformation may mask other structures at outcrop, such as trace fossils. Trace fossils are suspected, due to the presence of disrupted burrows in thin section and because of the number of gastropod and pelecypod fossils in the limestones; however, none have been encountered.

Carbonate Petrography

The predominant carbonate lithotype is micrite. Although micritic limestones may be found at any level, they are most common towards the base of the formation. The aforementioned "white" and "black" limestones are the only carbonate units which can be traced throughout the embayment. Figure 31 lists contrasts between the two limestones.

The "White" Limestone

The white limestone, which is up to four feet thick, is weakly laminated and has its primary micritic fabric cut by numerous fenestrae that are filled with drusy sparite (Figure 32). Siliciclastic grains (mostly quartz) are plentiful and in places help to define lamination. Organic carbon is rare.

Gastropods are the main body fossils, although *Chara* and ostracods also are abundant. The gastropods show replacement textures (after aragonite), whereas the *Chara* and ostracods preserve their primary fabric. Intraparticle porosity has been infilled by sparite and, less commonly, by

White Limestone	Black Limestone
Numerous fossils	Paucity of fossils apart from fish no gastropods
Less compaction	Compacted shells
Early cementation	Less rapid cementation
Siliclastic content high (up to 10%)	Low siliclastic content
Laminae poorly developed or disrupted	Well developed laminae
Abundant fenestrae	Fenestrae absent
Low organic carbon content	High organic carbon content
High carbonate content	Slighty less carbonate content

Figure 31. List of Contrasts Between the "White" and "Black" Limestone.

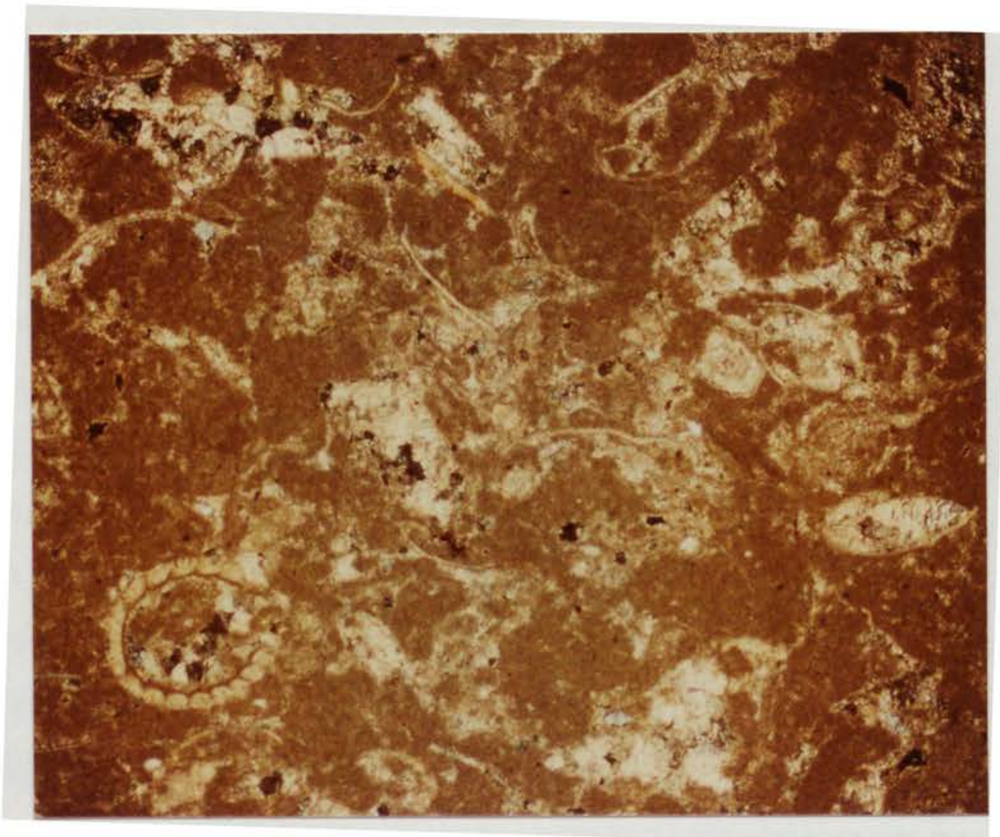


Figure 32. Photomicrograph of a Typical Micritic "White" Limestone Containing Chara, Ostracods, and Fenestrae (Crossed Nicols, 4X)

chert. Most of the fossils are complete and show no major effects due to compaction or corrosion. This indicates rapid cementation in waters supersaturated with calcite.

The "Black" Limestone

The "black" limestone is a laminated and kerogen-rich rock with siliciclastic mineralogy similar to that seen in the "white" limestone (Figure 33). Some ostracods and *Chara* are present; in addition the unit contains numerous fossil fish, predominantly fins and scales, but also including a complete (and as yet unidentified) head (Donovan, personal communication). Overall, the "black" limestone has a lower siliciclastic content than the "white" limestone and fenestrae are practically nonexistent. While the organic content is high (the rock smells of bitumen when freshly broken), the carbonate content is lower than normal for other Morrison limestones. Fossils, such as *Chara* and ostracods, show significant compaction, indicating a lower rate of lithification than that which influenced the "white" limestone.

Other Carbonates

Morrison limestones can be classified as micrites or sparse biomicrites, although some are true biomicrites (Figure 34). Sparite cements developed, particularly in uncommon pellet-rich lithologies.

The main body fossils are gastropods, of which there

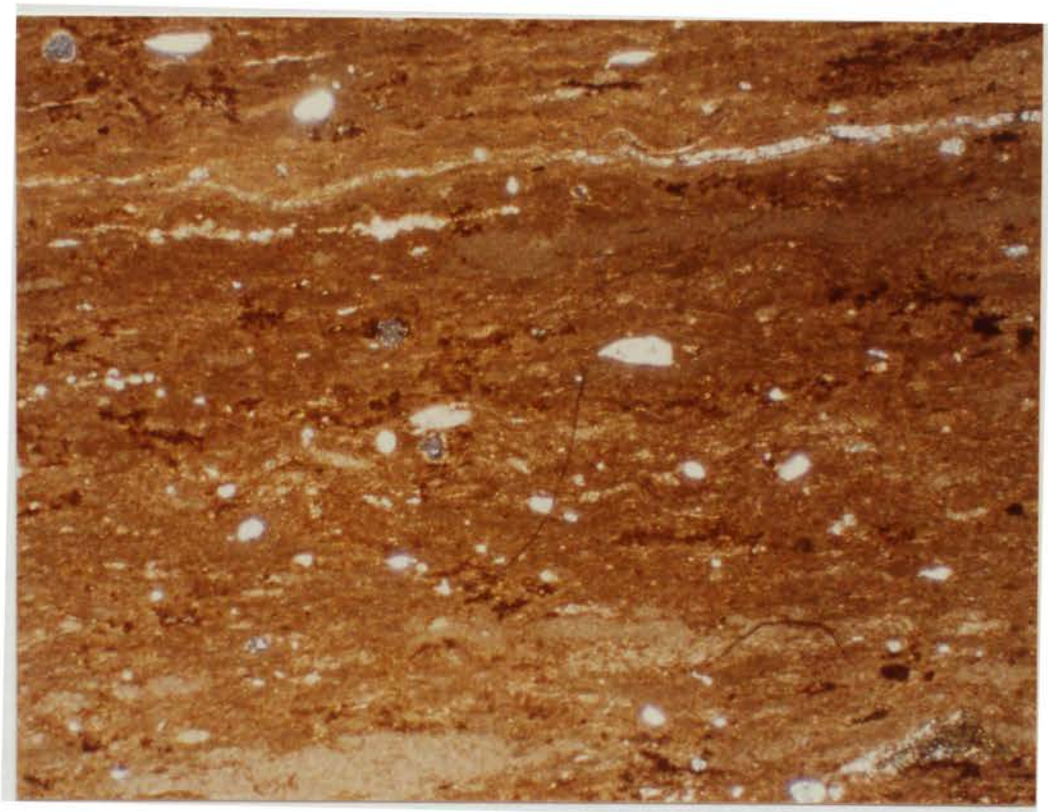


Figure 33. Photomicrograph of the "Black" Limestone at Grape Creek, Abundant Kerogen Alternates with Calcite and Micrite Laminae (Note the Crushed Appearance of Ostracods Along Laminae, X4, Crossed Nicols)

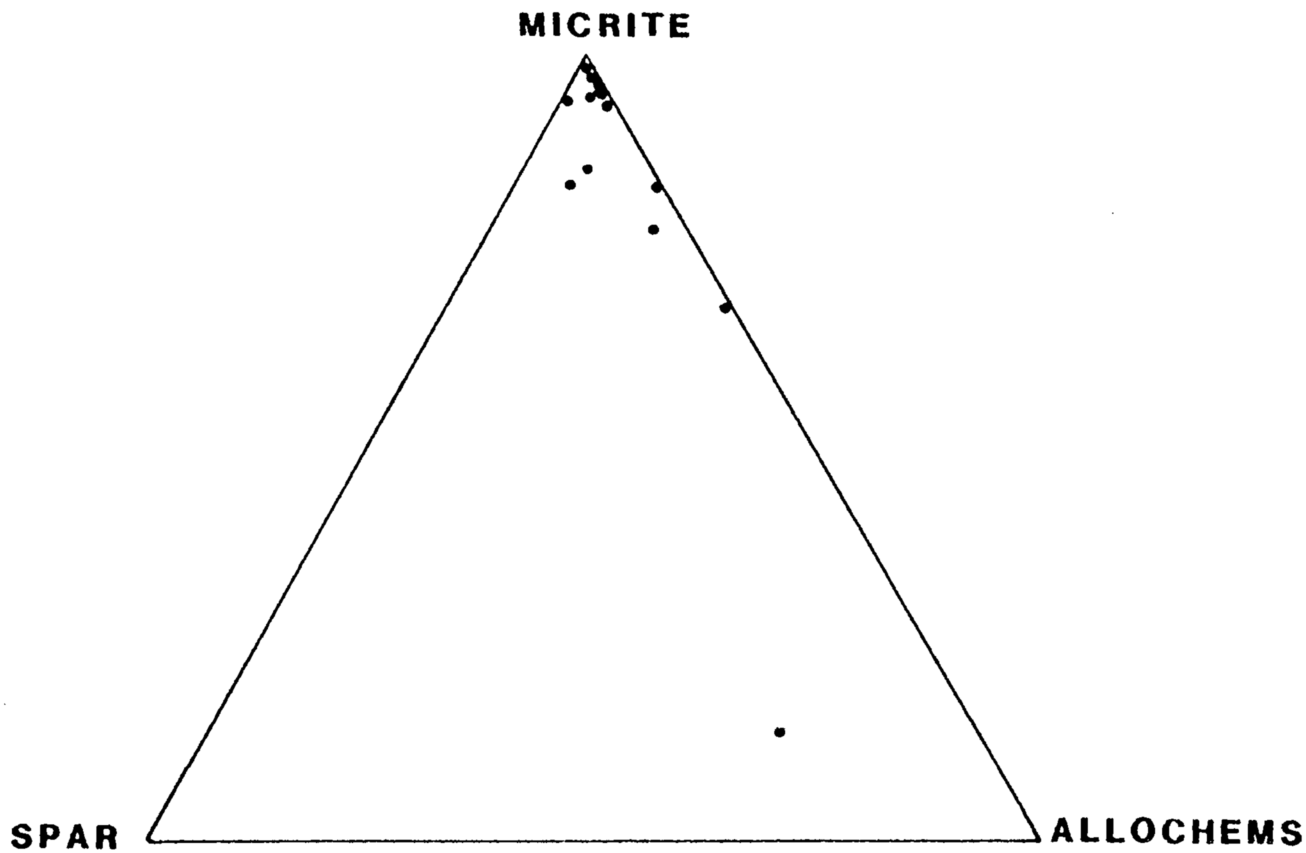


Figure 34. Ternary Diagram of Morrison Carbonates Taken from the Canon City Area.

are several varieties. The original aragonite of their shells has been replaced by both drusy sparite and silica; in addition, their intraparticle porosity has been infilled by both minerals. The silica varies in color; carnelian is most common but black and yellow varieties are also present. In thin section the silica is chert and chalcedony, the chalcedony being length-fast (chalcedonite) (Figure 35). Other important biota present include pelecypods, Chara, ostracods and fish, all of which are typical of fresh water lacustrine environments. Chara and ostracods are ubiquitous, while pelecypods are less common. Phosphatic fish scales and fins are limited to the organic carbon-rich carbonates such as the "black" limestone.

Fenestrae, which form as gas escapes from freshly deposited sediments, are commonly filled with drusy sparite. Burrows, seen only in thin section, are usually filled with either micrite or a mixture of micrite and sparite. Carbonaceous material is not common, except in the "black" limestone.

Some of the micrites have undergone neomorphism. Generally, these rocks have been incompletely recrystallized, leaving varying amounts of relict micrite along with incipiently neomorphosed micrite (micro-spar) in the rock. In addition, these rocks are composed of low-Mg calcite, silica and barite. The low-Mg calcite and barite are void filling cements, while the silica appears to replace the micrite.

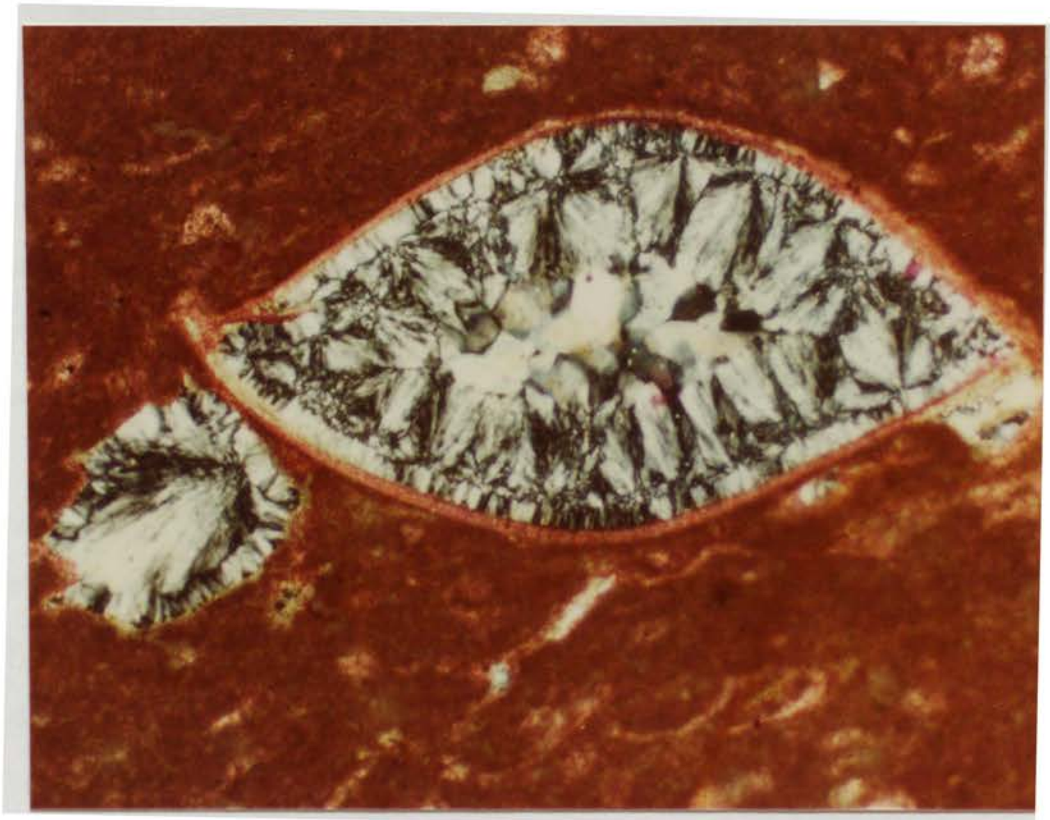


Figure 35. Photomicrograph of an Ostracod Filled with Fibrous Chalcedony and Mega-Quartz (Micrite Stained by Alizarin Red, Crossed Nicols, 10X)

Less common constituents in the limestones are oolites and pellets. Ooids are usually superficial (Figure 36); i.e., they are poorly developed with a single oolitic rim surrounding the nucleus. The nuclei may be quartz, various feldspars, pellets or carbonate grains. More rarely, well-developed ooids display both concentric and radial morphology. Many of the concentric ooids show alternation of micrite and sparite rings. A similar pattern is seen in the radial ooids where micrite spokes alternate with sparite ones (Figure 36). Some of the ooids are circular in cross-section, while others are more ovoid, but most are irregularly shaped (Figure 36).

Peloids are present in minor amounts in many of the limestones; however, in some they are the dominant constituent (Figure 37). Peloids range in size from 0.1 mm to 0.3 mm and are circular to elliptical. They are composed of dense micrite and are cemented by both micrite and sparite. The source of the peloids is uncertain; they may be fecal (from gastropods and pelecypods) or they may be clastic particles due to the reworking of a previous micritic sediment. Dense micrite envelopes have developed on some peloids, suggesting that they may have been coated by endolithic algae.

Dolomite

Most dolomite is present as dolomicrite, where it can form up to 80% of the rock. The dolomicrites display

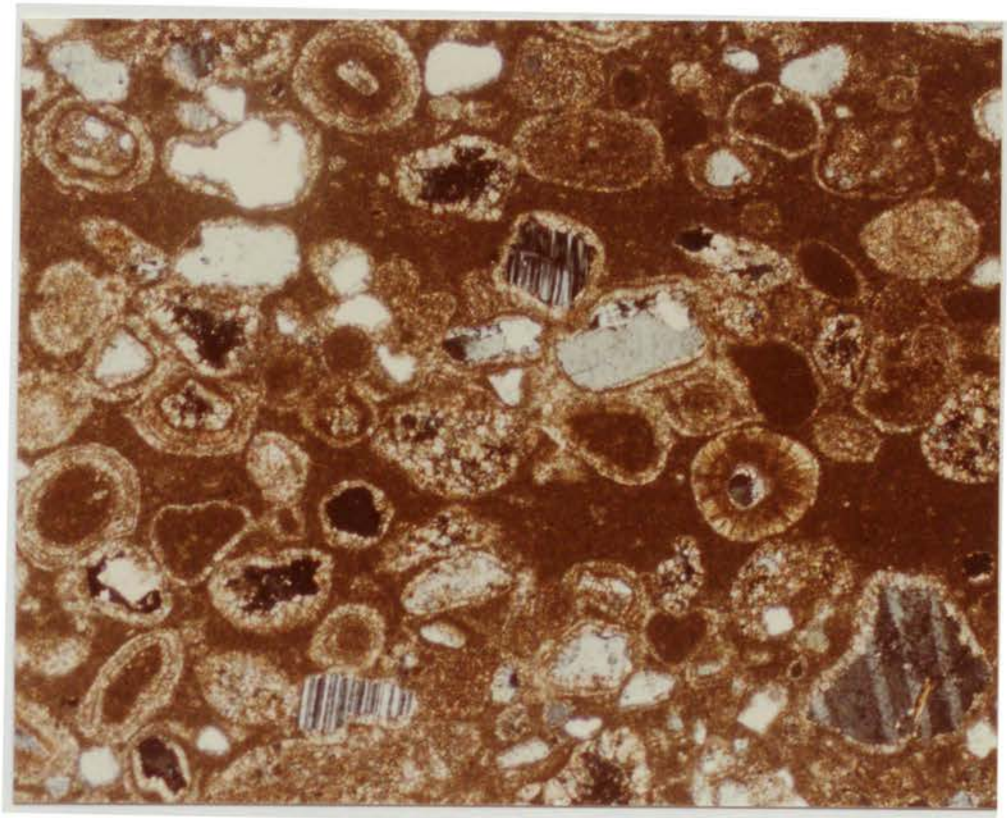


Figure 36. Photomicrograph of an Oomicrite from Garden Park, Superficial Ooids Surrounding a) Feldspar Nuclei, b) Micrite Nuclei, also Present are c) Radial Ooids and d) Concentric Ooids, Some of the Ooids are Squashed (X4, Crossed Nicols)

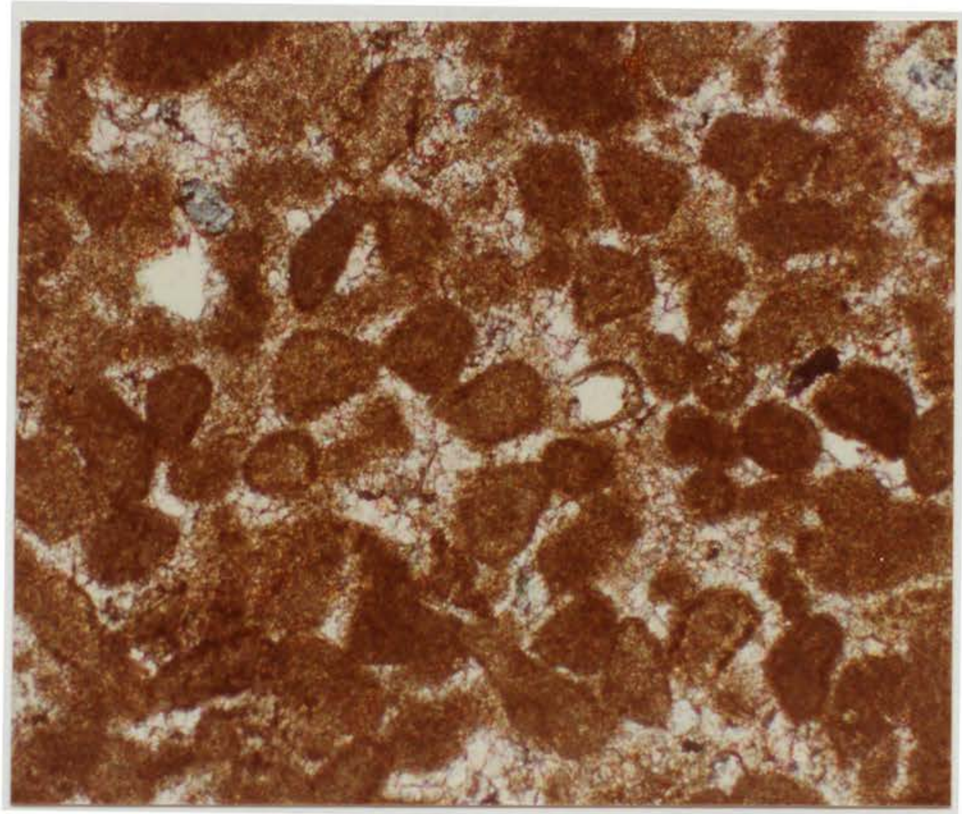


Figure 37. Photomicrograph of a Pelmicrite from Garden Park, Peloids are Both Circular and Eliptical in Shape with Dense Micrite Envelopes Surrounding Them, Suggesting They were Coated with Endolithic Algae

essentially the same features as calcmicrites; they contain small amounts of siliciclastics together with some normal invertebrate fossils associated with the Morrison. However, these fossils are less abundant than those found in typical limestones. Fenestrae in these dolomite-rich carbonates are usually filled with sparry low-Mg calcite cement.

Dolomite is also present as a patchy replacement in some limestones.

CHAPTER VII

CHERT

Minor amounts of chert are found throughout the lower portions of the Morrison near Canon City. Generally, chert replaces fossils and micrite in limestones; however, in the eastern portions of the study it is bedded.

Bedded Cherts in the BOC Section

Lee (1902) first described "curious" seams of remarkably persistent nodular silica in the Morrison Formation. Ogden (1954) described these cherts as being "welded" in appearance and suggested that they be used as time-surface stratigraphic markers. The bedded chert in the Morrison around the Canon City area was described by King and Merriam (1969). They suggested that the term "welded chert" is misleading because the unit is neither welded in the pyroclastic sense, nor is the type of silica restricted to chert. They pointed to the annular structures seen in the large globular masses as being characteristic of beekite.

In this study, the best development of bedded chert was found at the BOC section (Appendix E), where it overlies Ralston Creek gypsum. Here, more than eight silica-rich layers are found (a recent slump made access in the upper levels impossible). They are interbedded with thinly-bedded limestones, marlstones and shales. The irregular nodular masses are variably orange (carnelian), pink, white and blue. In thin section, three main types of silica are present: megaquartz, microquartz and chalcedony. The matrix in which the secondary quartz occurs consists of smectite and dolomite. Calcite-filled pseudomorphs after an unknown salt are also present. Non-ferroan calc-sparite and minor barite are present as cement.

Microquartz

Microquartz appears often in nodular form; generally it alternates with chalcedony, but is rarely a nodule composed of microquartz.

Chalcedony

Fibrous chalcedony is both pore-filling and replacive. It has two main morphologies: spherulitic chalcedony showing pseudo-uniaxial extinction (Figure 38) and fibrous chalcedony with continuous, unaltered extinction along fibers (Figure 39). Lutecite and quartzine, the two types of length slow chalcedony, are present. The lutecite creates a distinctive chevron-texture with the c-axis at approximately 30° to the fibers (Figure 40). Length slow chalcedony has been linked to evaporites and pore waters of high ionic strength (Folk and Pittman, 1971; Siedlecka,

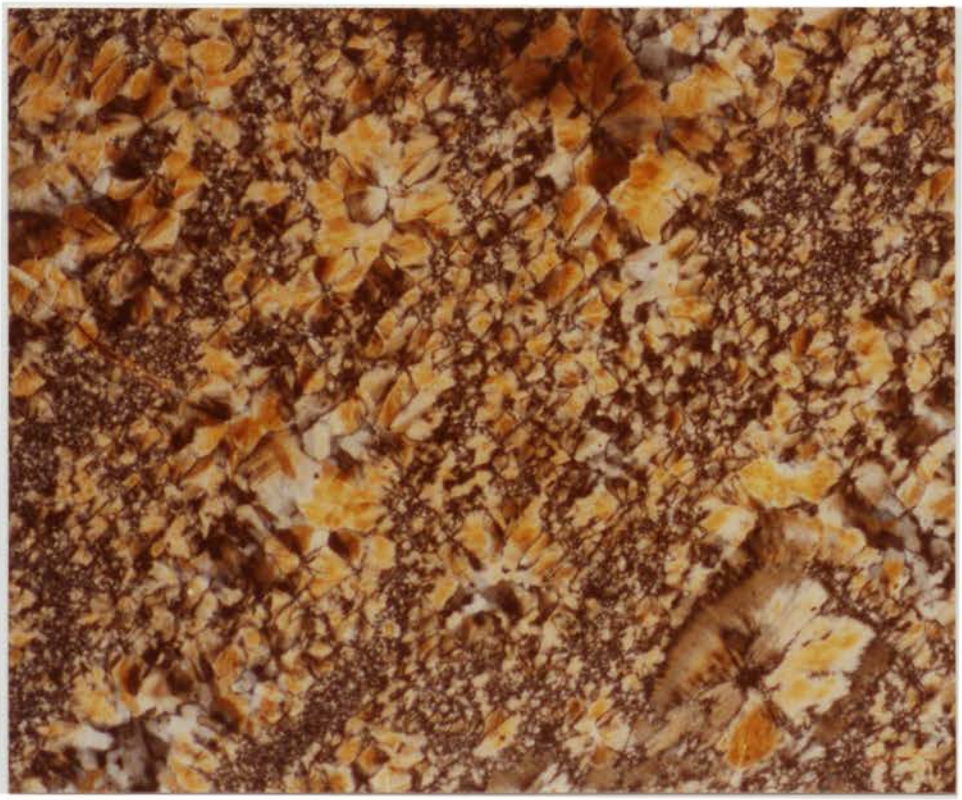


Figure 38. Photomicrograph of Spherulitic Chalcedony Showing Pseudouniaxial Extinction from the BOC Section (Thin Section is Thick, X4, Crossed Nicols)

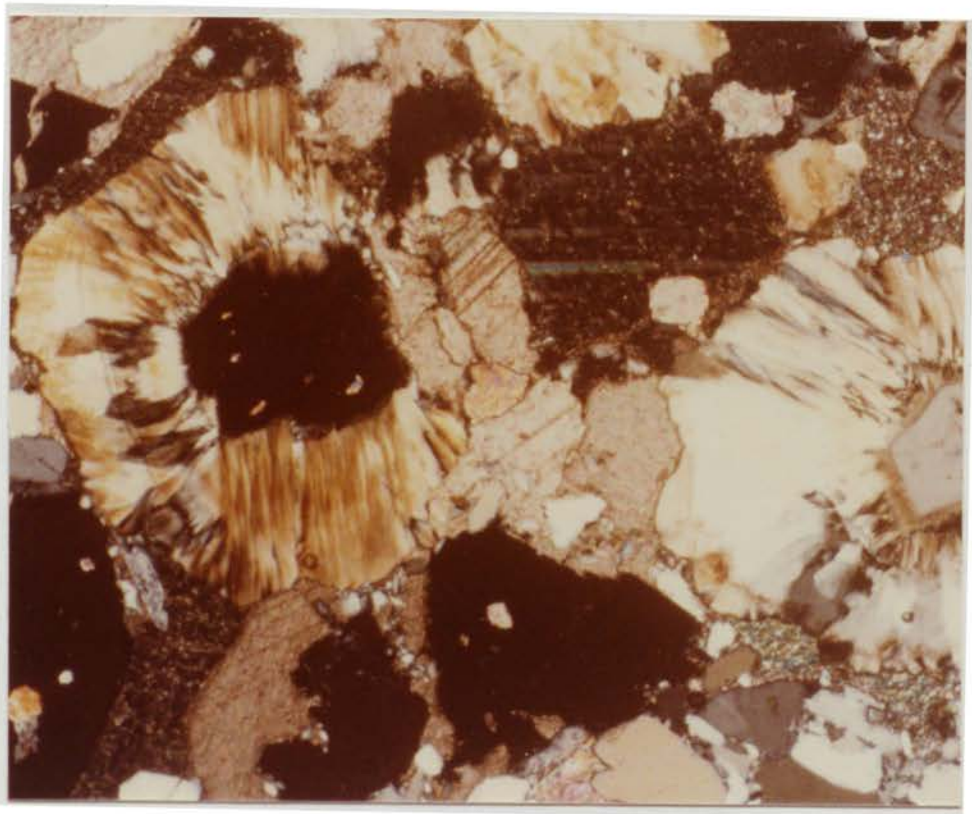


Figure 39. Photomicrograph of Length Slow Fibrous Chalcedony with Continuous and Unaltered Extinction Along Fibers, Corroded Euhedral Megaquartz is Also Present, Sparry Calcite Cement Surrounds Silica (X4, Crossed Nicols)

Figure 40. Photomicrograph of Lutecite Surrounded by Microcrystalline Quartz and a Minor Amount of Calcite Cement, Specimen from the BOC Section (X4, Crossed Nicols)

1972).

Megaquartz

Megaquartz is well developed and appears to be the earliest form of secondary silica present. In some hand specimens, well formed crystals occur in poorly developed geodes. In thin section, the euhedral outlines of the quartz are well displayed. Although most quartz crystals seem to have formed as a single growth phase, some show evidence of sequential growth in the form of multiple dust rims (Figure 41). Such a growth pattern is indicative of changing pH in pore waters. Changing concentrations of pore waters are suggested by flamboyant megaquartz which appears as continuous growth rims around some euhedral megaquartz (Figure 41). Much of the euhedral megaquartz has been corroded by later calcite cementation, although some crystals still maintain clear euhedral outlines. Some megaquartz contains mineral inclusions (Figure 42) which appear to be anhydrite. This sulphate was either leached from underlying gypsum (present in the Ralston Creek Formation) or, more probably, is a remnant of the original mineralogy of the bed prior to replacement by megaquartz.

Colloform Chert Varieties

The most outstanding form of silica seen in this study is a nodular form that exhibits colloform banding or beekite texture. These nodules are formed of either equant bands of

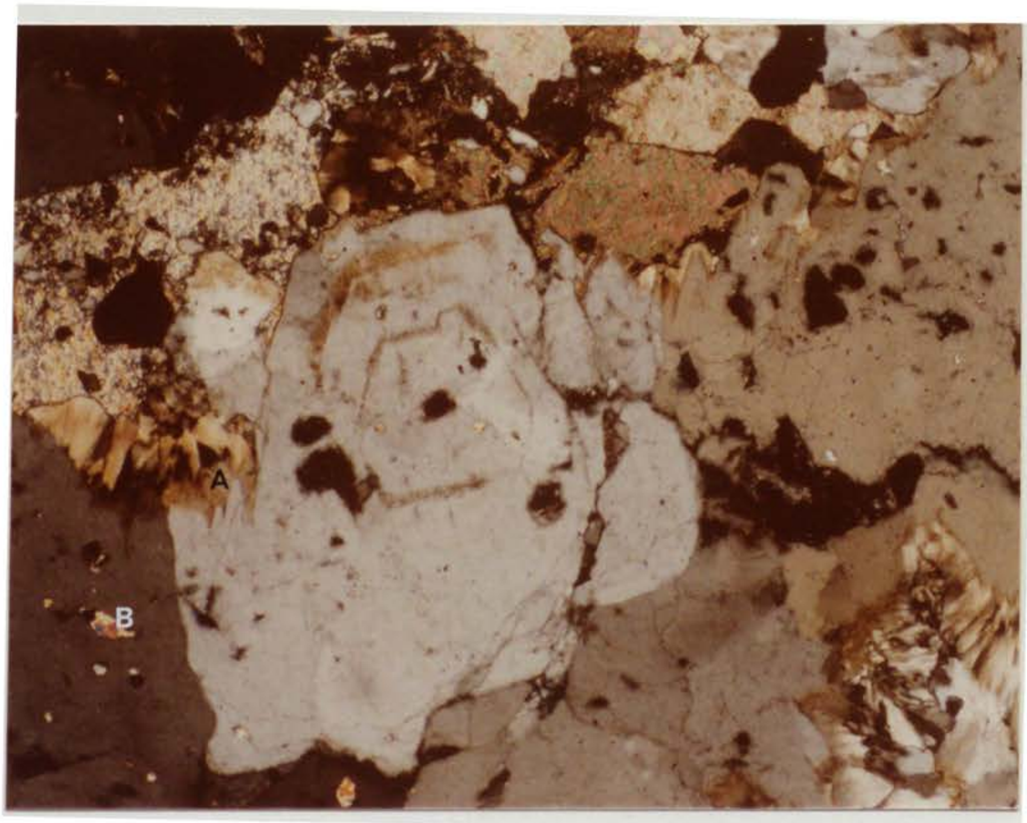


Figure 41. Photomicrograph of Megaquartz with Sequential Growth Rings (Note Multiple Dust Rims), Some of the Megaquartz Grades into a) Flamboyant Megaquartz; b) is Included with Anhydrite (X4, Crossed Nicols)

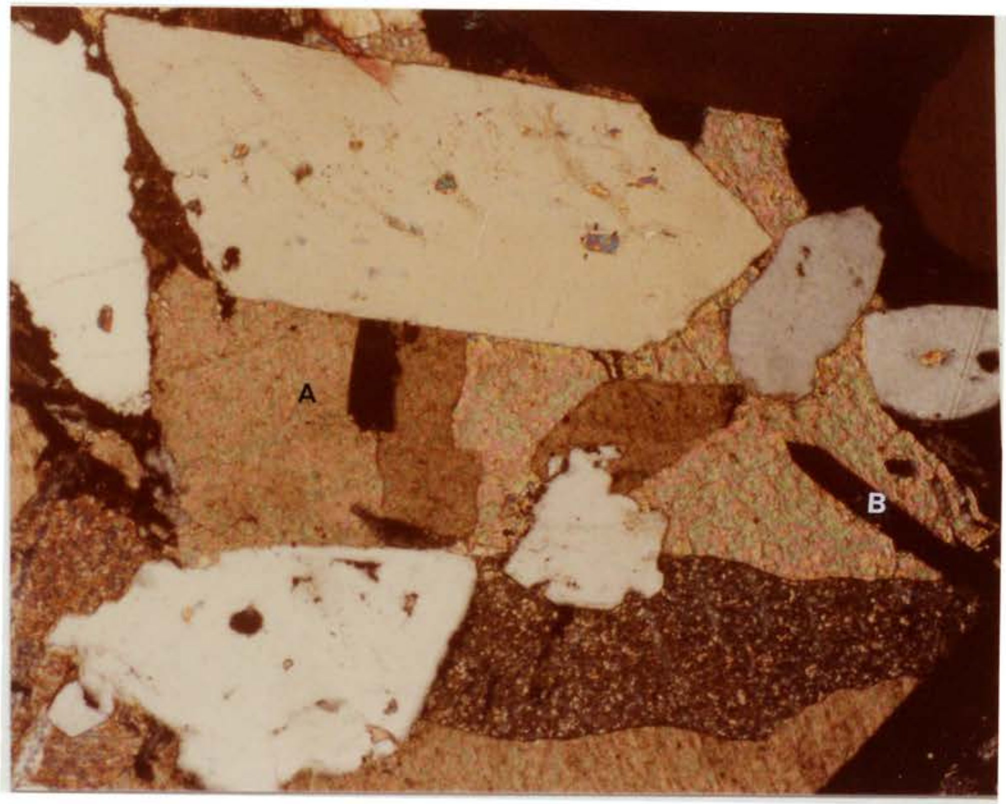


Figure 42. Photomicrograph of Euhedral Megaquartz with Anhydrite Inclusions Surrounded by a) Sparite, b) Barite Cements (X4, Crossed Nicols)

fibrous chalcedony (Figure 43) or alternation of fibrous chalcedony with microquartz (Figure 44). Many such nodules have megaquartz at their cores.

Cherts Associated with Limestones

Some limestones are partially replaced by megaquartz, chalcedonite (length fast chalcedony) and microquartz. The principal replacive texture consists of microquartz which replaces calc-micrite. Chalcedonite occurs as a precipitate in several locations: 1) molds once occupied by aragonite (as in gastropod shells) (Figure 45); 2) in internal cavities of gastropods and chara; and 3) in fenestrae and burrow cavities. Upon occasion gastropod shells are infilled with zebraic chalcedonite with discontinuous and alternating extinction (Figure 46). Megaquartz, the least common chert variety, occurs as a relatively late void-filling precipitate. It always postdates chalcedonite and records gradually decreasing concentrations of silica in pore waters.

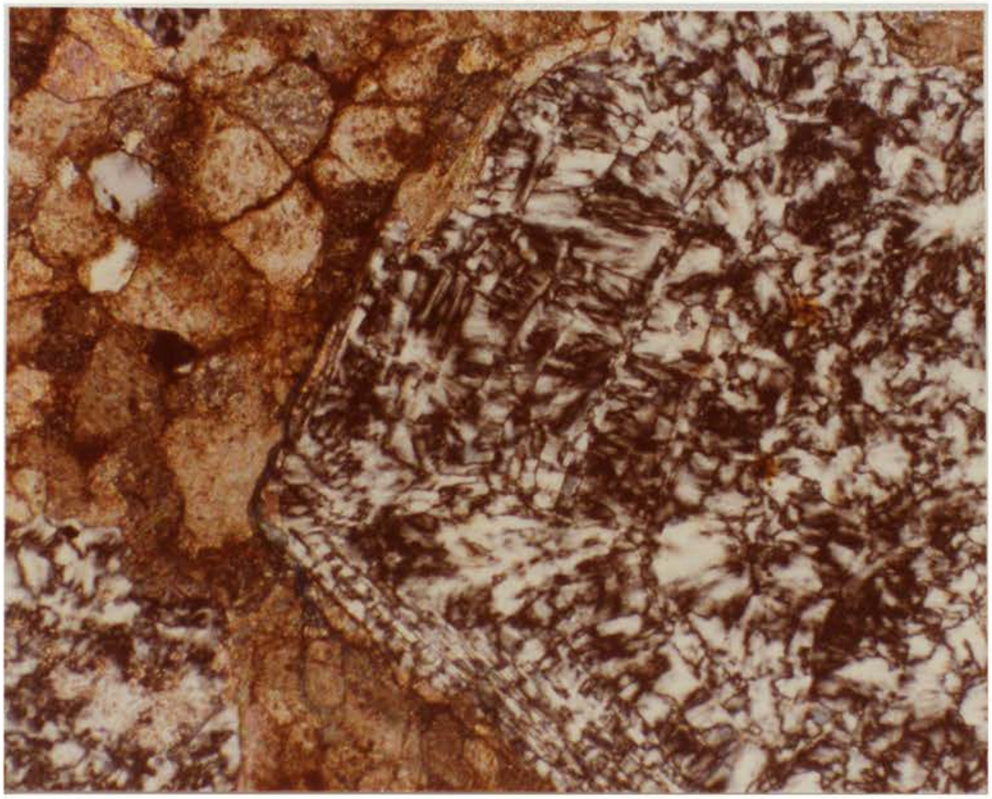


Figure 43. Photomicrograph of Equant Bands of Fibrous Chalcedony Forming Colloform Banding, the Nodule is Surrounded by Clay Rich Sparry Calcite (X10, Crossed Nicols)

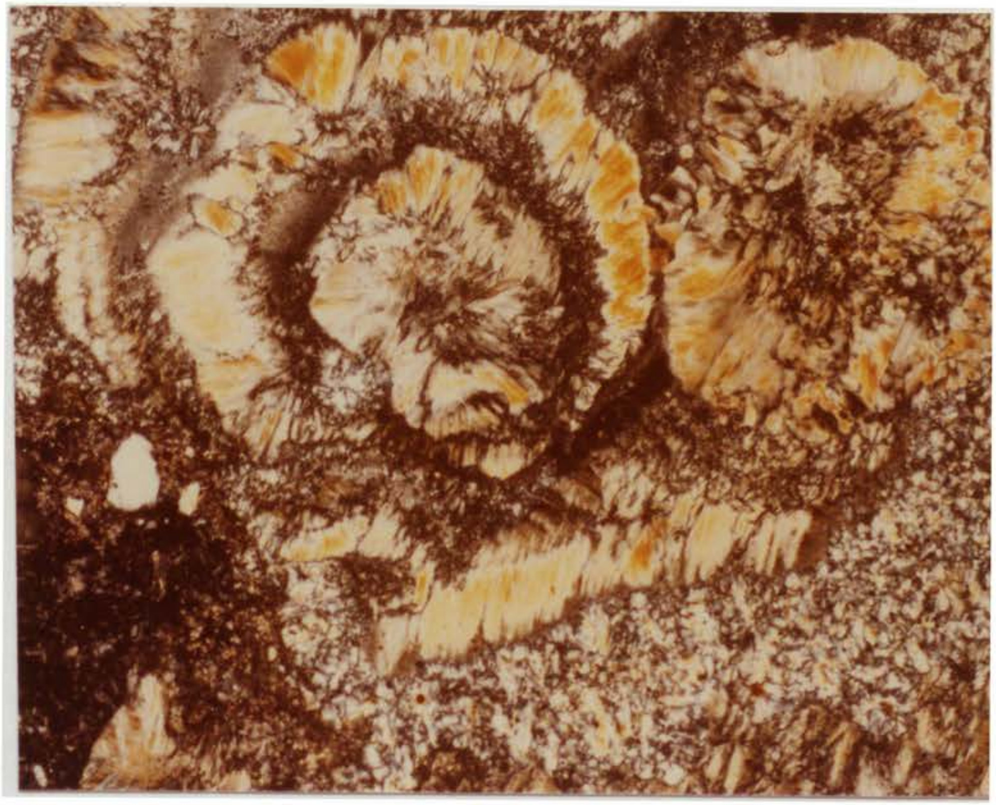


Figure 44. Photomicrograph of Colloform Texture Formed by Alternation of Fibrous Chalcedony and Microquartz (Thin Section is Thick, X4, Crossed Nicols)

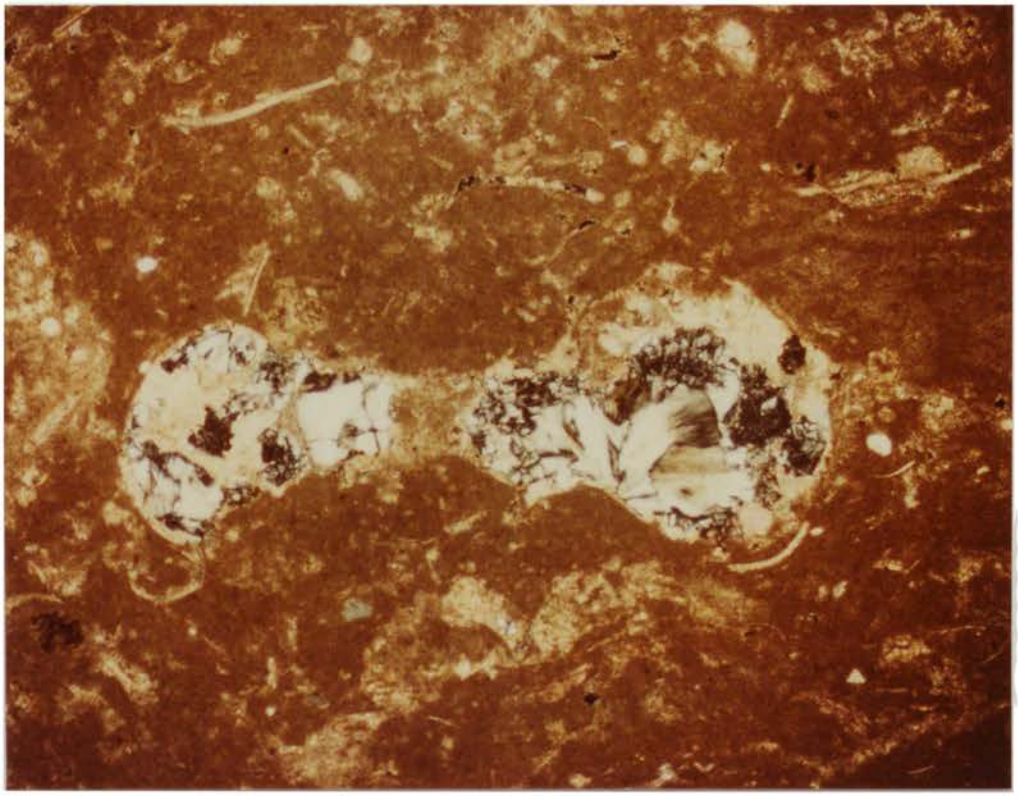


Figure 45. Photomicrograph of a Gastropod Partially Filled with Fibrous Chalcedony Surrounded by Micrite (Crossed Nicols, 4X)

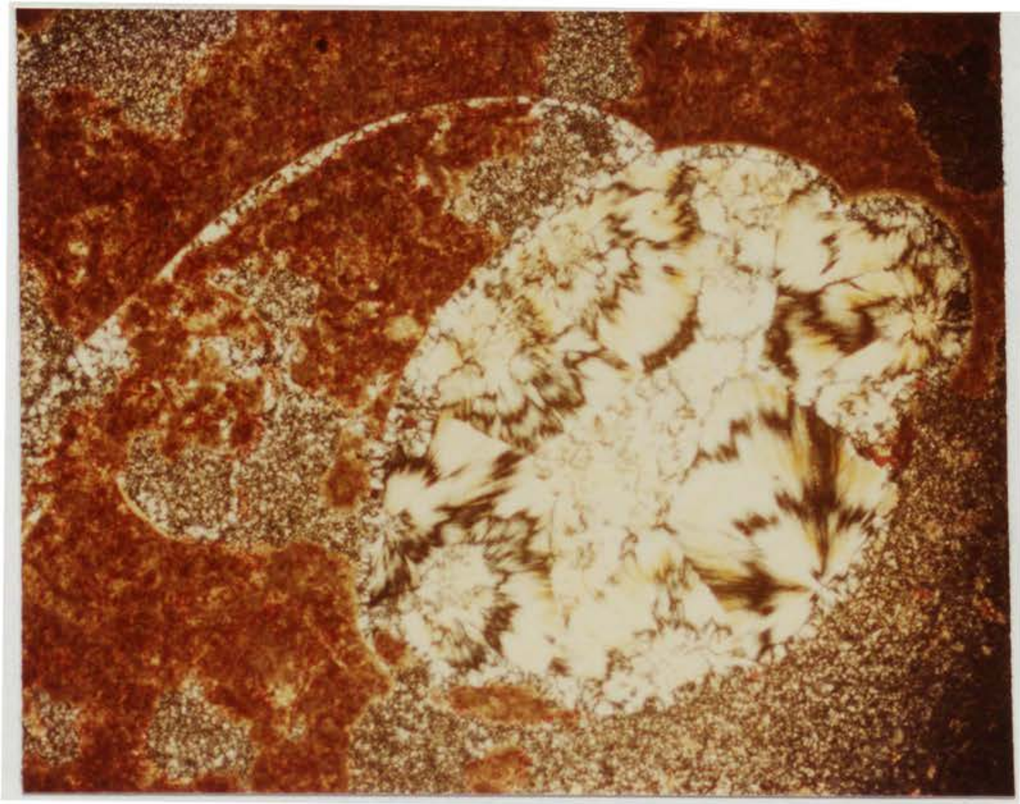


Figure 46. Photomicrograph of a Gastropod Filled with Zebraic Chalcedony, Microcrystalline Quartz is Replacing the Surrounding Micrite (Stained with Alizarin Red, Crossed Nicols, 4X)

CHAPTER VIII

PSEUDOMORPHS

Pseudomorphs after unknown evaporitic minerals are present throughout the lower portions of the Morrison in the vicinity of Canon City. Small accumulations are seen at Grape Creek and Garden Park, while the DMC section yielded the largest number of pseudomorphs. The original compositions of pseudomorphs pose a problem in that, while some have a selenite gypsum-like morphology (Figures 47 and 48), others do not.

DMC Section Pseudomorphs

The base of the measured section is located approximately 10 to 15 feet above the Ralston Creek/Morrison boundary (Appendix F). A limestone at the base of the measured section passes up into a chert horizon, then into shale. The first pseudomorph-rich horizon is in a limestone above this shale. The limestone passes up into mudstone, which in turn is overlain by two green highly calcareous pseudomorph-rich marl horizons. Another minor occurrence of pseudomorphs is located eight feet above the base of the section. Two types of pseudomorphed crystals are present, both replaced by calcite. The larger pseudomorphs are

Figure 47. Photograph of Gypsum-Type Pseudomorphs Located Mid-formation at Grape Creek.

Figure 48. Photograph of Gypsum-Type Pseudomorphs Found near the Base of the Formation at Garden Park.

between 4 and 5 cm long, and either radiate from a central point or, more commonly, have a disrupted appearance (Figure 49a). In thin section these larger crystals comprise a sparry calcite fabric. The second variety of pseudomorph is not apparent in hand specimen but in thin section can be seen to occur in large numbers in the green matrix surrounding the larger crystals. These smaller pseudomorphs appear as sparry calcite rhombohedra interspersed throughout a smectite-rich dolomite matrix (Figure 50). The rhombs are irregularly shaped, some having small birdtail-like protrusions on the corners. Possible interpretations for the origin of these crystals are that they are:

1) Products of dedolomitization

2) Recrystallized detrital calcite

3) Pseudomorphous replacement of an evaporitic mineral.

The rhombs do not have a true dolomite rhombohedral form (in particular dolomite rhombs do not have the birdtail-like terminations). Furthermore, the matrix surrounding the pseudomorphs contains much unaltered dolomicrite. These observations negate the dedolomitization hypothesis. Although the rhombohedra are somewhat irregular in shape, they show no signs of abrasion and in places interlock comprehensively, thus disproving the detrital hypothesis.

The preferred conclusion is that the rhombohedra are pseudomorphs after an evaporitive salt. Unusual salts are not well documented. However, salts with similar morphologies to those of the pseudomorphs are found in the

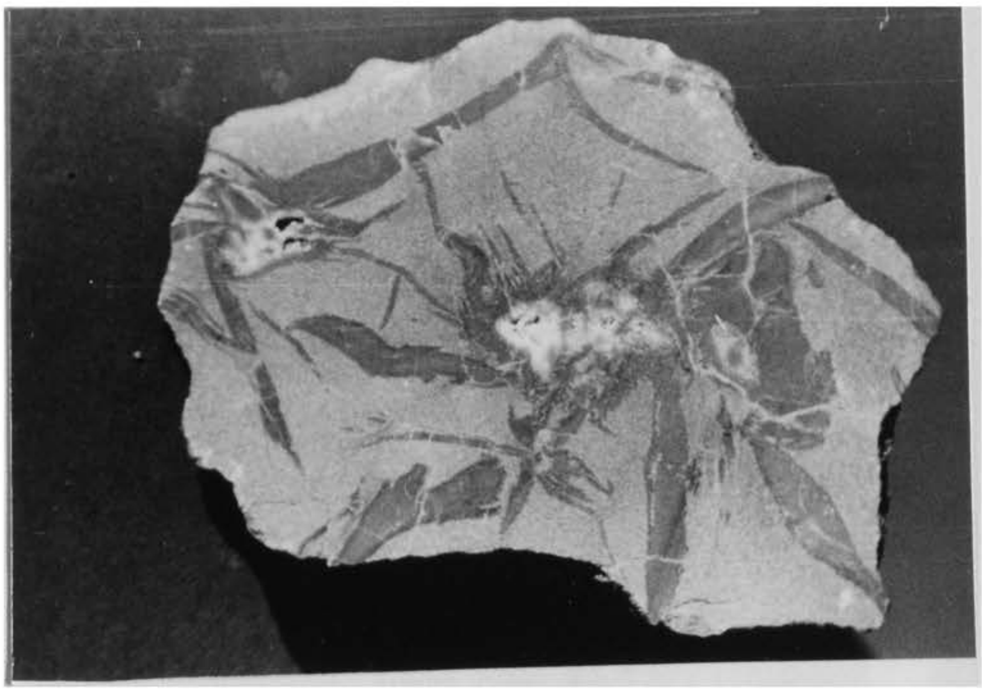


Figure 49a. Photograph of Trona-type Pseudomorphs Found Approximately 30 Feet from the Base of the Formation at the DMC Measured Section.

Figure 49b. Photograph of Trona Crystals from the Green River Formation (Photo from Bradley, 1969).

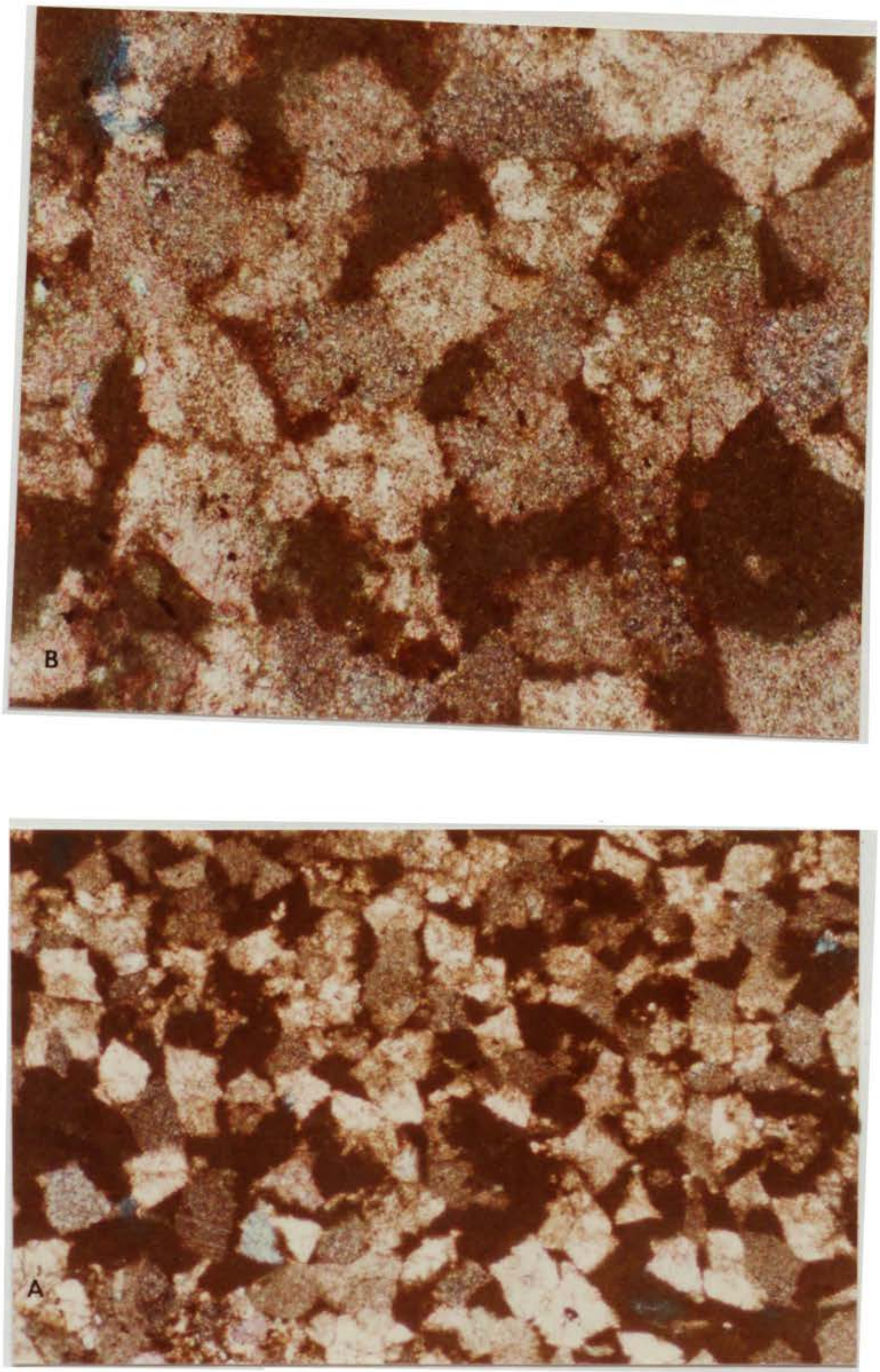


Figure 50. Photomicrographs of Gaylussite-type Pseudomorphs set in a Smectite-rich Dolomicrite Matrix a) Rhombs at X4 Magnification, b) Rhombs at X10 Magnification (Spar Stained with Alizarin Red, Crossed Nichols).

Green River Formation (Bradley and Eugster, 1969; Milton and Eugster, 1959). Pictures and descriptions (Figure 49b) of certain sodium carbonate minerals suggest a match with the Morrison pseudomorphs. In addition, Eugster and Hardie (1975) described calcite rhombs similar to those in the Morrison which they interpreted as a late diagenetic pseudomorphous replacement of an early diagenetic precursor (possibly shortite, pirssonite or gaylussite). While interstitial brines could have formed any of the three minerals (although shortite requires higher temperatures), gaylussite is a very common authigenic product in the muds of present-day alkaline lakes (Eugster and Hardie, 1975).

The larger pseudomorphs are possibly replacements of Trona ($Na_2CO_3 \cdot NaHCO_3 \cdot H_2O$) which crystallizes in the monocrystalline system. Trona is seen either as radiating crystals which form rosette-like clusters (Fahey, 1962), or as disaggregated crystals.

CHAPTER IX

PALEONTOLOGY

General

Vertebrate and invertebrate fossils are common in the Morrison Formation at many locations. Morrison invertebrates include: gastropods, pelecypods, and ostracods, while the vertebrate fauna consists of mammals, amphibians, fish, and an impressive variety of reptiles. The latter were the cause of a famous dispute between Marsh and Cope in the nineteenth century.

The first work on Morrison invertebrates was done by Meek and Hayden (1861). This work was followed by several outstanding summaries on invertebrate paleontology, including White (1886), Jones (1886), Logan (1900), Mook (1916), Roth (1934), Branson (1935), and Yen (1952).

Canon City Area

Invertebrate Paleontology

Extensive work has been done on the freshwater invertebrate fauna of the Morrison in the Canon City area. Table I is a tabulation of this fauna taken from Brady (1967), Yen (1952) and Branson (1935).

TABLE I

CLASSIFICATION OF INVERTEBRATE FAUNA FROM CANON CITY, COLORADO, AREA (AFTER BRADY, 1967, YEN, 1952, AND BRANSON, 1935)

Specimen List	Atlantosaurous Beds	Locality 4
Pelecypoda		
F. Unionidae		
Unio felchi White	X	
Unio toxonotus White	X	
Unio macropisthus White	X	
Unio iridoides White	X	
Unio lapilloides White	X	
Unio stewardi White	X	
Gastropoda		
F. Valvatidae		
Amplovalvata cyclostoma Yen		X
Amplovalvata scabrida Meek and Hayden	X	
F. Ellobiidae		
Mesauriculstra accelerata White	X	
Mesauriculstra morrisonensis Yen		X
Mesauriculstra morrisonensis ovalis Yen		X
F. Lymnaeidae		
Lymnaea ativuncula White	X	
Lymnaea morrisonensis Yen		X
Lymnaea consortis White	X	
Gyraulus veternus Meek and Hayden	X	
Ostracoda		
O. Podocopida		
F. Limnocytheridae		
Metacypris forbesi Jones	X	
Metacypris bradyi Jones	X	
Metacypris whitei Jones	X	
F. Cyprididae		
Cypris purbeckensis Forbes	X	
F. Darwinulidae		
Darwinula leguminella Forbes	X	

The earliest work published on the invertebrates in the Canon City area was by White in 1886. White described several genera of pelecypods and gastropods which he had collected from the so-called "Atlantosaurus" beds. These beds were named by Marsh and generally refer to the lower portions of the Morrison (where Marsh found dinosaur bones). In the same year, Jones described ostracods from the area. After these works, collections were made by several individuals, but remained undescribed until Yen (1952) tabulated them.

Results from this Study. While an invertebrate fauna occurs in most sections, the most prolific location is the Garden Park area. In this study, pelecypods of the genus *Unio* were found in the lower Morrison about 50 to 60 feet above the bases of the Garden Park and Grape Creek sections. Several species of gastropods (the most common being *Gyraulus veternus*, *Lymnea ativuncula* and *Mesauriculstra accelerata*) were obtained from several limestones located approximately 40 feet from the base of the formation. These gastropods have conoidal and evolute forms. Three genera of ostracods are associated with the Morrison carbonates at Canon City. Representatives of these ostracods are found throughout the formation in most of the carbonates but have not been identified specifically.

Fossil plants occur in some of the shales, especially the richly organic shales located near the base of the formation. Fern-like species of the *Cycadella* genus are most common. Another plant which is ubiquitous in most of the carbonates is *Chara*. It is particularly abundant in a distinctive orange weathering carbonate located 205 feet from the base of the Formation at Grape Creek.

Vertebrate Paleontology

The dinosaur remains are perhaps the most important fossils found in the Canon City area. They were discovered by the family of Mr. M. P. Felch in 1870 approximately 8 miles north of Canon City in the Garden Park area. The area was excavated by several workers, the most illustrious of whom are O. C. Marsh and E. D. Cope.

The fossils came from two horizons in the formation. One position is located approximately 100 to 125 feet from the base of the formation, and the other is found around 15 to 55 feet below the upper boundary of the formation. Marsh (1877-86), Hatch (1901), the Denver Museum of Natural History (1939) and the Cleveland Museum of Natural History (1954-57) obtained their specimens from the lower level, while Cope (1877) collected his at the upper level.

Table II gives a classification of vertebrate fauna taken from the Canon City area (Brady, 1976; Mook, 1972).

TABLE II

CLASSIFICATION OF THE VERTEBRATE FAUNA FROM CANON CITY, COLORADO, AREA (AFTER BRADY, 1967, AND MOOK, 1921)

Specimen List	Location within Atlantosaurous Beds	Morrison Upper Beds
Dinosauria:		
O. Saurischia		
S.O. Theropoda		
I.O. Coelurosauria		
Coelurus agilis Marsh	X	
Tichosteus lucasanus Cope		X
Tichosteus aequifacies Cope		X
I.O. Carnosauria		
Ceratosaurus nasicornis Marsh	X	
Creosaurus atrox Marsh	X	
Allosaurus fragilis Marsh	X	
Antrodemus lucaris Marsh	X	
Dryptosaurus trihedrodon Cope		X
Labrosaurus ferox Marsh	X	
S.O. Sauropodomorpha		
I.O. Sauropoda		
Amphicoelias altus Cope		X
Amphicoelias fragillimus Cope		X
Amphicoelias latus Cope		X
Brontosaurus sp.	X	
Diplodocus longus Marsh	X	
Haplocanthosaurus priscus Hatcher	X	
Haplocanthosaurus utterbacki Hatcher	X	
Apatosaurus sp.	X	
Brachiosaurus sp.	X	
Camarasaurus sp.	X	
Camarasaurus supremus Cope		X
Camarasaurus leptodirus Cope		X
Morosaurus agilis Marsh	X	
Epanterias amplexus Cope		X
Caulodon diversidens Cope		X
Caulodon leptoganus Cope		X
Symphyrophus musculosus Cope		X
Brachyrophus altarkansanus Cope		X

TABLE II (Continued)

Specimen List	Location within Atlantosaurous Beds	Morrison Upper Beds
O. Ornithischia		
S.O. Ornithopoda		
Laosaurus celer Marsh	X	
Laosaurus gracilus Marsh	X	
Camptosaurus medius Marsh	X	
S.O. Stegosauris		
Stegosaurus armatus (?) Marsh	X	
Stegosaurus discurus Cope		X
Stegosaurus stenops Marsh	X	
Hypsirhophus discurus Cope		X
Fish:		
O. Dipnoi		
Ceratodus guntheri Marsh	X	
Crocodiles:		
O. Crocodilia		
S.O. Mesosuchia		
Goniopholis felix Marsh	X	
Goniopholis lucasii Cope		X
Turtles:		
O. Chelonia		
S.O. Cryptodira		
Compsemys plicatulus Cope		X
S.O. Amphichelydia		
Probaena sculpta	X	
Glyptops plicatulus	X	
Mammalia:		
O. Pantotheria		
Kepolestes coloradensis Marsh	X	
Cryolestes gracilis Marsh	X	
O. Docodonta		
Docodon sp.	X	

CHAPTER X

DEPOSITIONAL ENVIRONMENTS OF THE MORRISON FORMATION

The Jurassic of the Western Interior

The Jurassic in the Western Interior of North America carries the imprint of four major marine transgressions, each having invaded from the north. The greatest accumulation of sediments occurred along the western margins of the Jurassic seas in southeastern Idaho, western Montana, western Wyoming and central Utah. However, the epicontinental seas never transgressed far into Colorado, and the only known evidence of Jurassic marine deposition is located in the northcentral and northwestern portions of the state. This transgression occurred during Callovian-Oxfordian times which in general was the most extensive (and final) marine transgression of the Jurassic. Following this event, non-marine conditions prevailed throughout the region. Suppositions as to the causes for this change are: 1) continued uplift of western (silciclastic) sources related to magmatic arc growth associated with tectonic activity; 2) low subsidence rates over the area as a whole; 3) a general global lowering of sea level due to a slow down in sea floor spreading.

This then was the paleotectonic setting at the commencement of Morrison deposition, which many authors believe to have occurred on a broad plain of low relief (Mook, 1912; Craig et al., 1955; Moberly, 1960; Dodson, 1980).

Paleolatitude

The Jurassic paleolatitude of the study area was approximately 33° N (Figure 51). Steiner (1983) plotted polar wandering paths for the Morrison in the area of the Colorado Plateau (Figure 52). She found that early in the deposition of the Morrison, paleolatitudes for the region were between 23° and 28° N. Late in the depositional history of the Morrison (Kimmeridgian) the paleolatitudes had changed to 33° N to 38° N from north to south across the plateau. This indicates that the plate on which the Morrison was deposited was moving rapidly during this time. This plate motion is related on a regional scale to the late Jurassic subduction zone to the west (Figure 53) and globally to the breakup of Pangea. The magmatic arc and positive areas of the Western Cordillera developed along the eastern border of the subduction zone. These positive areas formed one of the source areas (particularly for the conglomerates of the Colorado Plateau) of the Morrison Formation.

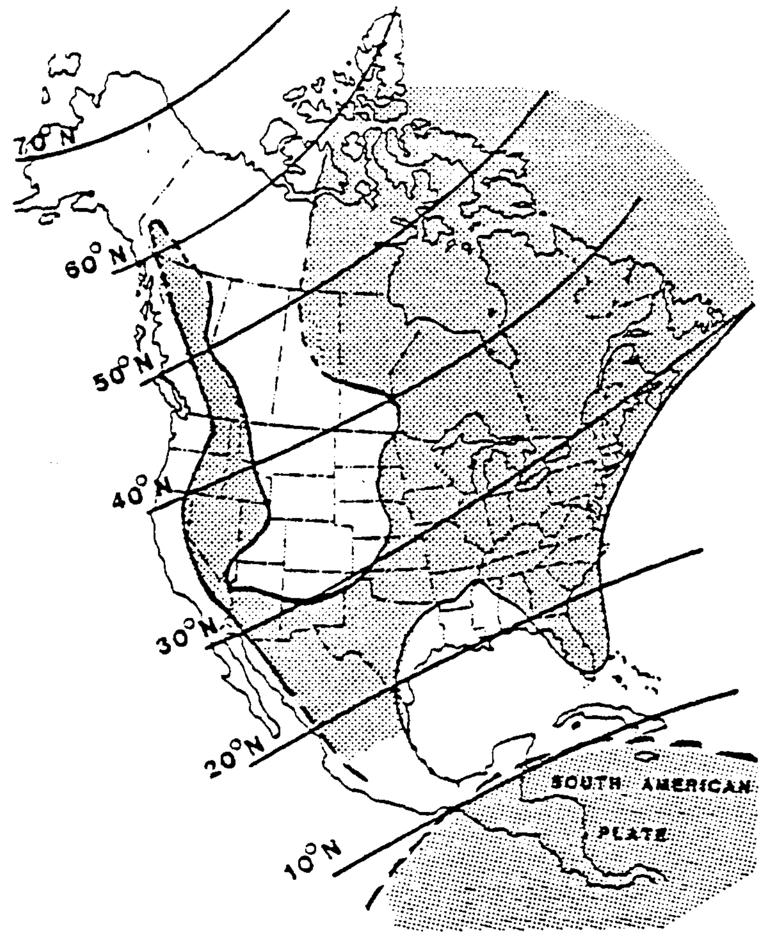


Figure 51. Paleogeographic Map of North America Showing the Western Interior and Paleolatitudes of the Late Jurassic (from Brenner, 1983).

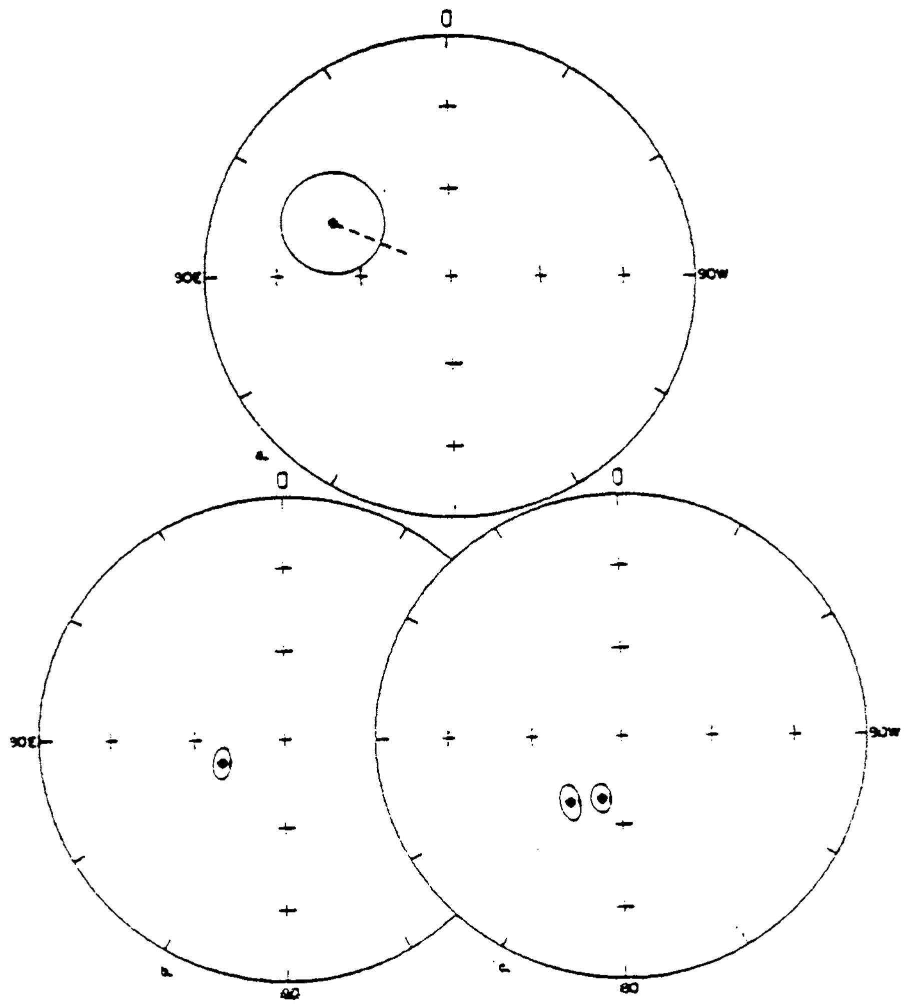


Figure 52. Pole Positions and Confidence Limits for Early through Late Jurassic Formations. a) Navajo Formation; b) Summerville Formation; c) Morrison Formation (Modified from Steiner, 1983).

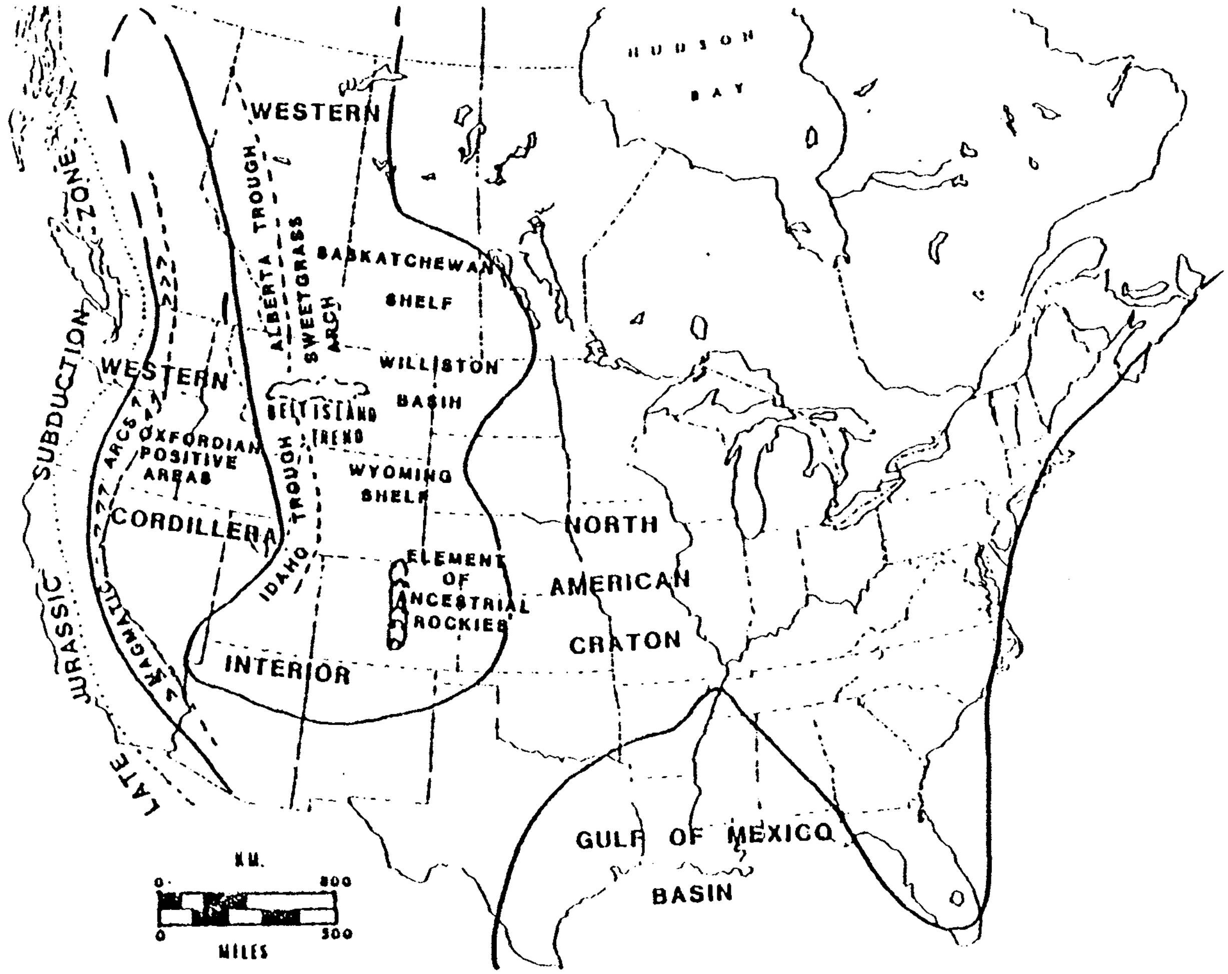


Figure 53. Late Jurassic Tectonic Elements and Locations of the Western Cordillera, Western Interior, North America Craton and the Gulf of Mexico Basin (Modified from Brenner, 1983).

Paleoclimate

Jurassic and Cretaceous times are generally considered to have been glacial-free, with no polar ice caps. Oxygen isotope data suggest that temperatures at polar latitudes may have reached 10° C (Habicht, 1979). Equatorial mean annual temperatures were slightly above 30° C. For the paleolatitudes at which the Morrison was deposited the mean surface temperature was approximately 28° C at the beginning of Kimmeridgian time. However, as previously noted, the area drifted gradually northward and by late Portlandian time the mean temperature had probably dropped to around 25° C. During this relatively mobile time, the climate gradually became more humid.

Boundaries and Source Areas

The boundaries of the Morrison are closely related to those of the Western Interior (Figure 53). The Western Interior is bounded by the magmatic arc to the west, the North American Craton to the east and the Uncompahgre Uplift to the South.

The major sources of sediment for the entire Morrison Formation were: 1) a western source from Idaho and Nevada (related to uplift east of the magmatic arc); 2) a northeastern source from the Transcontinental Arch (extending from northeasternmost to west central Colorado); and 3) a southern source from the Uncompahgre Uplift (extending from westernmost Colorado southeast into New

Mexico). The Transcontinental Arch and the Uncompahgre Uplift limited the southern extent of the Jurassic marine shorelines and influenced the overall distribution of sediments throughout the period (Berman, 1980).

Granite and metamorphic rock clasts found in thin section closely resemble those in the crystalline rocks located west of Canon City. Paleocurrent data from the Canon City area indicates a northern source. This evidence, along with the relative positioning of the Ancestral Rocky Mountains and the Transcontinental Arch, imply these entities were the major sources of Morrison sediment in the vicinity of Canon City.

Ancestral Rocky Mountains

Tectonic activity during the formation of the Ancestral Rocky Mountains involved block faulting during the late Paleozoic. This faulting reactivated Precambrian trends.

The Ancestral Rockies were entities of low relief which can be best visualized as monadnocks with gentle slopes. It was not until the Cretaceous that further uplift of the region took place.

The Ancestral Rocky Mountains, in the vicinity of Canon City, were composed of Precambrian igneous and metamorphic crystalline basement overlain by a sedimentary veneer which is mostly of Ordovician age. Overlying these rocks are Pennsylvanian and lower Jurassic fanglomerates, both of which are composed of detritus from the underlying Ancestral terrain. Despite the presence of these fanglomerates, it is clear from direct field observation that both the crystalline basement and Ordovician carbonates outcropped at the commencement of Morrison deposition.

Collectively, these source rocks could have produced not only all the extraformational detritus in the Morrison, but also the ions in solutions which were required to form the chemical precipitates and the early diagenetic minerals present. For example:

Silicates ---> silica

Plagioclase ---> Ca, HCO_3

Feldspar ---> Na, K

Depositional Rates

The Morrison is Kimmeridgian-Portlandian (c. 150 to 140 Myr BP). The Formation represents no more than 10 Myr of sediment accumulation (quite possibly less). Approximate calculations using the maximum thickness of the Morrison in the Canon City area give a near estimate of an overall sediment entrapment rate of 0.01 mm/yr. This very slow rate is based on the assumption that continuous sedimentation rates prevailed. However, this is clearly not the case, as deposition of the Morrison was influenced by various sedimentation processes; it is obvious that all these processes have the potential to produce sediment at a much greater rate than 0.01 mm/yr.

Therefore, the significance of this number is that it indicates a long surface residence time and much reworking for the sediments. Further evidence for long residence times is provided by the maturity of the sandstones (even though the source is very close), the number and variety of intraformational clasts (see Chapters IV and V), and the disarticulation of the dinosaur bones found in the area. This disarticulation indicates pre-burial taphonomic alteration. Dodson (1980) proposed that dinosaur carcasses decomposed in open areas on dry land or spent substantial amounts of time in stream channels prior to final burial. As a result, massed accumulations of fossils with remains of between 20 and 60 individuals preserved ("fossil graveyards") are commonly found in the formation.

Lacustrine Deposits in the Morrison

Several different types of lacustrine environments are believed to have been present during the deposition of the Morrison Formation. The following facies have been recognized:

1) open lacustrine stratified deposits
2) open lacustrine non-stratified deposits
3) lacustrine margin/shallow lake deposits
4) mixed lacustrine margin/distal (bottomset) deltaic deposits
5) coincident margin deposits (Donovan, 1975)
6) sulphate-rich playa deposits
7) sodium-rich playa deposits.

The controls on lake type are various and relate to each other in complex ways. These controls include:

a) thermal stratification

b) water depth (effective wave base)

c) nature of the lake margin

d) the presence or absence of a through-going drainage system

e) the ionic concentration of lake water

f) the types of ion present

g) the type of climate

With respect to climate, it is probable that the climate became more humid in the later history of Morrison deposition. This conclusion is supported both by the paleolatitudinal drift of the area and, independently, by the more common occurrence of evaporitic deposits in the lower Morrison. The presence of non-glacial varves in lacustrine facies deposited below the wave base suggests that the climate became markably seasonal.

Open Lacustrine Stratified Deposits

The development of thermal stratification in relatively deep lakes is a widely attested phenomena. This model is summarized as follows (Figure 54). In temperate lakes, thermal stratification begins in the spring after ice on the lake thaws and the lake water reaches a stable, isothermal temperature of 4^{o} C. The combined influence of surface heating and wind mixing creates a shallow layer of warmer isothermal water. Below this layer, hydrostatic stability

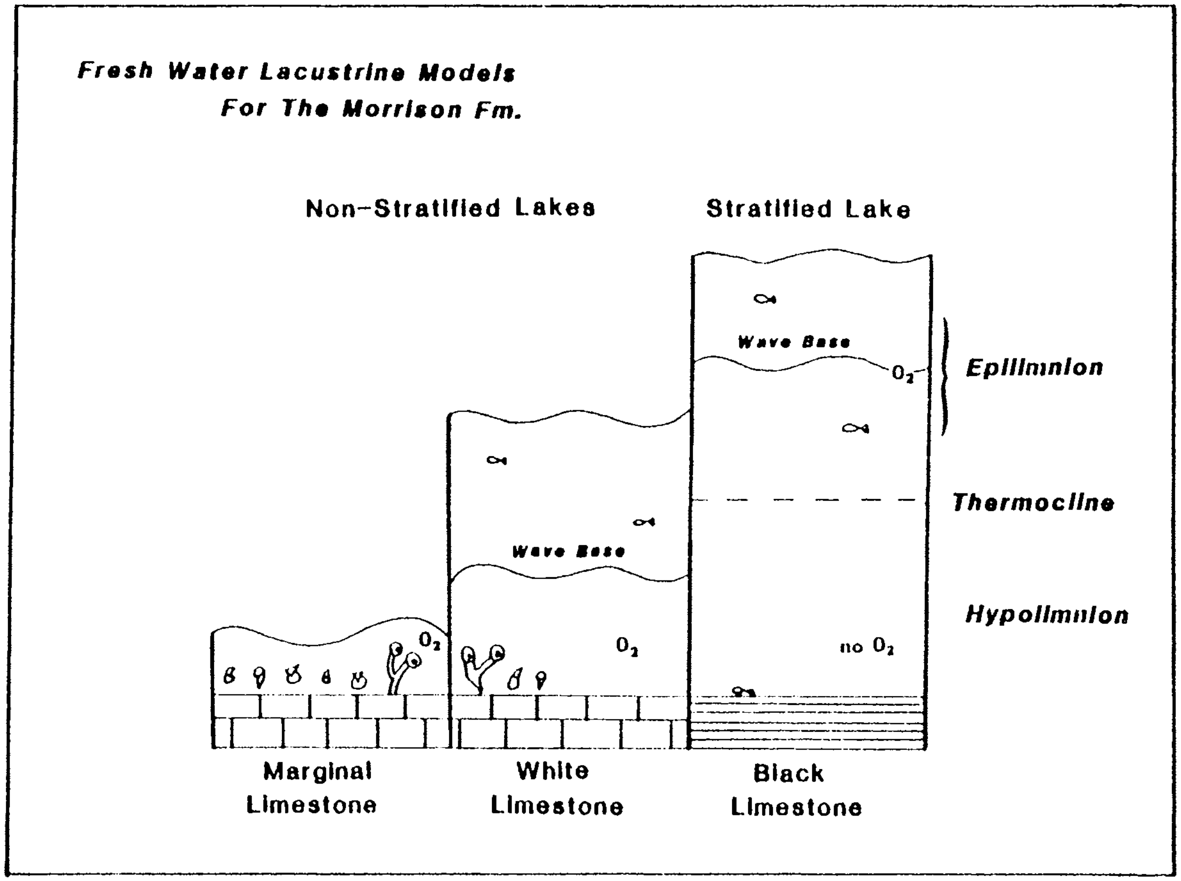


Figure 54. Fresh Water Lacustrine Models Illustrating Elements of Stratified and Non-Stratified Morrison Lakes

increases and a stable layer termed the thermocline develops (Ragotzkie, 1978). The thermocline separates the warmer oxygenated layer (epilimnion) from the deeper cooler anoxic layer (hypolimnion). Periods of high wind deepen mixing, resulting in a deeper thermocline. Lighter winds and continued heating result in yet another shallower thermocline. Therefore, at any one period of time, several thermoclines may coexist (Ragotzkie, 1978). The warmer waters of the epilimnion eventually consolidate and a single thermocline develops and exists throughout the summer and early fall (Figure 54). As the lake water cools, a layer of cooler denser water develops at the surface. These denser waters will descend and mix with the warmer waters of the epilimnion. This process will continue until the temperature of the epilimnion is the same as the hypolimnion. Winds will eventually mix the two, oxidating the anoxic hypolimnion and creating an isothermally stable lake.

Algal bloom occurs at times when lake stratification is well developed. These blooms lead to increased pH and a significant decrease in dissolved CO_2 (taken from the lake water by algae during photosynthesis); both of these conditions are conducive to the precipitation of low-Mg calcite. As algae die and sink to the bottom, they form organic carbon-rich layers. Slow anaerobic decomposition of algae in the hypolimnion produces slightly acidic conditions which tend to both weaken the shells of the ostracods and

Chara by dissolution and also lead to dissolution of some of the calcite precipitated during algal bloom. Thus when seasonal turnover occurs, the epilimnion of the lake waters is enriched with calcium, which is available for precipitation during the next bloom.

The siliciclastic content is lower than that seen in other limestones. Siliciclastics are attributed to both wind blown silt and to micro-turbidity flows.

This model has been widely applied to ancient lake sediments (Donovan, 1975; Ryder et al., 1976). In the Morrison, the facies is best exemplified by the "black" limestone. The "black" limestone is a laminated, kerogen-rich rock with fine particulate siliciclastics dispersed throughout. Minor amounts of ostracods and Chara are present, together with fish fins, scales and at least one complete fossil fish head. This lithology is attributed to the deepest and most distal portion of the fresh water open lacustrine environment.

Open Lacustrine Non-Stratified Deposits

This environment is similar to that of the stratified facies in that carbonate is deposited by an algal bloom mechanism in quiet waters below the effective wave base. However, either because of frequent overturn or because stratification never developed, the bottom waters of the lake were sufficiently oxygenated to recycle organic carbon. As a result, the deposits may be varved but are light in color as they contain little if any organic carbon. Other features developed in the facies may include fenestrae due to gas escape from the sediment following early oxidation and evidence of a bottom-dwelling fauna (which could not exist in a stratified lake).

The best example of this facies in the Morrison of the Canon City area is provided by the "white" limestone. This rock is a finely laminated carbonate with a widely dispersed siliciclastic content. Fenestrae are common and the bed contains at least four species of gastropods. Slump structures are present in several areas and indicate an unstable bottom (a feature common in lake beds). Dessication cracks on the top surface indicate that the white limestone lake finally dried up completely in some areas.

Lacustrine Margin/Shallow Lake Deposits

In the two facies previously discussed, the preservation of delicate lamination indicates that the lake bottom was below effective wave base. In a small lake this depth may not be too great. When the lake is shallower than the effective wave base, frequent stirring of the bottommuds destroys any lamination. The source of micrite may be algal bloom, but because the lake waters are thoroughly mixed no trace of organic carbon is preserved.

It is probable that most of the thin micritic limestones of the Morrison record an environment of this type. These rocks, although thin, are internally massive. They contain various amounts of siliciclastics and form a gradational series of rocks with the marls and marlstones which are such a common feature of the lower part of the Morrison.

Oolitic and pelloid-rich limestones form additional lake deposits. Formation of the ooids is linked with oscilation of the lake shore. The peloids may be formed by lake shore mud having been ripped up and subsequently rolled into pellet-form by shore line oscilation, or they may be of fecal origin. Both of these rock types are associated with the lake shore margin, and in the Morrison they grade lakeward into open lacustrine rocks (Figure 55).

Mixed Lacustrine Margin/Distal (Bottom Set) Deltaic Deposits

Distal deltaic sediments in the form of fine sand and silts often mix with rapidly precipitating low-Mg calcite to form marlstones and more distally marls (Figure 55). Siliciclastic grains grade in size and number distally. Also, as siliciclastic content decreases, carbonate increases. Fossils and fossil hash are associated with these sediments. Slump features may be associated with the more proximal marlstones.

Marlstones and marls are ubiquitous in the lower portions of the Morrison at Canon City. While many do show the aforementioned characteristics, most are more likely to

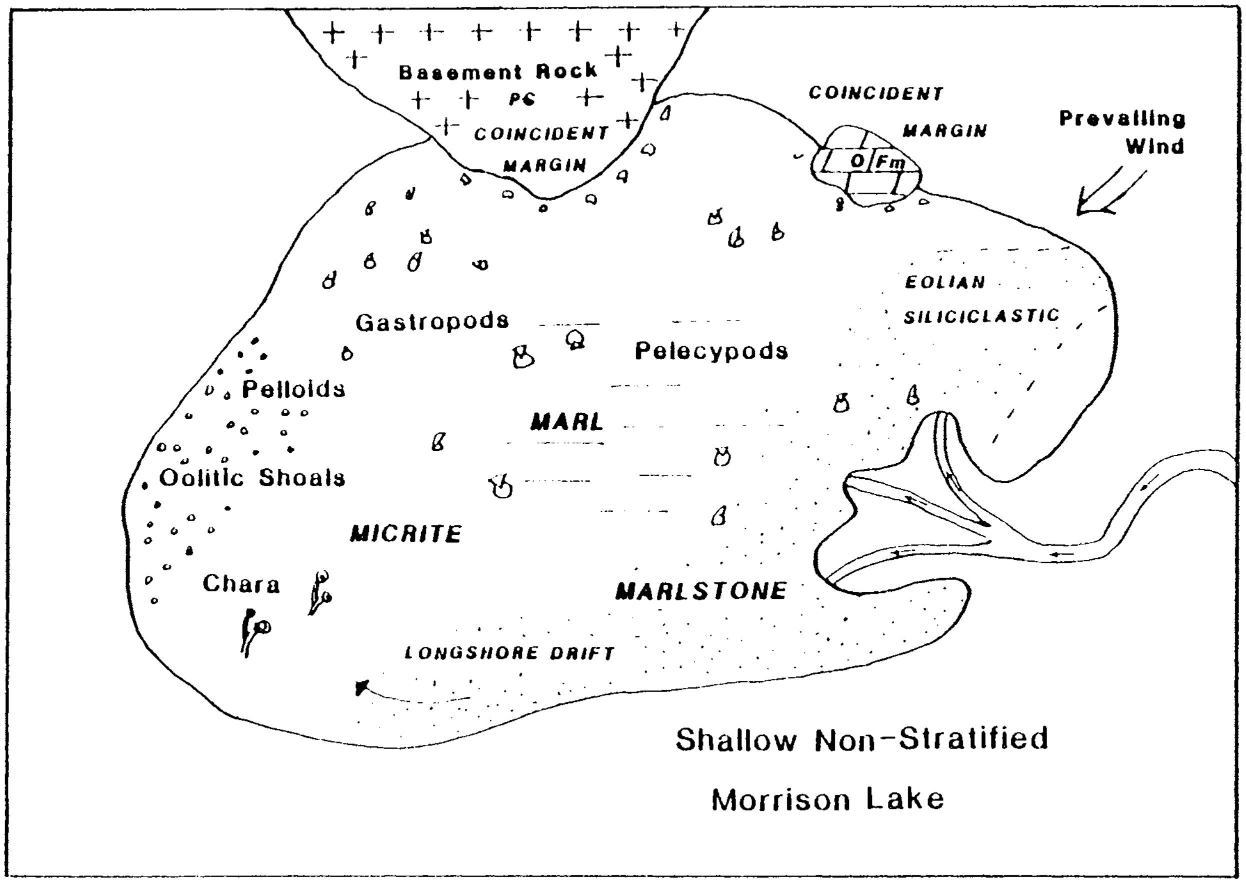


Figure 55. Facies Found in Shallow Non-stratified Morrison Lakes

have been formed on the carbonate mud flats surrounding the lake. The most prominent feature associated with the mud flats marlstones is ripple-marked surfaces.

Coincident Margin Deposits

During high water periods the lake margin can become coincident with the margin of the sedimentary basin (Figure 55) (Donovan, 1975). During these times, clastic supply is reduced and marginal topography is drowned. Unconformities between lacustrine deposits and basement or pre-existing underlying sedimentary rocks develop.

In the Morrison of Canon City, both types of unconformity exist. In the area of Bumback Gulch northwest of the city, limestones (similar in nature to the "white" limestone) onlap onto granite. Local granite-pebble conglomerates are banked against the steeper topography. The Morrison limestones also unconformably onlap onto the Ordovician Harding Formation north of Grape Creek.

Playa Environments

Eugster and Hardie (1978) stated three conditions necessary for the formation of an inland sabkha (playa): 1) outflow of water must be restricted (a hydrologically closed basin); 2) evaporation must exceed inflow; and 3) inflow must be sufficient to sustain a standing body of water. While neither closed basins or evaporative conditions are uncommon, when coupled with conditions of plentiful inflow (springs, ground water and rivers), the situation becomes less common. The most favorable environment for the development of a playa lake is that found in rain shadowed basins and plains. Here mountains act as precipitation traps, yet shield the valley floors, increasing their aridity.

The central ephemeral playa lake is generally surrounded by carbonate mud flats which are fringed by arid fans. During times of dessication, evaporative minerals grow in the efflorescent crusts on the playa lake bottoms and in interstitial pores and mud cracks on the mud flats.

Playa Sediments in the Morrison

As previously mentioned, the climate during the beginning of Morrison time was semi-arid to arid. A partial rain shadow was formed by the Ancestral Rocky Mountains; however, its effectiveness was limited due to their low relief.

The playa environments which developed can be envisioned as playa mud flats surrounding a small central playa lake (Figure 56). Two types of plays developed: 1) a sulphate-rich playa; and 2) a sodium carbonate-rich playa.

Sulphate-Rich Playas

At the base and near the middle of the formation, selenite-like pseudomorphs are found. These pseudomorphs are found in micritic limestones and marly sandstones. The

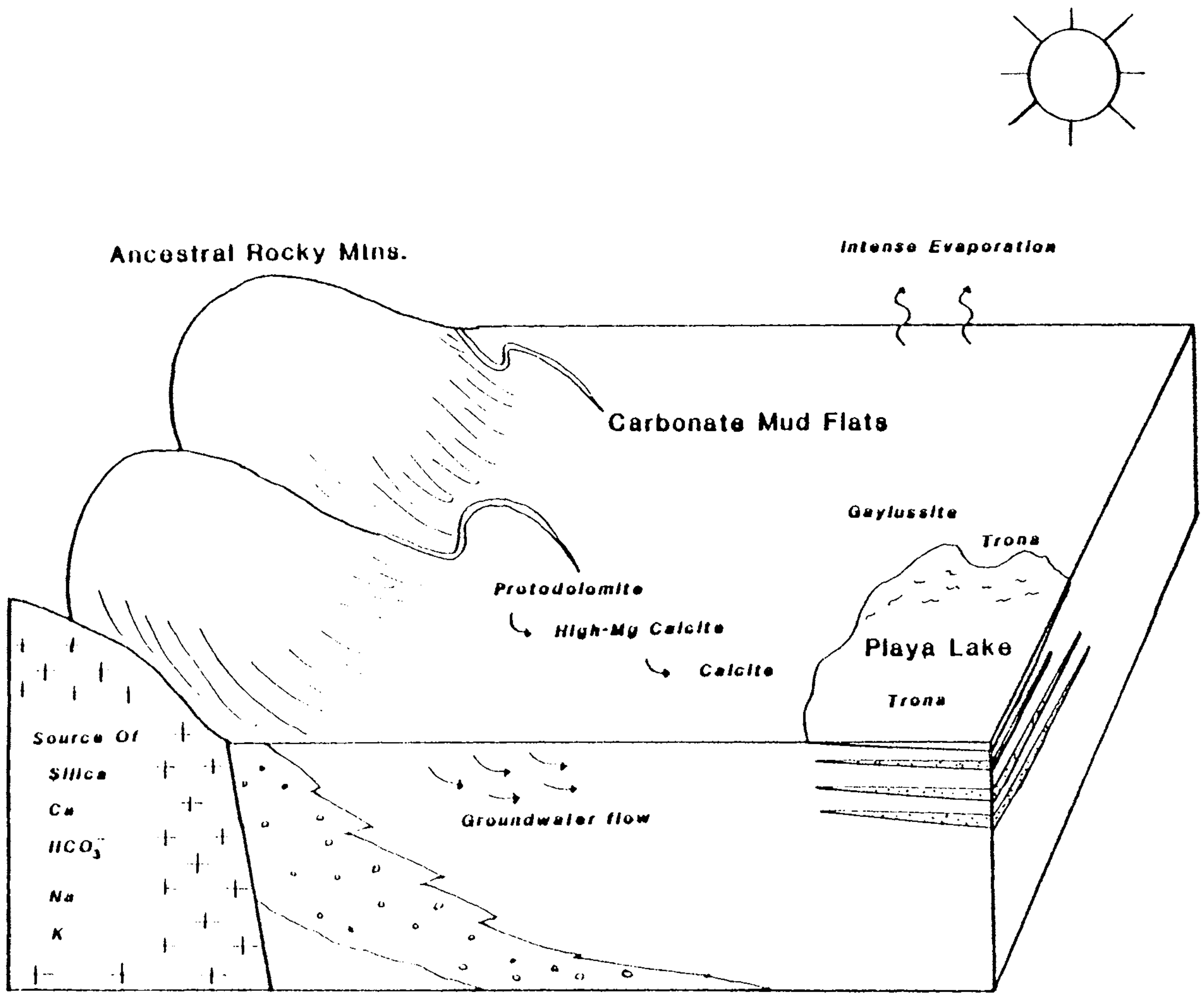


Figure 56. Schematic Block Diagram of a Sodium-Carbonate-Rich Playa Lake Setting

source of the sulphate-rich brines for the sulphates at the base of the Morrison was probably the underlying gypsiferous Ralston Creek sediments. The source for those found near mid-formation is not as clear. The crystals of selenite grew in the dessicated playa floor (much like those of the Great Salt Plains in north central Oklahoma). These crystals were later replaced by a variety of silicas, including length-slow chalcedony (BOC section) and elsewhere by calcite.

Sodium-Rich Playas

Calcite-filled pseudomorphs resembling trona ($Na_2CO_3NaHCO_3 \cdot 2H_2O$, Figure 48) and gaylussite ($CaCO_3Na_2CO_3 \cdot 5H_2O$, Figure 50) are found in the northeastern portion of the study area. The larger, radiating trona pseudomorphs (4 to 5 cm) form an interlocking network of crystals; gaylussite rhombs and smectite-rich dolomicritic muds infill the interstices between crystals.

Trona most commonly forms as efflorescent crusts on the dessicated playa lake floor, although it can also form on the mud flats. Sodium-rich brine is left in the interstices between crystals and during times when the lake onlaps onto the mud flats or the lake floor is flooded, carbonate mud and silts are added to the interstices. The addition of carbonate and the freshening of the system allows gaylussite to form (processes discussed in the following chapter). During the rainy season as the lake surface completely floods, clastic material is deposited (in the form of mud and silt partings) and trona is partly dissolved. Most of the trona is recycled on a seasonal basis (Eugster and Hardie, 1978). This recycling can be observed in the rounded appearance of some of the gaylussite rhombs seen in thin section.

Sandstones

Siliciclastic sandstones constitute the second most abundant lithology seen in the Morrison of the Canon City area. While their mineralogy is consistently quartz-rich (i.e. mature), the sandstone bodies show evidence for varying depositional environments.

Meandering River Channel Sandstones: General Summary

High-sinuosity meandering river channels are favored by comparatively low gradients and discharge. They typically develop in rivers with cohesive banks, with high suspended load/bed load ratio and relatively steady discharge.

Flow in meander bends is helicoidal (Reading, 1980), and is considered to be the most important factor affecting sedimentation. The flow mechanism is such that the surface flow is toward the outer bank (Figure 57). Maximum velocities are located along the outer bank (Reading, 1980). This flow pattern is significant in that it predicates that the outer, concave bank is the site of erosion and the

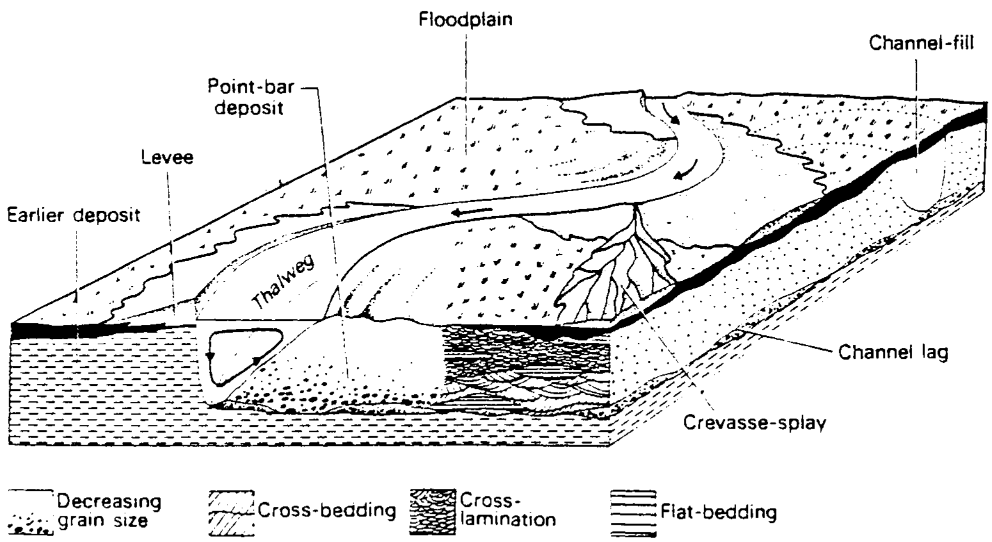


Figure 57. The Classical Point Bar Model for a Meandering Stream (From Reading, 1980)

inner, convex bank is the site of deposition. Material eroded from the cut bank tends to be deposited on the convex bank of the next meander downstream and not the one opposite itself (Reineck and Singh, 1980).

Sedimentation in meandering streams occurs on point bars, located on the convex bank. The flow pattern around the meander bend is the key to understanding deposition on the surface of the point bar. The upslope component of the helical flow is characterized by diminishing velocities, which gives upslope reduction of grain size (Reading, 1980). Lateral migration of the point bar surface gives a tabular sand unit overlying a near-horizontal erosion surface, which may have a channel lag conglomerate at its base. The vertical profile of this unit shows both an upward fining of grain size and and upwards reduction of set size in crossbeds (i.e., trough crossbedding grades into ripple cross-lamination or parallel lamination).

As lateral accretion of the point bar continues, epsilon crossbedding (longitudinal crossbedding) develops. Epsilon crossbedding shows a direction of dip at right angles to the direction derived from associated ripple and trough cross stratification. In essence, individual epsilon crossbeds represent stages in the migration of the face of the point bar (Reineck and Singh, 1980).

A meandering channel occupies only a small portion of the meander belt complex. The latter consists of active channels, abandoned channels and near channel subenvironments (Reading, 1980). A meander channel shifts position across the alluvial plain as a function of the river's sinuosity. High sinuosity is related to a high suspended load. Meander migration will continue either until large scale avulsion takes place or until an individual meander becomes stabilized by channel cut-off (Reading, 1980). In the latter case a clay plug may record the cut-off. Avulsion of a meander belt usually is initiated during times of flood when the channel bank is breached and the belt "avulses" into a new course.

Meandering rivers of lower sinosity have fewer cut-offs and clay plugs and are considered less stable (Reading, 1980). They sweep across their alluvial plain frequently and in this aspect of their behavior resemble low sinuosity braided rivers. It should be borne in mind that a gradation between high and low sinuosity systems exists.

Many investigators have concerned themselves with the identification and differentiation of ancient meandering and braided stream deposits. While many criteria have been developed, it should be noted that various combinations of these criteria can be exhibited by an individual stream along its course in conditions considered "normal" to the stream type. Moody-Stuart (1966) listed useful criteria which are common in meandering rivers:

1) Sand bodies are often associated with fine-grained channel fill deposits. The original channel form is present.

2) "Longitudinal" (epsilon) crossbedding produced from migration of point bars is well developed.

3) Thin natural levee deposits may be present on the top of point bar deposits.

4) Paleocurrent data shows wide variation.

Other important criteria noted by several authors are as follows:

a) High shale and clay/sand ratio.

b) Point bar deposits are cut deep into shales.

c) Limited lateral persistence, as compared to braided river deposits; sand bodies are tabular and relatively discontinuous due to the stability of the meander.

Meandering Channel Deposits in the Morrison

The Morrison has been described as having developed on a broad low-relief plain (Moberly, 1960; Dodson, 1980). As previously discussed, no tectonism took place in the area during the Morrison time frame and hence the upward increase in sandstone content is more likely to reflect the gradual increase in precipitation which marked the Morrison time period (as noted). In all the sections examined, the Morrison is characterized by thick passages of shale alternating with sandstones or limestones. This characteristic illustrates the existence of the high shale and clay/sand ratio required for development of cohesive bank materials.

Morrison sandstones are relatively fine grained, although some contain isolated basal conglomerates lenses, interpreted as channel lags. Most of the sand bodies fine upwards and generally show an upwards reduction in crossbedding set size. Some of the thicker sandstones are interpreted as multistoried on the basis of several channel lag horizons and more complex fining upward profiles. Epsilon crossbedding is well developed in several places, but is most spectacularly exposed at Garden Park in a point bar located approximately 140 feet from the base of the formation (Figure 11).

This point bar has been interpreted in a paper written with R. N. Donovan and presented in Appendix F. The most pertinent conclusion drawn by this paper is that most of the Morrison rivers were highly sinuous but of modest size and discharge.

Conclusions drawn in this paper are applicable to most Morrison sandstones. Generally, sand bodies are discontinuous and show little lateral persistence. Most of the sand bodies are small, although isolated larger entities are located in the highest levels of the formations. Figure 58, while illustrating great channel sinuosity because of the variability of the paleocurrent data obtained, also shows that most of the drainage in the Canon City area was from the north.

The interpretation given here supports the traditional view that the Morrison flood plain was tranversed by small meandering streams with high suspended loads. Dodson (1980) has speculated that if any of the rivers were large when they reached the flat Morrison plain, they would have split

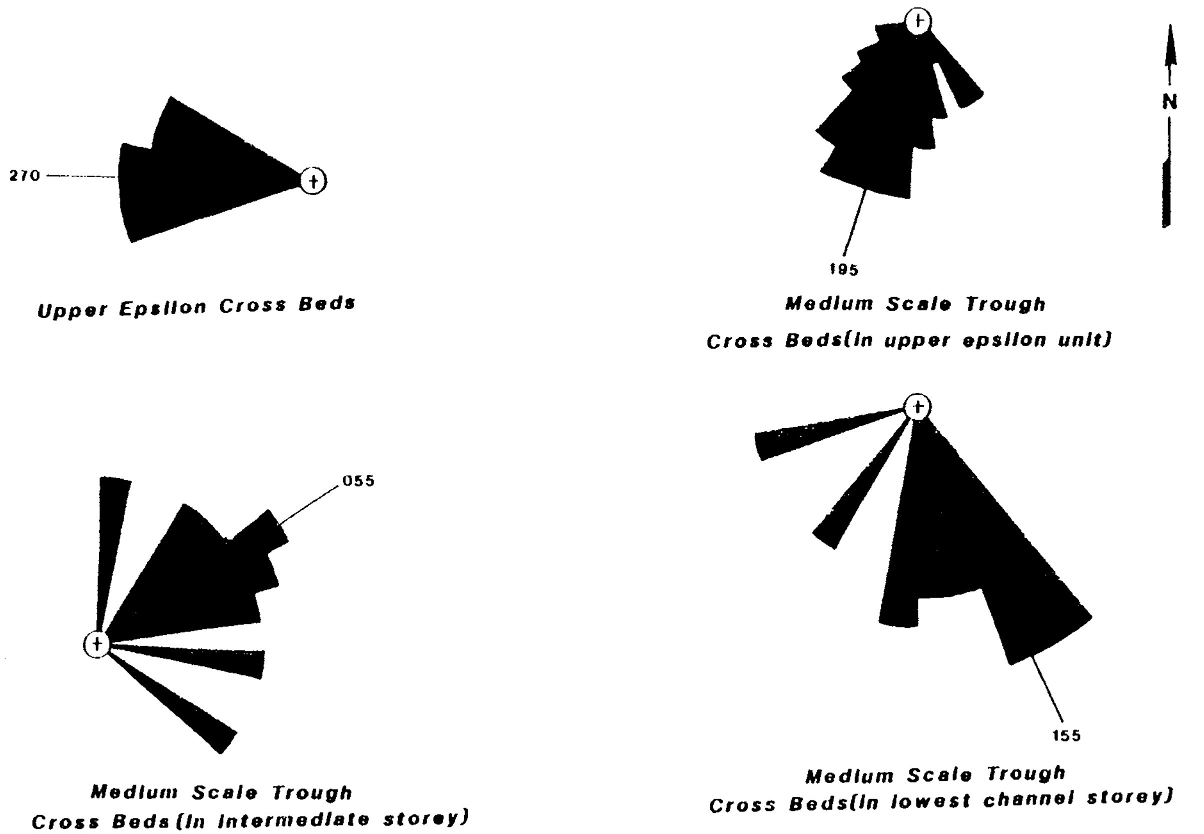


Figure 58. Cummulative Paleocurrent Data for Morrison Sandstones in the Study Area (Data Accumulated with Cooperation of R. N. Donovan)

into a complex of small highly sinuous rivers. This interpretation cannot be sustained or negated by evidence seen in this study. The limited lateral extent of many of the channels does suggest frequent avulsion, probably because of low gradient.

The Fluvial Floodplain Environment: Levee Deposits

Meandering river systems have complex overbank environments. Levees are the most distinctive overbank environment; they are sites of inter-channel deposition located adjacent to the channel. Levees form ridges on the concave erosional banks of meandering rivers which slope away from the channel (Reading, 1980). They are submerged only at flood stage. Levees result from fallout of the coarser part of the suspended load as water escapes from the channel onto the overbank area. As the water loses competence coarser sands and silts further out on the flood plain. Climbing ripples are a common feature of the levees and record loss of stream power (and hence competence) on the flood plain.

Levee Deposits in the Morrison

Figure 59 shows a measured section through one levee deposit found near the BOC section northeast of Canon City. This (and similar sand bodies) shows the ribbon-like geometry typical of levee deposits. It is triangular in

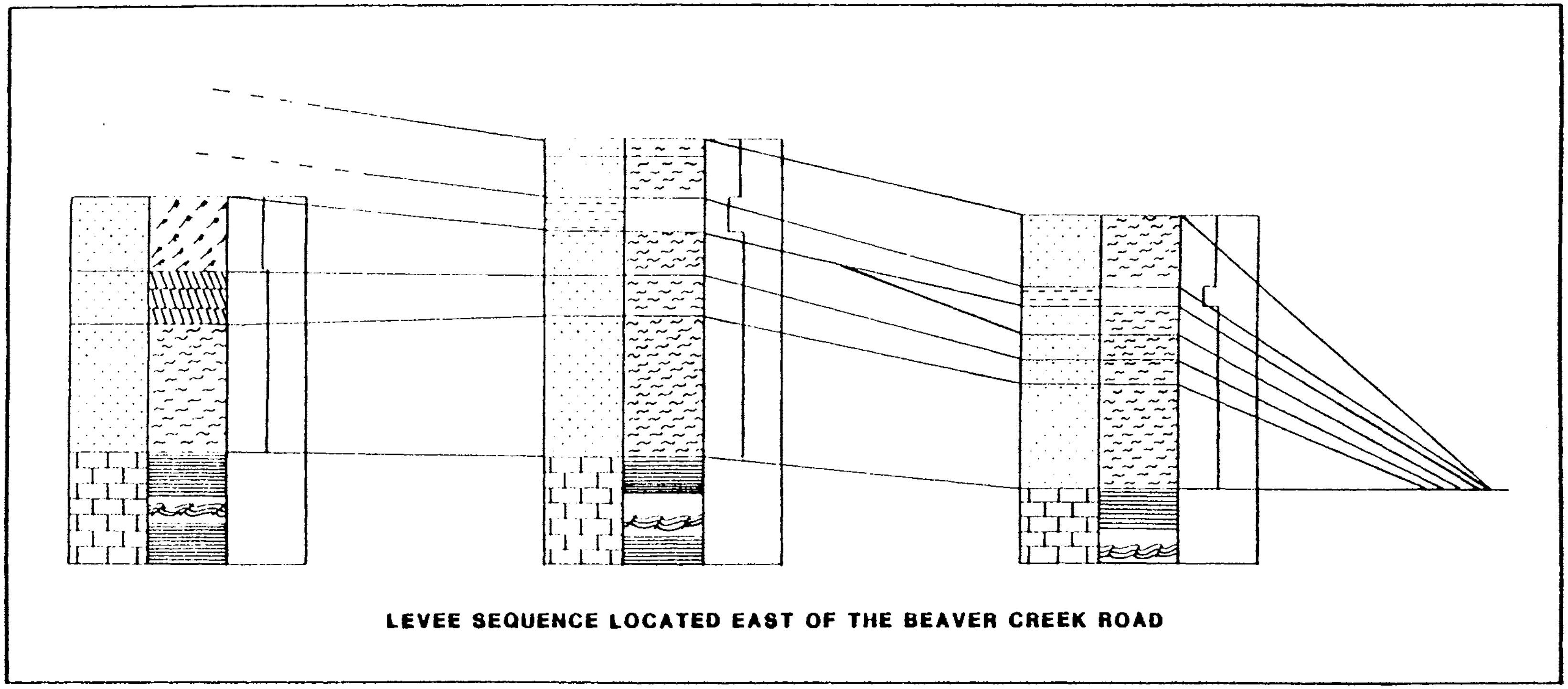


Figure 59. Levee Sequence Measured in the Vicinity of the BOC Measured Section

cross section and grades laterally from the channel into shales. Grain size fines laterally away from the channel and the predominant sedimentary structure is climbing ripple cross-stratification of variable trends away from the channel. Although this example is extremely well preserved, levee deposits usually do not have a high preservation potential because they are deposited on the erosive cut bank. In the present instance the channel has a clay plug, and it is apparent that the levee was preserved because of avulsion or cut-off of the channel.

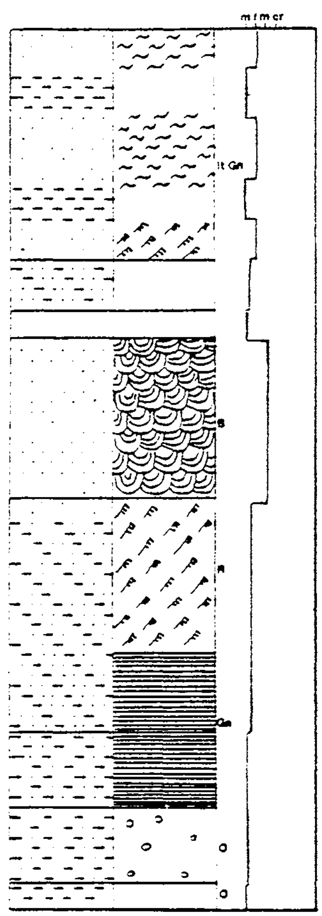
Lacustrine Delta Sandstones: Summary

Deltaic sedimentation was a prime contributor to sandstone accumulation. Deltas are subaerial or submerged contiguous sediment masses deposited into a body of water (oceans, semi-enclosed seas, barrier-sheltered lagoons and lakes) primarily by river processes (Reineck and Singh, 1980).

As stream channels enter a lake, basin sedimentation increases and a deltaic wedge begins to form on the lacustrine floor. The vertical sequence shown by these sediments normally displays a coarsening upward trend (Coleman, 1982). Lacustrine organic carbon-rich limestones or clays are usually at the base of the deltaic sediments. Quite commonly, shell accumulations encased in organic-rich clays form the lowermost units of the delta. As sedimentation begins on the distal delta, laminations of sand and silt develop. As the delta progrades and infills the lake, sediments gradually become coarser and the depositional slope becomes steeper. Within the major part of the sand body itself, small scale crossbedding is the most common sedimentary structure. Small slump structures and loadcoasts are common (Coleman and Prior, 1982). The small scale structures grade up into larger scale crossbedding; at times these foreset beds can have dips up to 10 to 12° if the lake is steep. As the delta completes its infilling process, coarse sediments are covered with the fine silt and clays of the topset environment.

Deltaic Sandstones in the Morrison Formation

At Grape Creek, there is a sequence of sandstones located above the black limestone which has characteristics similar to the aforementioned (Figure 60). From the black limestone, the section first passes up into a black pelecypod-rich mudstone and into a series of mudstones that alternate with laminated siltstones. In the overlying sandstone, which coarsens upward, the lowermost beds are laminated very fine grained sandstones. Overlying beds exhibit small scale crossbedding, while medium scale crossbedding is seen in the topmost medium grain sandstones. At the top of the sequence, crossbedding becomes smaller in size and passes into climbing ripples. The sequence is interpreted as recording the progradation of a small delta.



DELTAIC SEQUENCE LOCATED 70 FEET

FROM THE BASE GRAPE CREEK SECTION

Figure 60. Deltaic Sequence Measured at Grape Creek

No distributary channels cut the exposed section. The topmost beds apparently record a crevasse splaying event.

Shale Formation

Shales are the most common type of sedimentary rock. They can be deposited in a great variety of settings: interchannel areas in river systems, lakes, and areas affected by volcanic activity. As previously established, the Morrison is a continental deposit; therefore, discussions on marine settings are not pertinent.

In river systems, mud deposition on the distal flood plain is common. Sedimentation takes place when overbank flooding occurs. Most sediment on distal flood plains is from the suspended load which settles out after coarser material is deposited on levees and cravasse splays (Reineck and Singh, 1980). Although the precise rate of sedimentation depends on climate (especially rainfall), accumulation is generally slow, perhaps no more than 1 or 2 cm thick during a single flood period (Reineck and Singh, 1980).

Keller (1953) noticed that kaolinite is often associated with fluvial systems. In order for kaolinite to form, ambient waters must be relatively low in metal cations, but have H^+ levels high enough to be acid (i.e., pH must be less than 7.0). Waters of this type are often associated with fluvial systems; runoff does not allow metal ions to concentrate, and humic and other soil acids ensure low pH. In Keller's analysis of the Morrison type section, he located a kaolinite-rich zone near the top of the formation. On independent evidence he determined that these shales were fluvial in origin. Interestingly, near the top of the Morrison in Canon City, there is a relatively thick section of sandstones (up to 20 feet thick) which, as previously noted, is of fluvial origin. Associated with these sandstones are red and purple kaolinite-rich shales. The mineralogy of the shales, together with their association with fluvial channel sandstones suggests that they are overbank in origin.

Shales are deposited in permanent lakes by settling of the suspended load, including authigenic carbonates and organic carbon "fossils" (as previously discussed). Much of the fine-grained lacustrine siliciclastics can be interpreted as suspended debris brought into the basin by influent streams. Fine grain size lamination in the shales suggests either seasonal control and/or periodic flooding by these streams.

Wind blown silt and sand may have constituted an additional source of suspended debris.

Another lacustrine sub-environment where mudstones could have developed is on fringing lacustrine mud flats. Here, mud would have been deposited from suspension as the lake level oscillated across the flats. Evidence for the existence of this environment is the horizons of mud cracks seen in the calcareous marlstones and shales in the lower part of the Morrison. The principal clay mineral found in such rocks is illite.

Illite is formed in solutions that are not renewed or refreshed often (Keller, 1953). Mg^{2+}, Ca^{2+}, Fe^{2+} and K must be abundant and the SiO_2/Al_2O_3 ratio should be greater than three. These conditions are found in areas that are mildly alkaline, somewhat reducing and infrequently leached by fresh water. As a result of the latter condition, metal cation concentrations are higher than on fluvial flood plains. These conditions can be found in shallow lakes, characterized by infrequent turnover, limited inflow and an absence of evaporitic brines. Such a condition could develop either early in the life of an evaporitic lake or late in the life of a "fresh water" lake (depending upon climate).

In the vicinity of Canon City, illite is found both in the shale about 25 feet from the base of the formation, and in the upper portions. In the lower illite zone, lake limestones which developed in stratified conditions are common. Illite in shales both above and below these limestones records mildly alkaline conditions in the lakes at this time. Isolated limestones are also found in the upper portions of the formation and the associated illitic shales can be similarly interpreted as having formed in shallow lakes which were never evaporitic. In all probability, such lakes were always connected to the through-going fluvial drainage system developed in the

Morrison and were not isolated water bodies where evaporation was able to produce high ionic concentrations and highly alkaline conditions.

During the Jurassic, volcanic activity was common. Two main centers of activity were located along the magmatic arc in the Western Cordillera and in northern New Mexico on the Uncompahgre Uplift. Volcanism located along the subduction zone west of the Cordillera is responsible for the volcanic-derived shales developed in the Morrison in Utah, western Colorado, Wyoming and Montana. Volcanism from the Uncompahgre Uplift was not as extensive but played a large part in the development of shales in New Mexico, Arizona and parts of Colorado.

Shales derived from volcanic ash are generally smectitic and either contain volcanic glass shards or are highly siliceous (Pettyjohn, 1975). Montmorillonite-rich shales are common depositional products form volcanic dust of sialic to intermediate composition. They form in an environment where hydrolysis is active but removal of cations is not complete. These conditions are found in alluvial fans, flood plains, loess blankets and in poorly-drained marshes or interior lakes (Keller, 1953). Keller (1953) recorded a thick (95 feet) sequence of smectite-rich shales in the Morrison type section. He attributed this zone to an abundance of volcanic dust deposited in the aforementioned environments.

Shales of a similar type have been identified in the

Morrison in several areas. However, in the Canon City area, evidence is not as clearly defined. Although workers have found volcanic glass shards in green shales near mid-formation, none were seen in this study (Brady, 1967; King et al., 1969). However, there is a thin zone (20-30 feet) of smectite-rich shales found around mid-formation at Canon City. In this portion of the formation there is no independent evidence for evaporitic conditions (of which smectite is also characteristic), and therefore this zone is probably correlatable with the volcanic-derived shales of the type section.

CHAPTER XI

DIAGENESIS OF THE MORRISON FORMATION

A number of diagenetic processes have altered each lithotype of the Morrison Formation. Each system must be dealt with separately in order to unravel the complexity of processes involved. However, at the same time it must be understood that no single alteration can be considered as an isolated event.

Diagenesis of Sandstones

Dissolution, alteration, cementation and replacement are processes which have affected the sandstones in differing degrees. Physical diagenetic effects such as fracturing were not important in the evolution of Morrison sediments.

Dissolution

Dissolution has affected quartz, feldspar and matrix. Most of the quartz grains have embayed margins (Figure 17) although the degree of corrosion differs widely. Similarly, very few unaltered feldspars exist. Some grains show slight sericitization while others are almost completely dissolved except for a faint honeycomb skeleton (Figure 61).

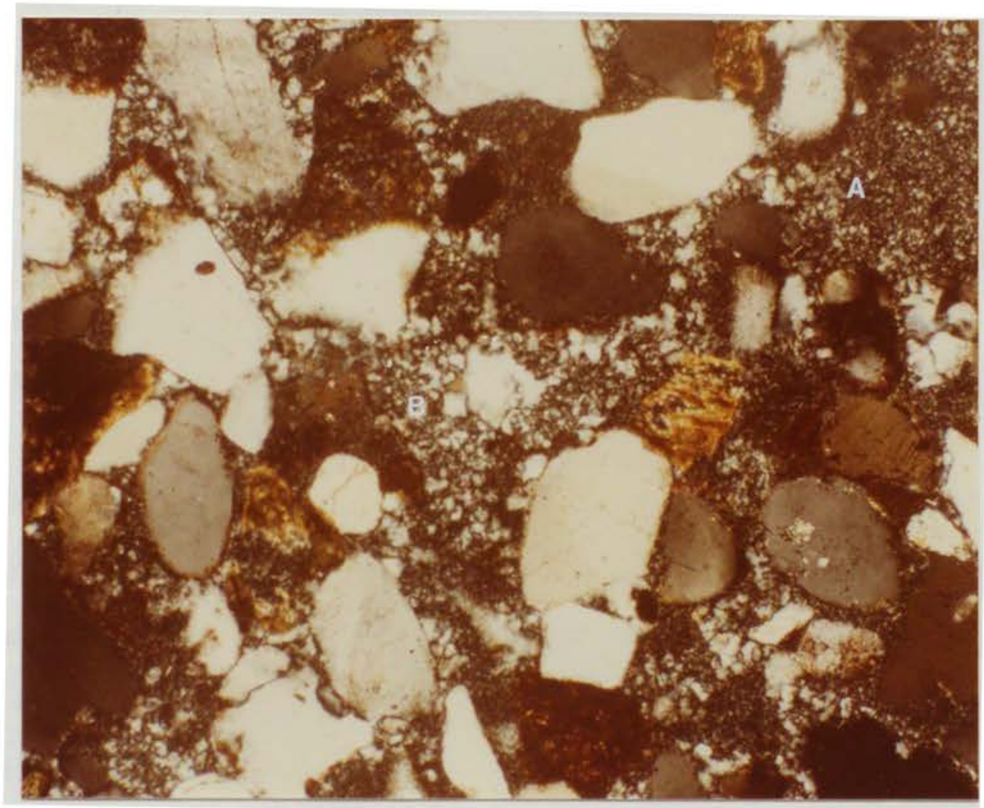


Figure 61. Photomicrograph of Microcrystalline Quartz Cement Showing a) Pinpoin Extinction and b) a Coarser Mosaic (Crossed Nicols, 10X)

Plagioclase feldspars have undergone more dissolution than microcline. Detrital matrix also displays dissolution features; however, such features are rare since most of the matrix is unaltered.

Precipitates

Finely crystalline dolomite was the first cement precipitated, but it is patchy in distribution. Non-ferroan calcite (precipitated after dolomite) is much more abundant. Textures observed are both equant and poikilitic. Rare ferroan calcite and ferroan dolomite were late carbonate cements.

Quartz cement appears in two forms: quartz overgrowths and microcrystalline quartz. Syntaxial quartz overgrowths have a patchy distribution. They are demarcated by dust rims around original grains. As with monocrystalline quartz, the overgrowths are generally corroded (Figure 20). Microcrystalline quartz is common and occurs in two forms, one of which is very fine (with pinpoint extinction), while the other is seen as a coarser mosaic (Figure 61).

Replacement

Some detrital grains, such as quartz and feldspar, have been replaced by non-ferroan calcite and dolomite.

Microcrystalline quartz cements can be seen to have replaced carbonate cement. Evidence for this is seen as traces of calcite remaining around detrital grains which are otherwise surrounded by microcrystalline quartz.

Alteration

Dissolution of feldspars created kaolinite, some smectite and illite. Subsequently, much of the smectite has been altered to form illite and mixed-layer smectite-illite clays.

Chemistry of Diagenesis

The Relationship Between Calcite and Quartz

The pH of ions in solution is a major factor affecting dissolution and precipitation of quartz and calcite (Figure 62). With the introduction of hydrogen ions (produced when CO_2 is dissolved in water), pH decreases (i.e., the acidity of pore water increases). When the available CO_2 decreases the availability of hydrogen ions also decreases and thus the pH increases. A simplified statement for the precipitation and solution of calcite is that as pH increases (>7) calcite precipitates, and as pH decreases (<7) calcite goes into solution.

The pH of the solutions also affects silica. However, the reactions proceed in an opposite direction to those governing $CaCO_3$ behavior. Silica is soluble in alkaline solutions but almost insoluble when the pH is less than 9.5 (Figure 62).

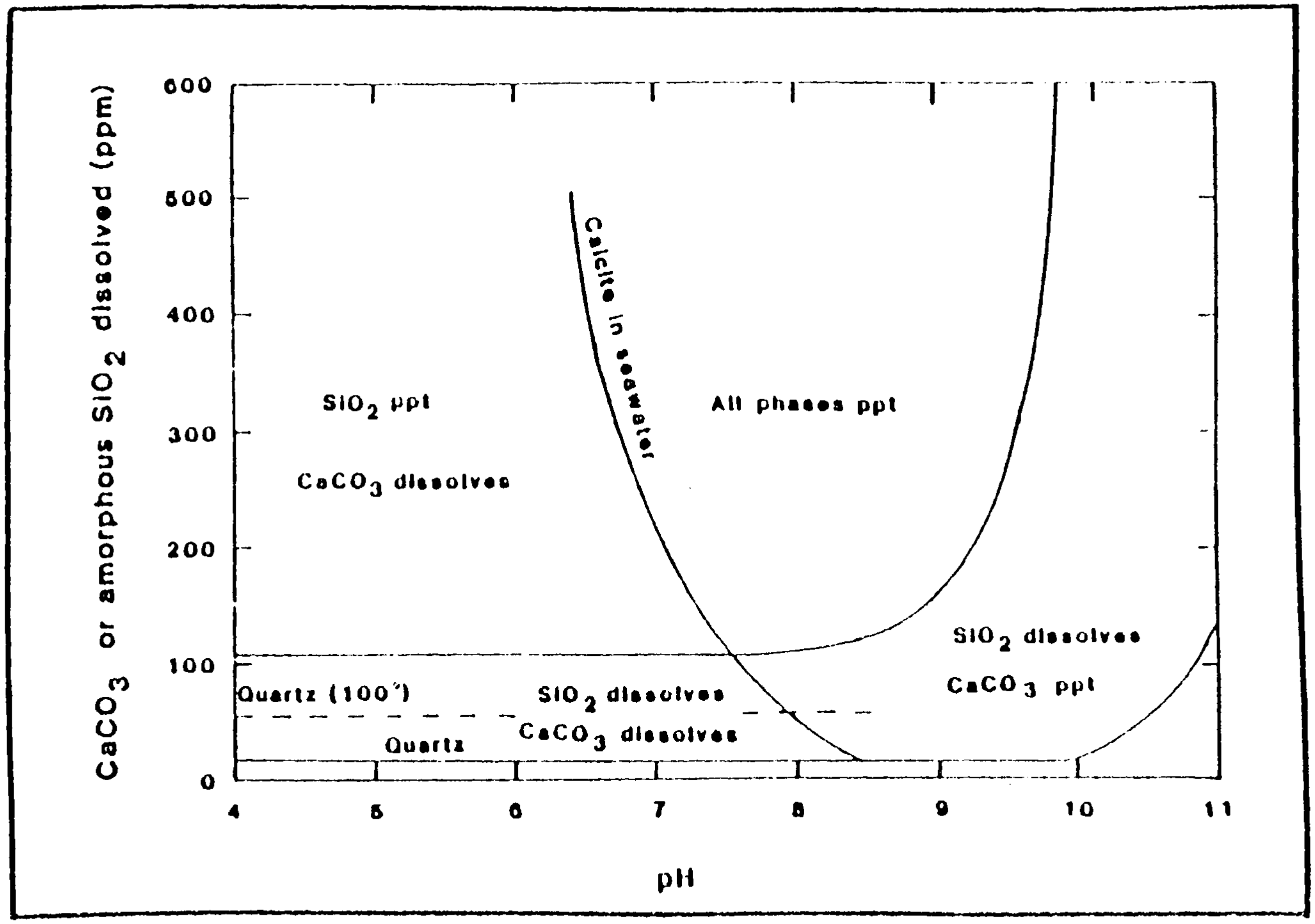


Figure 62. Phase Diagram Showing the Relationship Between Silica and Calcium Carbonate Versus pH (From Blatt, 1982)

Feldspars

As already mentioned, most of the feldspars in the Morrison show dissolution features. This honeycombing process is triggered by a decrease in pH. As mentioned in the previous discussion, an increase in dissolved CO_2 will decrease pH and increase the acidity of solutions. This reaction dissolves feldspar.

When feldspar is dissolved, an alkaline micro-environment is established around the grain and a small amount of dissolved silica ($HSiO_4$) is produced. As a result, quartz grains close to dissolving feldspars often exhibit signs of dissolution. This explains why some feldspar grains appear to be "eating" into quartz.

Another result of dissolving feldspar is the release of K^+, Na^+, Ca^{++}. This makes it possible for clay alteration products to be produced by the hydrolysis of feldspars.

Illitization of Smectite

Smectite is an abundant clay mineral in the Morrison. It co-exists with illite and mixed layer illite/smectite clays. Illite is produced both by hydrolysis of feldspars and by the illitization of smectite. Boles and Franks (1979) stated that in order for smectite to alter to illite, the following processes must take place:

1) substitution of the interlayer cations by K^+;
2) an increase in the wet negative layer charge of the expandable layers; this charge increase must result

from either substitution of Al for Si in the tetrahedral layer, or by the substitution of divalent cation (Mg^{+2} or Fe^{+2}) for Al^{+3} in the octahedral layer.

Hower (1976) suggested the following illitization reaction:

Smectite + Al^{+3} + K^{+} = illite + Si^{+4} (with an additional loss of Fe and Mg from smectite).

The additional Al and K needed for this reaction could be produced by the hydrolysis of feldspars.

Paragenesis

Figure 63 illustrates the general paragenetic sequence which has affected the Morrison sandstones in the Canon City area. In this diagram, diagenetic events are plotted against relative time. The sequence was determined from grain relationships noted in thin section and SEM studies. It should be noted however, that not all of the diagenetic effects are present in any given rock.

Non-ferroan dolomite was probably the first cement, but it is only seen in a few rocks. Following a hiatus, a later generation of ferroan dolomite cement precipitated. Hematite (another early cement) formed particulate rims around some quartz grains. Some of these hematite rims are preserved by later syntaxial quartz overgrowths. Non-ferroan calcite then cemented the rocks, forming poikilotropic textures. Following a change in pore water chemistry,

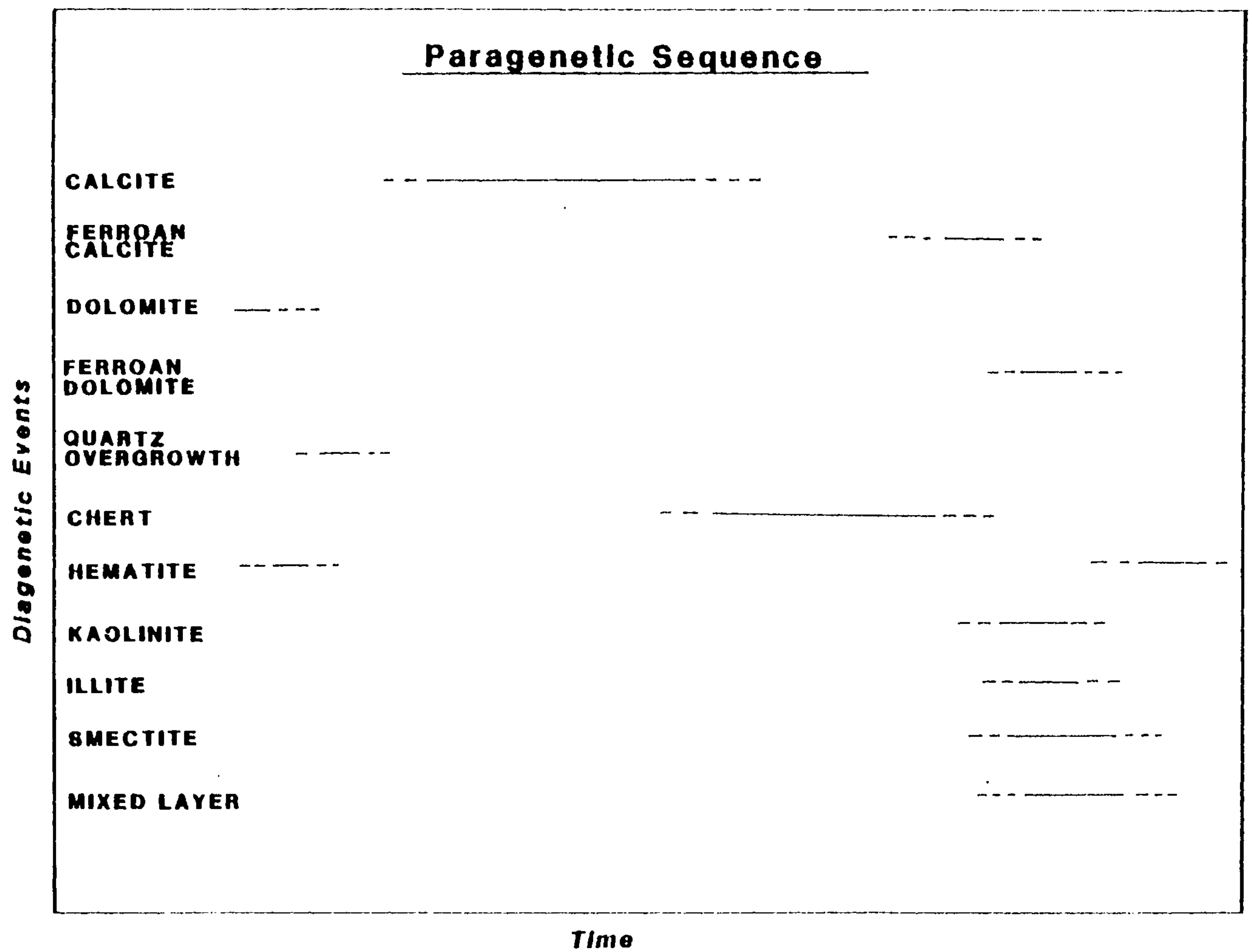


Figure 63. Paragenetic Sequence for Morrison Sandstones

microcrystalline quartz precipitated. Microcrystalline quartz is well developed in some areas, and may completely cement the rock. Following a short period of ferroan calcite cementation, illite, smectite, kaolinite and mixed layer clays began to form. These clays precipitated as grain-rimming, pore-filling and pore-bridging cements. A second generation of hematite was the last authigenic constituent to develop, possibly as a result of oxidation of ferrous iron-bearing minerals.

Limestone Diagenesis

Physical Diagenesis

Both physical and chemical diagenesis acted upon Morrison carbonates. In many cases, physical alteration of the fossils can be linked to the ionic state of the waters in which they were deposited.

Physical diagenesis was mostly restricted to the deeper sediments of the stratified lake sequences. Thus in the "black" limestone, fossils have been flattened and broken by compaction. The degree of compaction appears to increase with the amount of organic material present. This phenomenon is due to the anaerobic, somewhat acidic conditions that developed in the hypolimnion as algae died and sank to the bottom of the lake. The acidic nature of the waters retarded cementation and later compaction crushed the fossils. Compaction in other carbonate lithotypes is less evident.

Chemical Diagenesis

Chemical diagenetic alterations were much more extensive than those due to physical diagenesis. Polymorphic transformation, replacement and recrystallization all played an important role in the evolution of the Morrison carbonates.

The Aragonite to Calcite Polymorph Transformations

Although micrite is the predominant component of Morrison carbonates, a number of fossils, pellets and ooids are also present. Of these allochems, some fossils (gastropods and pelecypods) and probably some if not all of the ooliths are thought to have originally been aragonitic (by uniformitarian analogy).

Dodd (1966) identified two processes of aragonite to calcite polymorph conversion (calcitization). One process is in the *in situ* conversion (polymorphic transformation) whereby conversion took place without the development of significant void space. In this type, relics of original shell structure are visible and inclusions related to the original shell structure are common. Calcite crystal boundaries are usually irregular and crystal size varies. The solution-precipitation process involves dissolving aragonite and then being replaced by drusy calcite. It is this second process which has commonly occurred in gastropods of the Morrison Formation. The solution of aragonite and subsequent infilling of the resulting void by drusy calcite has produced casts of original shells. A variant of this mechanism which has affected pelecypods is the solution of aragonite followed by the partial collapse of the resulting void prior to infill of this void with drusy calcite.

In addition, a number of gastropods show evidence of *in situ* polymorphic transformation; the most significant evidence for this is the irregular crystal size and boundaries of the calc-sparite now constituting the shell.

Recrystallized Carbonates

Neomorphically altered carbonates are present in minor amounts in the Morrison Formation. Crystalline limestones were the only form of crystalline carbonates seen, although Brady (1967) found crystalline dolomite northwest of Canon City.

The neomorphically-altered limestones are homogeneous, being composed of low Mg calc-spar, minor amounts of micrite, silica and barite cement. The micrite is present both in its original form and as incipiently neomorphosed micro-spar (Figure 64).

The neomorphic spar identified in this study is recognized by 1) irregular and curved intercrystalline boundaries (as opposed to plane intercrystalline boundaries); 2) irregular crystal size distribution and patchy development of coarse mosaic; and 3) gradational

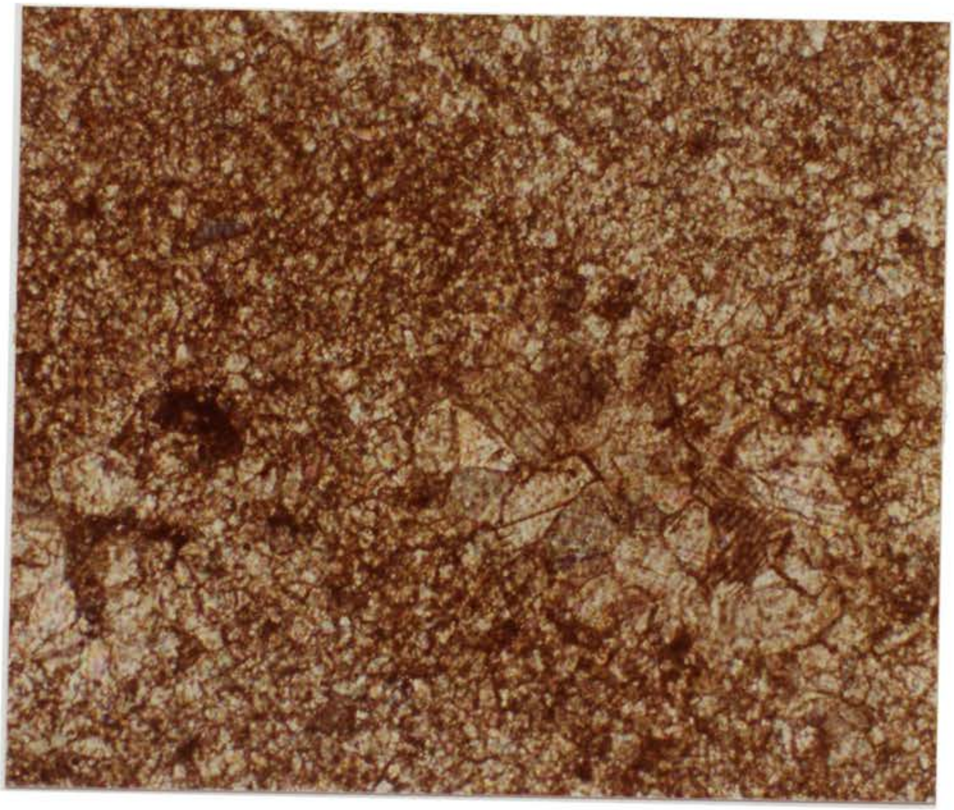


Figure 64. Photomicrograph of Incipiently Neomorphosed Microspar (Crossed Nicols, 10X)

boundaries with areas of original carbonate texture (Tucker, 1981).

These characteristics are clearly different from those of void filling cement seen in the Morrison. Fabric criteria for cements include: 1) intercrystalline boundaries which are made up of plane interfaces; 2) a high percentage of enfacial junctions among the triple junctions; 3) an increase in the size of crystals away from the initial substrate; and 4) unaltered micrite (Bathurst, 1975). These criteria are present in cemented voids left by gas escape (fenestrae), burrowing and fracturing.

Silica

Silica appears to be both replacive and void filling. The silica source is probably the abundant siliciclastics and crystalline rocks in the area. Replacement took place on a one to one basis (micrite to microquartz) or as dissolution of an entire fossil and subsequent replacement. One to one replacement is thought to occur across a fluid film only a few microns thick (Folk and Pittman, 1971). This fluid film develops along a front of least resistance where pore waters that are rich in $[H_4SiO_4]$ move toward the film and solutions rich in $[Ca^{2+}] + [HCO_3]$ move toward the pore water. When the ion activity product of the H_4SiO_4 exceeds the solubility product, SiO_2 precipitates.

Replacement of fossils is controlled by changes in fluid (i.e., pore water) chemistry). In particular the solubility of calcite and silica is controlled by their relative solubility, concentration, temperature, pressure and the pH of the system. Calcite dissolves and silica precipitates when formation waters become acidic (pH<7). Silica dissolves and calcite precipitates when the waters are alkaline. This is an oversimplified statement, due to the fact that the relative solubility of calcite is much greater than that of silica. Furthermore, fluctuations in pressure and temperature change the thresholds of solubility and precipitation for both minerals.

In the Morrison, the calcite or aragonite of the fossils was dissolved in acidic conditions. These conditions were then favorable for the precipitation of silica in the resulting voids (providing dissolved silica was present in solution). Silica precipitation in the voids followed a pattern of initial microquartz precipitation, then chalcedonite and finally megaquartz. This pattern indicates falling concentrations of silica (Figure 62) (Chowns, 1974).

Paragenesis of Limestones

The primary carbonate fabric is a dense micrite representing a well-cemented lime mud. Fenestral textures in this lime mud probably resulted from gas escape following the decay of organic material. Fenestrae and fossils were then incompletely filled by silica deposited by relatively low pH ground waters of low ionic strength. The remaining porosity in the voids (both fenestral and fossil) was then filled by sparry calcite cement, following an increase in pH values. The recrystallization of micrite poses a problem in that it is difficult to pin down the exact time of neomorphism. The neomorphism probably took place at a time when the pore solutions were passive but super-saturated with $CaCO_3$, possibly late in the rock's diagenetic history. Barite was precipitated at a time when pore waters became sulphate-rich, possibly late in the diagenetic history. Figure 65 is a summary of the paragenesis of fresh water limestones.

Diagenesis of Alkaline Deposits

Two types of alkaline-rich environments developed early in the history of the Morrison. The first were sulphate-rich playas whose existence was recorded, both at the very base of the formation and also at a later time in the middle portion of the formation. The second was a sodium-rich playa in which sodium carbonates were precipitated. This phase post-dated the earliest sulphate-rich playa.

Sulphate-Rich Playa

At the base of the Morrison in the northeastern portion of the study area, there is a number of chert beds which overlie the gypsum of the Ralston Creek Formation. These cherts are thought to have replaced sulphates deposited in and below the surface of the playa. The silica-rich layers

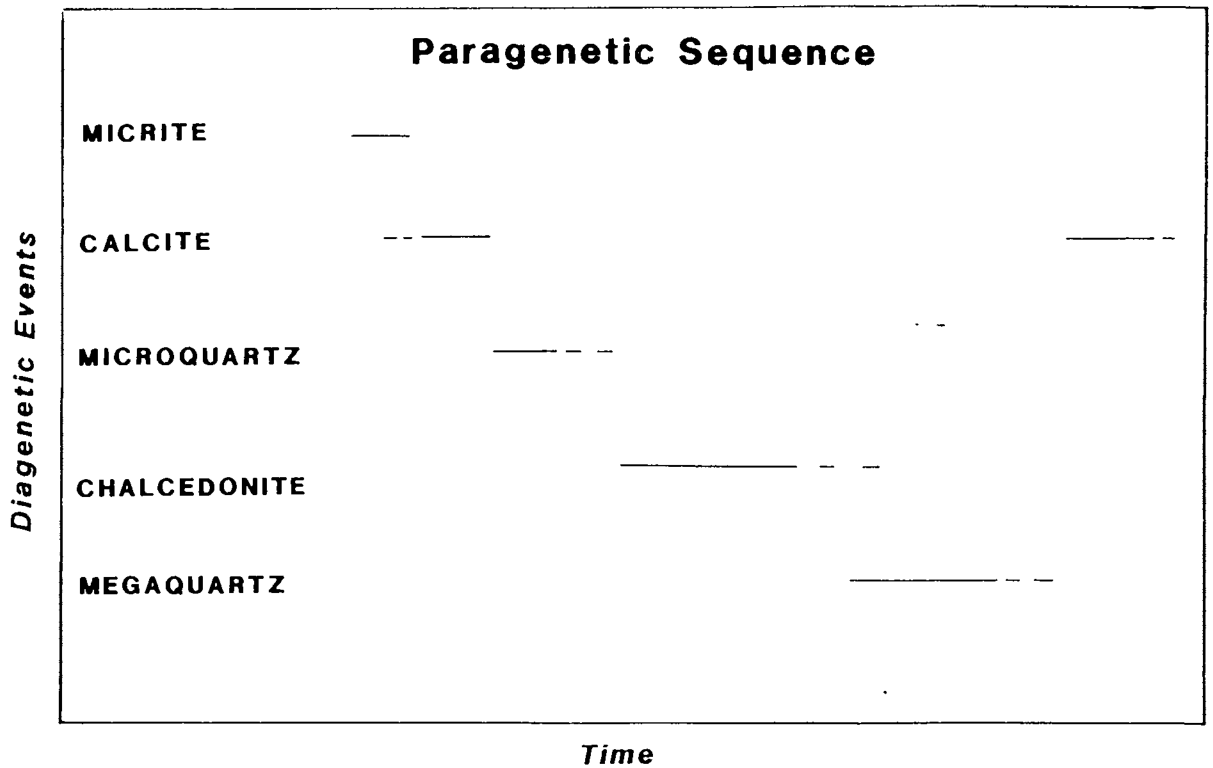


Figure 65. Paragenetic Sequence for Morrison "Fresh" Water Limestones

are composed of megaquartz, length slow chalcedony and microquartz. Traces of anhydrite and perhaps gypsum are still present in the megaquartz. The following is a brief outline of the events which took place in the replacement of sulphates by quartz in the Morrison (modified from Chowns and Elkins, 1974; Tucker, 1976; Ragland, 1983):

1) Nodular sulphate (gypsum and anhydrite) developed within sediments by precipitation of hypersaline ground waters in a playa setting.

2) Alkaline waters rich in dissolved silica were introduced to or formed in the playa. A freshening of the system then occurred, which lowered the pH and simultaneously dissolved sulfates and replaced them with silica.

3) As replacement of calcium sulfate continued, sulphate solution was more rapid than silica precipitation and voids developed. Megaquartz developed in these voids, signaling a changeover from quartz replacement to direct quartz precipitation in which quartz crystals were free to grow without the constraint of the lost sulphate, and as a result formed large euhedral quartz crystals.

4) Subsequently, concentrations of silica increased and quartzine and luticite developed (Figure 66). Many of the nodules are composed of alternating microquartz and quartzine layers. This alternation suggests a short-term variability of concentration which may even have been seasonal.

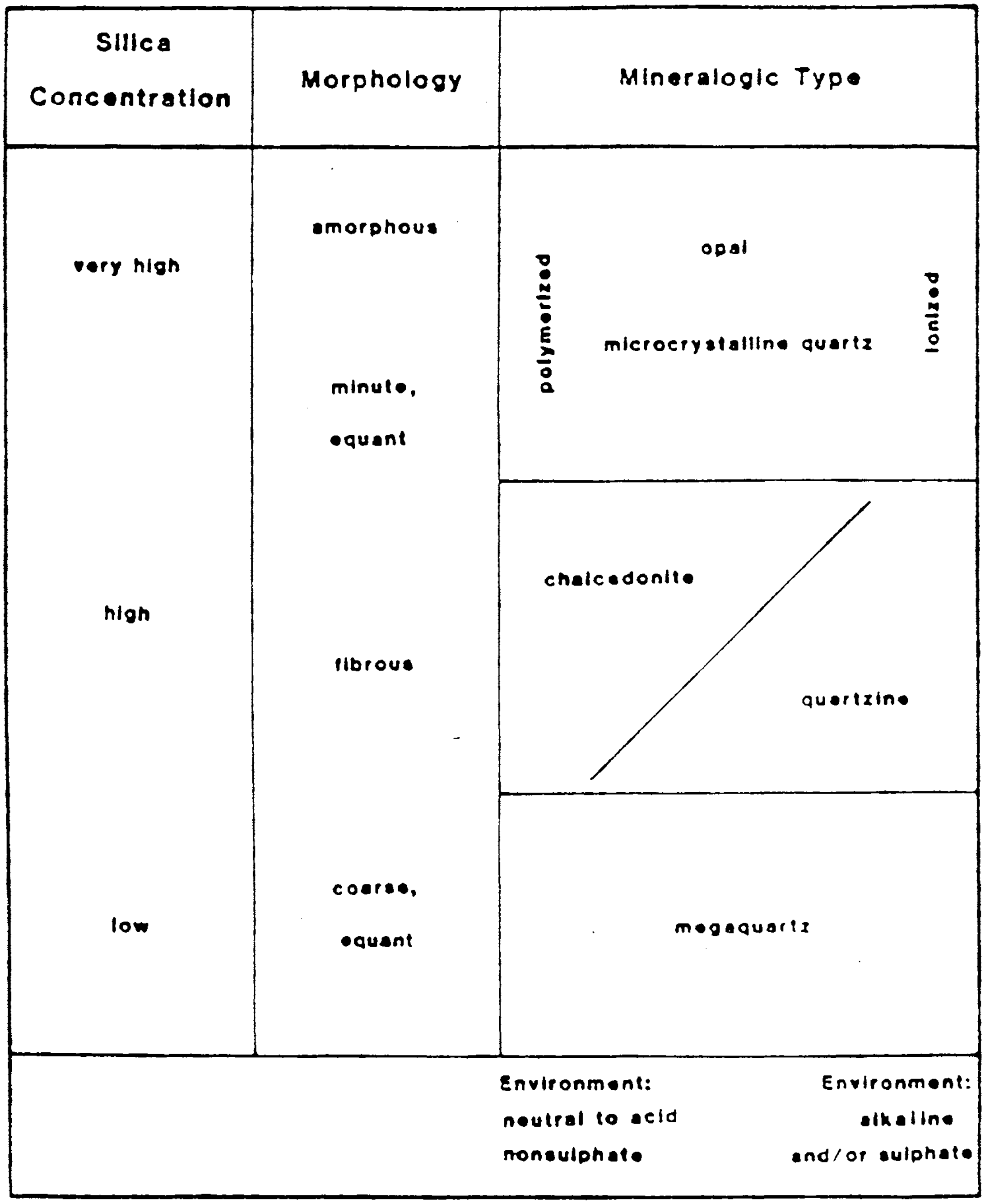


Figure 66. Diagram Illustrating the Silica Type Produced as a Function of Environment and Silica Concentration (Modified from Folk and Pittman, 1971)

The alternation of microquartz and quartzine formation is not the only evidence for rapidly changing pore water chemistry. For example, lutecite appears to be "growing" out of microquartz (Figure 40), which would indicate a decrease in silica concentration. On the other hand, flamboyant megaquartz (representing a stage intermediate between quartzine and megaquartz) fringes the boundaries of equant megaquartz (Figure 67) and apparently records increased silica concentrations. Furthermore, some grains of megaquartz show evidence of sequential growth in the form of multiple dust rims (Figure 41).

Gypsum Pseudomorphs

Clusters and twined aggregates of crystal pseudomorphs from 3 cm to 15 cm across are developed at the base and middle of the formation at Garden Park, Grape Creek and Skyline Drive. The form of these crystals is typical of gypsum. They are now replaced by sparite. Some gypsum crystals show partial dissolution with subsequent precipitation of silica. This phenomenon is rare and incomplete. The hosts in which these pseudomorphs are found are micrites and marlstones. They appear to record a playa which was radically affected by silica-rich solutions in its early diagenic history.

Sodium-Rich Playa

Two types of pseudomorphs related to sodium carbonates

Figure 67. Photomicrograph of Flamboyant Megaquartz Fringing the Boundaries of Equant Megaquartz (Crossed Nicols, 4X)

were seen in the Morrison approximately 30 feet from the base of the formation northeast of Canon City. They are interpreted as having been gaylussite ($NaCO_3 \cdot CaCO_3 \cdot 5H_2O$) and trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$).

Gaylussite probably does not form as a precipitate but either by interaction of interstitial brines with the sediment or by the mixing of fresh waters with interstitial brines in the sediments (Eugster and Hardie, 1978). If there is an interaction between calcium carbonate sediment and sodium carbonate-rich brines, gaylussite will form by the following reaction:

$$CaCO_3 + 2Na^+ + CO_3^{2-} + 5H_2O \dashrightarrow Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$$

Alternatively, when dilute runoff waters containing Ca and HCO_3 come into contact with alkaline brine waters on the playa mud flats, gaylussite (or prissonite $Na_2CO_3 \cdot CaCO_3 \cdot 2H_2O$ if the amount of H_2O present is low) will form. Both mechanisms may have operated during the formation of the Morrison deposits.

In modern sediments, gaylussite is often found in close association with trona ($Na_2CO_3NaHCO_3 \cdot 2H_2O$). Trona deposition requires parent waters that are rich in Na and have a high $HCO_3^-/(Ca^{2+}, Mg^{2+})$ ratio. Cl^- and SO_4^{--} anions must be minor. This implies that igneous and metamorphic rocks rather than pyritic shales and evaporites are the sources of ions for the solutions. Weathering reactions of silicates (mainly feldspars) with carbonic acid produce silica, Ca, Na, K and HCO_3^-. The following sequence of events must occur in order for trona to precipitate (modified from Eugster and Hardie, 1975):

1) Ca^{2+}, Mg^{2+} and CO_3^{2-} is lost from solution early in the evolution of the alkaline brine. This occurs on carbonate mud flats fringing the playa where alkaline-earth carbonates precipitate (i.e., calcite, high-Mg calcite, and protodolomite).

2) After the removal of Ca^{2+} and Mg^{2+}, pH will have reached values >9.

3) As evaporation continues, PCO_2 increases and CO_2 is lost to the atmosphere, causing pH to increase still further.

4) As evaporation continues, concentrations increase until finally,

5) Trona precipitates.

The resulting trona-body consists of interlocking trona needles (with up to 50% porosity) the interstices of which are filled with sodium carbonate brine. The brine level never drops more than a couple of feet due to the efflorescent crust which inhibits total evaporation. When the lake surface becomes inundated by flood waters during rainy seasons, some trona is dissolved by fresh waters and clastics and ripped-up carbonates from the surrounding flats are deposited in the remaining interstices. When surface waters begin to evaporate, trona precipitates again (most of it has been preserved). Sodium carbonate brine waters may then interact with $CaCO_3$ (from the recycled carbonates) and gaylussite precipitates. The process of precipitation-dissolution (due to a seasonally wet climate) may round the gaylussite rhombs and disaggregate the trona.

Such a process presumably took place during deposition of the Morrison deposits. However, in the Morrison both trona and gaylussite were subsequently replaced by sparry calcite while the remaining porosity was filled by drusy sparite. The host sediment for these pseudomorphs consists of dolomicrite and smectite. The presence of both minerals is in accord with the model presented above. The dolomite records initial precipitation on a fringing playa flat. Smectite is the clay mineral which would be expected to form in a highly alkaline environment.

Paragenesis

The diagenesis and paragenesis of the two playa systems must be treated separately. The diagenetic processes which affected the sodium carbonate-rich playa are few, and relatively simple to interpret. Figure 68 is a summary of the paragenetic sequence for these sediments. It is in the sulphate-rich playa that complexity arises. The number and interrelationship of silica types makes the precise sequence of formation difficult to determine (Figure 69).

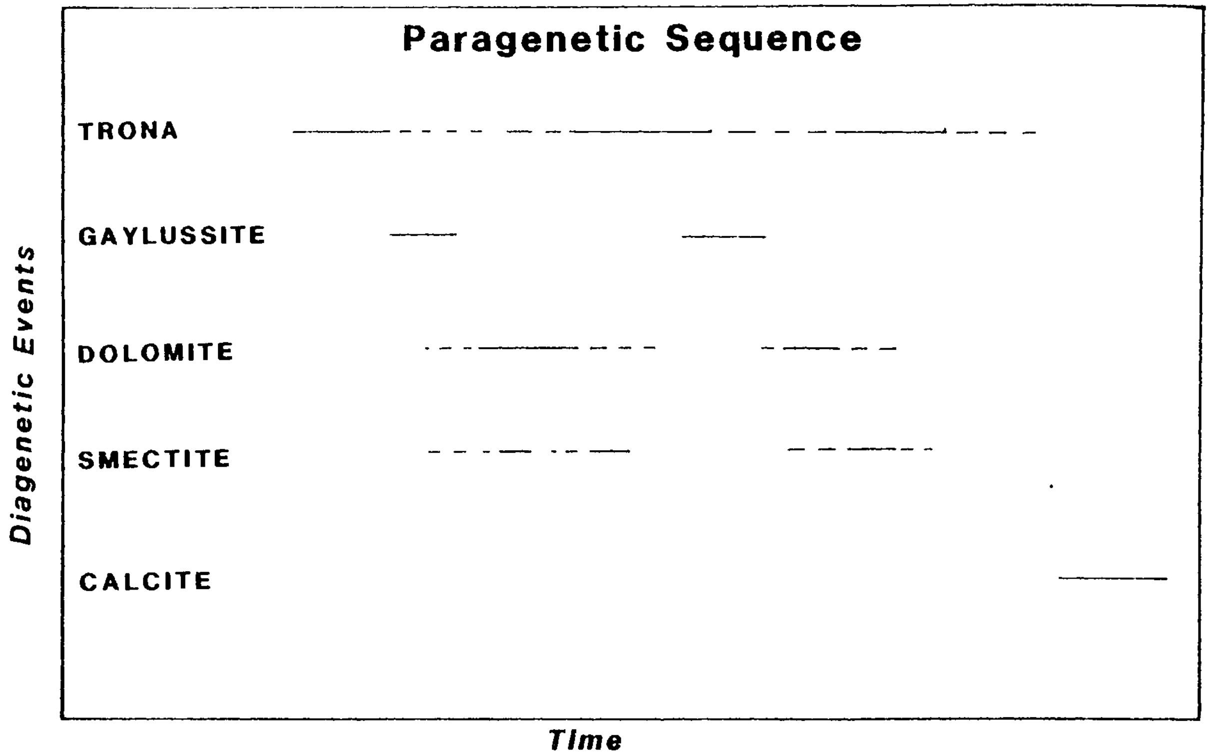


Figure 68. Paragenetic Sequence for Sodium Carbonates in the Morrison

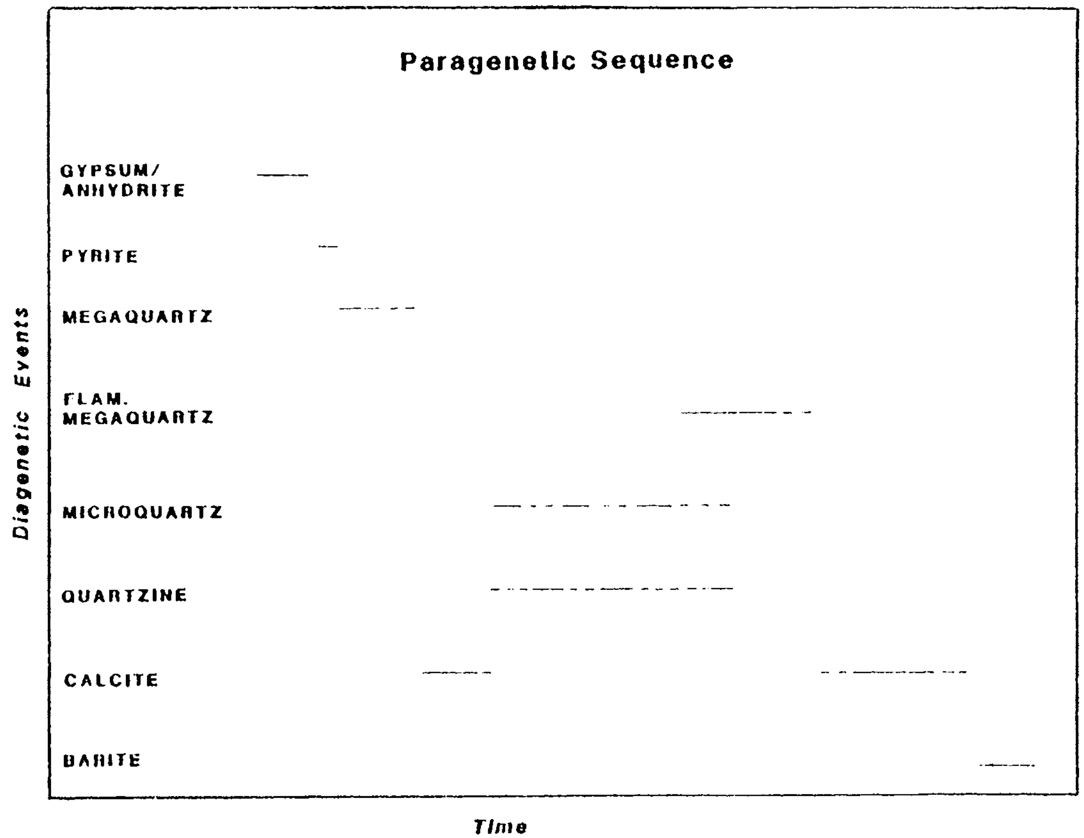


Figure 69. Paragenetic Sequence for Sulphate-rich Playa Sediments

CHAPTER XII

SUMMARY AND CONCLUSIONS

The purpose of this thesis is to describe and interpret the sedimentary geology of the Jurassic Morrison Formation in the vicinity of Canon City, Colorado.

Three types of exposures occur in the Canon City area. The formation can be seen on the steep scarps of the prominent hogbacks where the eroded shaly Morrison is capped by the Lytle; it is also exposed along stream gullies, and it occurs in combinations of hogbacks and stream gully exposures.

Lithostratigraphic Findings

The principal lithostratigraphic relationships found are:

1) The Morrison lies nonconformably on Precambrian Pikes Peak Granite and the Idaho Springs metamorphic complex to the west and northwest of Canon City. In one small area the Morrison lies unconformably on the Ordovician Fremont Formation.

2) To the east and near the Canon City area, the Morrison lies with apparent conformity on the Jurassic Ralston Creek Formation. The later is composed of two

lithotypes:

a) In the most eastern portion of the study area, the Ralston Creek is composed of bedded gypsum which is overlain by Morrison "welded" cherts.

b) In the western portions of the area and in Canon City itself, the Ralston Creek is composed of interbedded arkoses and thin conglomerates.

3) The Lower Cretaceous Lytle Sandstone overlies the Morrison. The disconformable contact between the two formations is usually denoted by a basal conglomerate in the Lytle.

4) The maximal thickness of the Morrison in the Canon City area is approximately 320 feet.

Petrographic and Sedimentologic Findings

The field characteristics and petrography of the following lithologies were studied:

1) Sandstones (up to 20 feet) occur throughout the formation but are thickest near the top. These sandstones are lenticular and are interbedded with shales and siltstones. Average width:thickness ratios of individual sandstone bodies is 15:1. The sandstones are characterized by the following features:

a) Their bases are abrupt or erosive, may be modified by load structures and many are marked by intraformational conglomerates.

b) Although some of the sandstones are massive, most exhibit sedimentary structures associated with weak flow regimes; e.g., parallel lamination, small scale trough and planar crossbedding, straight-crested and linguoid ripple marks and climbing ripple cross stratification (rib and furrow structure).

c) Medium scale trough cross bedding (set thickness up to 12") is common in the thicker and coarser-grained units.

d) Large scale cross bedding of the epsilon variety is seen in some units.

e) Trace fossils attributable to crawling and browsing organisms are common in some of the finer-grained sandstones.

f) Dewatering structures and convolute bedding are the most common soft sediment deformation structures present.

The principal petiographic characteristics of the sandstones are as follows:

a) Grain size varies from silt to coarse sand with very fine to fine sand being predominant. The grains are subrounded to subangular, sphericity is low to medium and the sorting is generally poor; overall the rocks are texturally submature.

b) Monocrystalline quartz, chert rock fragments and feldspars are the most common constituents. Lithic fragments, trace minerals and detrital matrix are less common.

c) The sandstones are cemented by calcite, dolomite and quartz. Illite, smectite, kaolinite and mixed layer clays are the four types of authigenic clays present.

d) The sandstones are classified as being either sublitharenites or quartz arenites.

2) Intraformational conglomerates are generally polymictic. Grain populations are bimodal and individual grains are subrounded to rounded with high sphericity. The most common types of conglomerates present are quartz- and chert-pebble conglomerates. However, limestone- and shale-rich conglomerates are also seen.

3) Multicolored claystones and shales containing silt, sand, carbonate, hematite and organite materials constitute the largest percentage of the Morrison lithologies. The claystones and shales can be subdivided on the basis of color and clay content as follows:

I. A basal grey unit rich in smectite and illite;

II. A grey shale and limestone unit rich in illite, kaolinite and mixed layered clay;

III. A green shale unit rich in illite (including a small zone of smectite near mid-formation);

IV. A red shale unit rich in illite with some kaolinite;

V. A variegated sandstone and shale unit rich in kaolinite with some illite.

4) Relatively thin carbonates, generally of limited lateral extent are most commonly found in the lower portions of the Morrison. These carbonates show a variety of sedimentary structures including: laminations, fenestrae, dewatering structures, convolute bedding and buttock folding. Lithotypes include:

a) Micrite containing siliciclastic grains, gastropods, pelecypods, *Chara* and ostracods. Two relatively widespread micrite beds are present.

   i) The "white" limestone contains abundant fossils and a significant amount of siliciclastic grains. Laminae are generally disturbed by fenestrae desiccation. No organic carbon is present.

   ii) The "black" limestone is laminated, kerogen-rich and contains *Chara*, ostracods, disarticulated fossil fish and minor amounts of siliciclastics. No fenestrae and desiccation features are present.

b) Oolitic limestones are generally composed of superficial ooids (with various types of nuclei). More rarely, well-developed ooids display both concentric and radial morphologies.

c) Pelmicrites composed primarily of pelloids are uncommon. The pelloids range in size from 0.01 to 0.3 mm and are circular to elliptical in shape.

d) Several carbonate units consist of up to 80% dolomicrite. Texturally these rocks show the same features as the calc-micrites.

5) Chert is found in minor amounts throughout the lower portions of the Morrison. Generally, it replaces micrite in limestones with microquartz and infills fossil molds and fenestrae with megaquartz, microquartz and length fast chalcedony. However, in the eastern portions more substantial cherts are interbedded with thinly-bedded limestones, marlstones and shales. These cherts comprise irregular masses consisting of microquartz, megaquartz, flamboyant megaquartz, quartzine (length slow chalcedony) and lutecite.

Pseudomorphs, after unknown evaporites are present at two distinct levels in lower portions and, more rarely in the middle of formation. There are three types of crystals present:

a) larger pseudomorphs (4 to 5 cm long) which either radiate from a central point or more commonly have a disrupted appearance;

b) medium size pseudomorphs which range between land 2 cm long and are either prisms or have a rhombic shape;

c) smaller pseudomorphs (apparent only in thin section) which appear as rhombohedra dispersed throughout a smectite-dolomite matrix. Many of the rhombs are irregularly shaped, having small birdtail-like protrusions on some corners.

The three types of pseudomorphs are interpreted respectively as: trona ($Na_2CO_3NaHCO_3 \cdot 2H_2O$), gypsum ($CaSO_4 \cdot 2H_2O$) and gaylussite ($NaCO_3 \cdot CaCO_3 \cdot 5H_2O$).

Paleontological Findings

The Morrison contains a number of vertebrate and invertebrate fossils. Invertebrate fossils include gastropods, pelecypods and ostracods. the vertebrate fossils, which brought notoriety to the Morrison, consist of mammals, amphibians, fish and a large variety of reptiles. The two most common fossil plants identified are *Chara* and a fern-like genus, *Cycadella*.

Controls on Morrison Depositional Systems; General Conclusions

The Jurassic in the Western Interior of North America carries the imprint of four major transgressions. The final and most extensive transgression occurred during Callovian-Oxfordian times. Following this event non-marine conditions prevailed throughout the region. Paleolatitudes during the period of deposition of the Morrison gradually changed from 23^o-28^o N to 33^o-38^o N. This 10^o change is related to relatively rapid movement of the plate upon which the Morrison was deposited. For the paleolatitudes at which the sediments were deposited in the Canon City area, the mean surface temperature was approximately 28^o C at the beginning of Morrison time. However, due to northward drift, mean temperatures dropped to about 25^{o} C by the end of Morrison deposition. During this time the climate changed from semi-arid to humid.

Both the presence of granite and metamorphic clasts found in the Morrison sediments and paleocurrent data suggest that the Ancestral Rocky Mountains (ARM) and the Transcontinental Arch were the major sources of Morrison sediment in the study area. The Ancestral Rockies were entities of low relief which can best be visualized as monadnocks with gentle slopes. In addition to being a source of siliciclastics, the igneous and metamorphic rocks of the ARM were also the source of silica, Ca, HCO_3^-, Al, Na and K in pore waters. Approximate calculations, involving the maximum thickness of the Morrison in the area and the approximate time range of the formation, give an estimate of an overall sediment entrapment rate of 0.01 m/yr. The significance of this number is that it indicates a long surface residence time and much sediment reworking. This conclusion is supported by the mineralogical maturity of the sediments.

From these facts a hypothesis as to the environment is as follows. Early in the history of Morrison deposition, the Ancestral Rocky Mountains created a rain shadow, partially sheltering the low-lying Canon City area from rain, yet acting as a runoff trap. This, coupled with a reasonably warm climate, resulted in semi-arid conditions.

On the valley floor two types of playas developed; sulphate-rich and (at a later date) sodium-carbonate rich. These Morrison saline lakes were never as extensive as the more famous Eocene saline lake of the Rocky Mountain area (i.e., Lake Gositute) due to several factors. Firstly, the mature Ancestral Rockies did not form a perfect rain shadow; secondly, there is no evidence for alkaline springs in the area; and thirdly, the climate gradually became more humid.

Descriptions of the alkaline playas are as follows: At the beginning of Kimmeridgian time a sulfate-rich playa developed. Brines in this environment were enriched in alkaline earth carbonates but impoverished in sodium carbonate. Hence, with continued evaporative concentration, saturation with respect to gypsum occurred. Alkaline earth carbonates precipitated first on the playa mud flats. Gypsum then precipitated as selenite blades in the lake edge sediments. Halite, if present, would have formed efflorescent crusts. However, no evidence for this has been preserved. After this initial phase of playa development, thin sandstones and shales were deposited, marking a period of low-energy alluviation. At this time, or perhaps later, silica-saturated ground waters more or less completely replaced the sulphates with varieties of secondary silica.

Following this brief hiatus in playa sedimentation, a sodium carbonate-rich environment developed, in which carbonate mud flats surrounded a central playa brine lake. Mudstones deposited on the mud flats were subject to early cementation by alkaline earth carbonates; intersitial brines concentrated during periods of high evaporation. In all probability sedimentation in this playa followed the general model whereby low-Mg calcite was precipitated first, then high-Mg calcite and finally protodolomite. As carbonates continued to be precipitated, waters depleted in Ca^{2+} and Mg^{2+} flowed into the central brine body. During the driest seasons uniformitarian analogy suggests that efflorescent crusts of trona developed by complete evaporation to dryness. The resulting trona body would have consisted of interlocking trona needles (with up to 50% porosity), the interstices of which were filled with sodium carbonate brine. Periodic flooding would have freshened the brine as well as transporting clastics and ripped-up carbonates on to the playa floor. The interstitial sodium carbonate brines would have leached with the carbonate clasts, and as a result, gaylussite would have precipitated. As the surface waters began to evaporate again, trona would have reprecipitated (most trona is recycled in this fashion in modern environments).

As the climate became more humid and probably a little cooler, temperate fresh water lakes evolved. Two major facies record these lakes: open lacustrine and marginal lacustrine. The open lacustrine facies consists of mud-supported carbonate. Distally, it is represented by laminated kerogen-rich micrites; nearer to shore the rocks contain abundant fossils (gastropods, pelecypods, ostracods and *Chara*) plus dewatering and desiccation features. Both types of open lacustrine facies record depositional sites which were relatively uninfluenced by major influxes.

The marginal lacustrine facies is composed either of green calcareous mudstones with invertebrate fossils and some organic carbon present or, less commonly, of grain-supported carbonates composed of ooliths and pelloids. Furthermore, in some areas sandstone sequences which coarsen upwards are present. The general depositional environment is interpreted as one in which non-evaporite-producing lake margin carbonate flats interfingered with non-Gilbert type deltas building out into the lake. Lake margin carbonate-flat sediment grade basinward from oolith and pelloid grain-supported textures to a mixed mud and grain-supported textures to a mixed mud and grain-supported texture.

Lacustrine deposits are less common in the upper part of the Morrison. With time, increasing amounts of siliciclastics were transported into the Canon City area by meandering streams; as a result, sandstones became more prominent in the section.

Sandstones in the Morrison are related to several depositional environments: 1) point bars of meandering stream channels; 2) levee deposits; (3) sheet floods across shallow lakes; and 4) deltas.

Channel sandstones increase both in size and number towards the top of the formation, possibly both documenting a general increase in runoff and increased erosion in the hinterland.

Shales (the most abundant lithotype in the formation) were also deposited in a number of settings: 1) as overbank deposits in river systems; 2) in lakes (by settling of the suspended load; 3) on lacustrine mud flats; and 4) as volcanic ash (near mid-formation). Clay mineralogy aids in the identification of the associated environment.

Diagenetic Overprints: Findings and Conclusions

Sandstones are affected diagenetically by dissolution, precipitation, replacement and alteration. Quartz, feldspars, and matrix commonly exhibit dissolution features. Respectively, non-ferroan dolomite, hematite, non-ferroan calcite, quartz and ferroan calcite precipitated as cements. Quartz and feldspar have been variably replaced by non-ferroan calcite and dolomite; monocrystalline quartz has replaced carbonate cement. Alteration of feldspars has created kaolinite and some illite. Smectite has altered to form illite and mixed layer illite-smectite clays.

Fresh water limestones have been altered both physically (by compaction) and chemically. Aragonite has altered to calcite by two processes: 1) *in situ* conversion (polymorphic transformation); and 2) solution and subsequent precipitation. Some micrite is changed to microspar through aggrading neomorphism.

Silica is both replacive and void filling.

Microcrystalline quartz commonly has replaced micrite, while megaquartz and fibrous and zebraic chalcedonite (length fast chalcedony) have replaced fossils and infilled fossil molds and fenestrae.

Sulfates of the aforementioned sulfate-rich playa were replaced by silica to form the "welded" cherts at the base of the formation. Microquartz, megaquartz, fibrous and flamboyant megaquartz, plus length slow quartzine and lutecite, are present. The length slow silica along with anhydrite inclusions in the megaquartz provide evidence for the character of the initial evaporites. In the higher level playa deposits, gypsum, trona and gaylussite crystals have been pseudomorphed by sparite.

Unresolved Problems Arising from this Study

The study of a formation as complex as the Morrison poses many questions, not all of which have been resolved. The most important of these problems is related to the interpretation of two black shale-rich sequences located near the base of the formation at Garden Park (Appendix C). These carbonaceous deposits appear to be prodelta sediments related to the advance of a Gilbert-type delta into a relatively deep lake.

If this conclusion is correct, then a conflict arises, both with the recognition of playa deposits at the base of the Morrison elsewhere, and with the overall semi-arid to arid climate assigned to the early Morrison depositional environment.

The first part of this conflict could be resolved by recognition of stratigraphic confusion in determining the base of the Morrison. The markedly variable character of the underlying Ralston Creek Formation and the abruptly varying character of Morrison facies more or less predicate the confusion. Furthermore, the recognition of coincident margin sites in the west of the study area indicates that the Morrison sediments onlapped the Ancestral Rockies. Therefore, the basal Morrison at the BOC and DMC sections may well be considerably older than it is in the Garden Park section (which is located much closer to the Ancestral Rocky highlands). While this solution is quite plausible, more field observations are needed for positive verification.

The second part of the conflict, the nature of the Morrison climate, may be resolved if the Morrison area was subjected to the same 20,000 year climate cycles which have affected both Pleistocene and Devonian lakes (Donovan, 1981). With this in mind, the best way to augment and develop the study offered here is by a further more intensive study of the lacustrine deposits, including stable isotope data.

BIBLIOGRAPHY

Allen, J. R., 1965a, The Sedimentation and Paleogeography of the Old Red Sandstone of Anglesey, North Wales. Proc. Yorks. Geol. Soc., Vol. 35, pp. 139-185.

Al-Shaieb, Z. and Shelton, J. W., 1981, Migration of Hydrocarbons and Secondary Porosity in Sandstones: Amer. Assoc. Petrol. Geol. Bull., Vol. 65, No. 11, pp. 2433-2436.

Berman, A. E., Poleschook, D., Dimelow, T. E., 1980, Jurassic and Cretaceous Systems of Colorado, in Colorado Geology, Rocky Mount. Assoc. Geol., Denver, pp. 111-128.

Blatt, H., 1982, Sedimentary Petrology: W. H. Freeman, San Francisco.

Boles, J. R. and Franks, S. G., 1979, Clay Diagenesis in Wilcox Sandstones of Southwest Texas: Implications of Smectite Diagenesis on Sandstone Cementation: Jour. Sed. Pet., Vol. 49, No. 1, pp. 0055-0070.

Boos, M. C. and Boos, M. F., 1957, Tectonics of the Eastern Flank and Foothills of Front Range Colorado: Amer. Assoc. Petrol. Geol. Bull., Vol. 41, No. 12, pp. 2603-2676.

Boyer, B. W., 1981, Tertiary Lacustrine Sediments From Sentinel Butte, North Dakota and the Sedimentary Record of Ectogenic Metromins: Jour. of Sed. Pet., Vol. 51, No. 2, pp. 429-440.

Bradley, W. H. and H. P. Eugster, 1969, Geochemistry and Paleolimnology of Trona Deposits and Associated Authigenic Minerals of the Green River Form of Wyoming: U.S. Geol. Survey Prof. Paper 496-B, 71 pp.

Brady, L. L., 1967, Stratigraphy and Petrology of the Morrison Formation (Jurassic) in the Vicinity of Canon City, Colorado: Unpublished Master's Thesis, University of Kansas, 111 pp.

______, 1969, Stratigraphy and Petrology of the Morrison Formation of the Canon City, Colorado Area: Jour. of Set. Pet., Vol. 39, pp. 632-648.

Branson, C. C., 1935, Fresh-Water Invertebrates from the Morrison of Wyoming, Jour. of Paleontology, Vol. 9, No. 6, pp. 514-522.

Carlston, C. W. 1965, The Relation of Free Meander Geometry to Stream Discharge and its Geomorphic Implications: Am. Jour. Sci., Vol. 263, pp. 864-885.

Chowns, J. M. and Elkins, J. E., 1974, The Origin of Quartz Geodes and Cauliflower Cherts Through Silification of Anhydrite Nodules: Jour. of Sed. Pet., Vol. 44, pp. 885-903.

Coleman, J. M. and Prior, D. B., 1983, Deltaic Environments of Deposition: in Sandstone Depositional Environments, eds. Scholle, P. A. and Spearing, D., Amer. Assoc. Petro. Geol., Tulsa, 410 pp.

Cope, E. D., 1877a, On Reptilian Remains from the Dakota Beds of Colorado: Am. Philos. Soc. Proc., Vol. 17, pp. 193-196.

______, 1877b, On Gigantic Saurian from the Dakota Epoch of Colo: Paleontological Bull., No. 25, 9 p.

______, 1878, A New Genus of Dinosauria from Colorado: Am. Naturalist, Vol. 12, pp. 188-189.

Curtis, B. F., 1960, Major Geologic Features of Colorado: in Guide to the Geology of Colorado, Rocky Mount. Geol., pp. 1-9.

Craig, L. C., et al., 1955, Stratigraphy of the Morrison and Related Formations, Colorado Plateau Region - a Preliminary Report: U.S. Geol. Survey Bull. 1009-E, pp. 125-168.

Cross, W., 1894, Description of the Pikes Peak Sheet: U.S. Geol. Survey, Geol. Atlas, folio 7.

Desborough, G. A., 1978, A Biogenic-chemical Stratified Lake Model for the Origin of Oil Shale of the Green River Formation: An Alternative to the Playa Model: Geol. Soc. of Amer. Bull., Vol. 89, pp. 961-971.

Dodd, R. J., 1966, Processes of Conversion of Aragonite to Calcite with Examples from the Cretaceous of Texas: Jour. of Sed. Petr., Vol. 36, No. 3, pp. 733-741.

Dodson, P., Behrensmeyer, A. K., Bakker, R. T., 1980, Taphonomy and Paleoecology of the Dinosaur Beds of the Jurassic Morrison Formation: Paleobiology, Vol. 6, No. 2, pp. 208-282.

Donovan, R. N., 1975, Devonian Lacustrine Limestone at the Margin of the Orcadian Basin, Scotland: J. Geol. Soc. Loud., Vol. 131, pp. 489-510.

Donovan, R. N., 1978, Origin of Complex Sulphide Nodules Related to the Diagenesis of Lacustrine Sediments of Middle Devonian Age from Shetland Islands: Scott. J. Geol., Vol. 14, No. 4, pp. 289-299.

Donovan, R. N., 1984, Personal Communication.

Dott, R. H., Jr. and Kocurek, G., 1983, Jurassic Paleogeography and Paleoclimate of the Central and Southern Rocky Mountain Region: in Mesozoic Paleogeography of West-Central United States, Rocky Mount. Section, Soc. Econ. Paleo. and Min., pp. 101-119.

Eldridge, G. H., 1894, Description of the Anthracite-Crested Butte Sheets: U.S. Geol. Survey, Geol. Atlas, folio 9.

Eugster, H. P. and Hardie, L. A., 1975, Sedimentation in an Ancient Playa-Lake Complex: The Wilkins Peak Member of the Green River Formation of Wyoming: Geol. Soc. of Am. Bull., Vol. 86, pp. 319-334.

Eugster, H. P. and Hardie, L. A., 1978, Saline Lakes: in Lakes, Chemistry Geology Physics, ed. Abraham Lerman, Springer-Verlag New York, 363 pp.

Fahey, J. J., 1962, Saline Minerals of the Green River Formation: U.S. Geol. Survey Prof. Paper 405, 50 pp.

Folk, R. L. and Pittman, J. S., 1971, Length-Slow Chalcedony: A New Testament for Vanished Evaporites: Jour. Sed. Petr., Vol. 41, No. 4, pp. 1045-1058.

Frederickson, E. A., DeLay, J. M., Taylor, W. W., 1956, Ralston Formation of Canon City Embayment, Colorado: Amer. Assoc. Petrol. Geol., Vol. 40, No. 9, pp. 2120-2148.

Friedman, G. M., 1965, Terminology of Crystallization Textures and Fabrics in Sedimentary Rocks: Jour. of Sed. Petr., Vol. 35, No. 3, pp. 643-655.

Friedman, G. M., 1979, Dolomite is Evaporite-Mineral Evidence from Rock Record and from Sea-Marginal Pools of the Red Sea: Amer. Assoc. Petr. Geol. Bull., Vol. 63, No. 3, pp. 453-454.

Goddard, E. N., et al., 1948, Rock-Color Chert: Washington, Nat'l Research Council.

Habicht, J. K. A., 1979, Paleoclimate, Paleomagnetism, and Continental Drift: AAPG Studies in Geology No. 9, AAPG, Tulsa, Okla.

Hatcher, J. B., 1901, The Jurassic Dinosaur Deposits near Canon City, Colorado: Annals Carnegie Museum, Vol. 1, pp. 327-341.

______, 1903a, A new sauropod dinosaur from the Jurassic of Colorado: Biol. Soc. Wash. Proc., Vol. 16, p. 1.

______, 1903b, Osteology of Haplocanthosaurus with Description of a New Species, and Remarks on the Probable Habits of the Sauropoda and the Age of the Atlantosaurus Beds: Carnegie Mus. Mem. Vol. 2, p. 27.

Jones, T. R., 1886, On Some Fossil Ostracods from Colorado: Geol. Mag., Vol. 3, pp. 145-148.

Keller, W. D., 1953, Illite and Montmorillonite in Green Sedimentary Rocks: Jour. of Sed. Petr., Vol. 23, No. 1, pp. 3-9.

______, 1953, Clay Minerals in the Type Section of the Morrison Formation: Jour. of Sed. Pet., Vol. 23, No. 2, pp. 93-105.

______, 1962, Clay Minerals in the Morrison Formation of the Colorado Plateau: U.S. Geol. Survey Bull. 1150, pp. 1-90.

______, 1970, Environmental Aspects of Clay Minerals: Jour. of Sed. Petr., Vol. 40, pp. 488-813.

Kelts, K. and Hsn, K. J., 1978, Freshwater Carbonate Sedimentation: in Lakes Chemistry Geology Physics, ed. Abraham Lerman, Springer-Verlag, New York, pp. 295-321.

King, R. J. and Merriam, D. F., 1969, Origin of the "Welded Chert" Morrison Formation (Jurassic), Colorado: Bull. Geol. Soc. Amer., Vol. 80, pp. 1141-1148.

Krauskopf, K. B., 1979, Introduction to Geochemistry, McGraw Hill Book Company, New York, 206 pp.

Lee, W. T., 1902, Morrison Shales of Southern Colorado and Northern New Mexico: Jour. Geol., Vol. 10, pp. 36-58.

Leeder, M. R., 1973, Flaviatite Fining - Upwards Cycles and the Magnitude of Paleochannels: Geol. Mag., Vol. 110, pp. 265-276.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1966, *Fluvial Processes in Geomorphology*: Freeman, San Francisco, 522 pp.

Logan, W. W., 1900, The Stratigraphy and Invertebrate Faunas of the Jurassic Formation in the Freeze-out Hills of Wyoming: Kan. Univ. Quart., Vol. 19, pp. 109-134.

Marsh, O. C., 1877, Notice of New Dinosaur Reptiles from the Jurassic Form: Am. Jour. Sci., 3rd Ser., Vol. 14, pp. 514-516.

_____, 1877a, Notice of New Dinosaurian Reptiles: Am. Jour. Sci., 3rd Ser., Vol. 16, pp. 411-416.

_____, 1878b, Principal Characters of American Jurassic Dinosaurs: Part I: Am. Jour. Sci., 3rd Ser., Vol. lb, pp. 411-416.

Marsh, O. C., 1891, Vertebrate Fossils in *Geology of the Denver Basin in Colorado*: U.S. Geol. Survey Mon. 27, pp. 478-550.

Meek, F. B. and Hayden, F. V., 1861, Descriptions of New Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary Fossils Collected in Nebraska Territory with Some Remarks on the Rock from Which they were Obtained: Acad. Nat. Sci. Philadelphia, Proc., pp. 415-447.

Milton, C., 1957, Authigenic Minerals of the Green River Formation of the Unita Basin, Utah: in *Guidebook to the Geology of the Unita Basin*, Intermountain Assoc. of Petr. Geol., No. 8, pp. 136-143.

Milton, C. and Engster, H. P., 1959, Mineral Assemblages of the Green River Formation: in *Researchers in Geochemistry*, John Wiley & Sons, Inc., New York, pp. 118-150.

Mirsky, A., 1962, Stratigraphy of Non-marine Upper Jurassic and Lower Cretaceous Rocks, Southern Big Horn Mountains, Wyoming: Amer. Assoc. Petr. Geol. Bull., Vol. 46, No. 9, pp. 1653-1680.

Mook, C. C., 1916, Study of the Morrison Formation: Annals N. Y. Acad. Sci., Vol. 27, pp. 39-191.

Ogden, L., 1954, Rocky Mountain Jurassic Time Surface: Amer. Assoc. Petr. Geol., Vol. 38, pp. 914-916.

Oriel, S. S. and Craig, L. C., 1960, Lower Mesozoic Rocks: Weimer, H. J. et al., eds., in *Guide to the Geology of Colorado*: Rocky Mount. Assoc. Geol., p. 43-58.

Osborn, H. F., 1931, Cope Master Naturalist: Princeton Univ. Press, London, 287 pp.

Peterson, J. A., 1972, Jurassic System: in Geologic Atlas of the Rocky Mountain Region, Mallory, W. W. ed., Rocky Mount. Assoc. of Geol., pp. 177-189.

Pettijohn, F. J., 1975, Sedimentary Rocks: Harper and Row, Publ., New York, 628 pp.

Ragland, D. A., 1983, Sedimentary Geology of the Ordovician Cool Creek Formation as it is Exposed in the Washita Mountains of Southwestern Oklahoma: Unpublished Master's Thesis, Oklahoma State University, 144 pp.

Reading, H. G., 1980, Sedimentary Environment and Facies: Elsevier, New York, 557 pp.

Reeves, C. C., 1968, Introduction to Paleolimnology: Elsevier Publishing Co., Amsterdam, 228 pp.

Reineck, H. E., and I. B. Singh, 1980, Depositional Sedimentary Environments, Springer-Verlag, New YOrk, 549 pp.

Roth, R., 1933, Some Morrison Ostracoda: Jour. of Paleo., Vol. 7, pp. 393-405.

Roth, R., 1934, Some Morrison Ostracoda: Jour. of Paleo., Vol. 7, pp. 398-405.

Ryder, R. T., Fouch, T. O., Elison, J. H., 1976, Early Tertiary Sedimentation in the Western Unita Basin, Utah: Bull. Geol. Soc. Amer., Vol. 87, pp. 496-512.

Scholle, R. A., 1978, A Color Illustrated Guide to Carbonate Rock Constituents, Textures, Cements and Porosities: Amer. Assoc. Petr. Geol. Bull., Memoir 27, Tulsa, 241 pp.

Scholle, P. A., 1979, A Color Illustrated Guide to Constituents, Textures, Cements and Porosity of Sandstones and Associated Rocks: Amer. Assoc. Petro. Geol. Bull., Memoir 28, Tulsa, 201 pp.

Schulze, J. D., 1954, The Pre-dakota Geology of the Northern Half of the Canon City Embayment, Colorado: Unpublished Master's Thesis, University of Oklahoma, 163 pp.

Siedilecka, A., 1972, Length-slow Chalcedony and Relicts of Sulphates - Evidences of Evaporitic Environments in the Upper Carboniferous and Permian Beds of Bear Island, Svalbard: Jour. Sed. Pet., Vol. 42, No. 4, pp. 812-816.

Simpson, G. G., 1926, The Age of the Morrison Formation: Am. J. Sci., Vol. 5, No. 12, pp. 198-216.

Stanley, K. O., Surdham, R. C., 1978, Sedimentation on the Front of Eocene Gilbert-type Deltas, Washakie Basin, Wyoming, Jour. Sed. Pet., Vol. 48, No. 2, pp. 557-573.

Steiner, M. B. and Helsley, C. E., 1975, Late Jurassic Magnetic Polarity Sequence: Earth and Planetary Sci. Letters, Vol. 27, pp. 108-112.

Steiner, M. B., 1980, Investigation of the Geomagnetic Field Polarity During the Jurassic: Jour. of Geophys. Research, Vol. 85, No. 137, pp. 3572-3586.

Steiner, M. B., 1983, Mesozoic Apparent Polar Wander and Plate Motions of North America in Mesozoic Paleogeography of the West-central United States, Reynolds, M. W. and Dolly, D. D., eds., Rocky Mtn. Section of S.E.P.M., pp. 1-11.

Stokes, W. L., 1944, Morrison Formation and Related Deposits in and Adjacent to the Colorado Plateau: Bull. Geol. Soc. Amer., Vol. 55, pp. 951-995.

Tank, W. R., 1956, Clay Mineralogy of the Morrison Formation, Black Hills Area, Wyoming and South Dakota: Amer. Assoc. Petro. Geol. Bull., Vol. 40, No. 5, pp. 871-878.

Tucker, M. E., 1976, Quartz Replaced Anhydrite Nodules ("Bristol Diamonds") from the Triassic of the Bristol District: Geol. Mag., Vol. 113, No. 6, pp. 569-574.

Tucker, M. E., 1981, Sedimentary Petrology: John Wiley & Sons, New York, 250 pp.

Wahlstrom, E. E., 1966, Geochemistry and Petrology of the Morrison Formation Dillon, Colorado: Bull. Geol. Soc. Amer., Vol. 77, pp. 727-740.

Waldschmidt, W. A. and Leroy, L. W., 1944, Reconsideration of the Morrison Formation in the Type Area, Jefferson County, Colorado: Bull. Geol. Soc. of Amer., Vol. 55, pp. 1097-1114.

White, C. A., 1886, On the Fresh-water Invertebrates of the North American Jurassic: U.S. Geol. Survey Bull. 29.

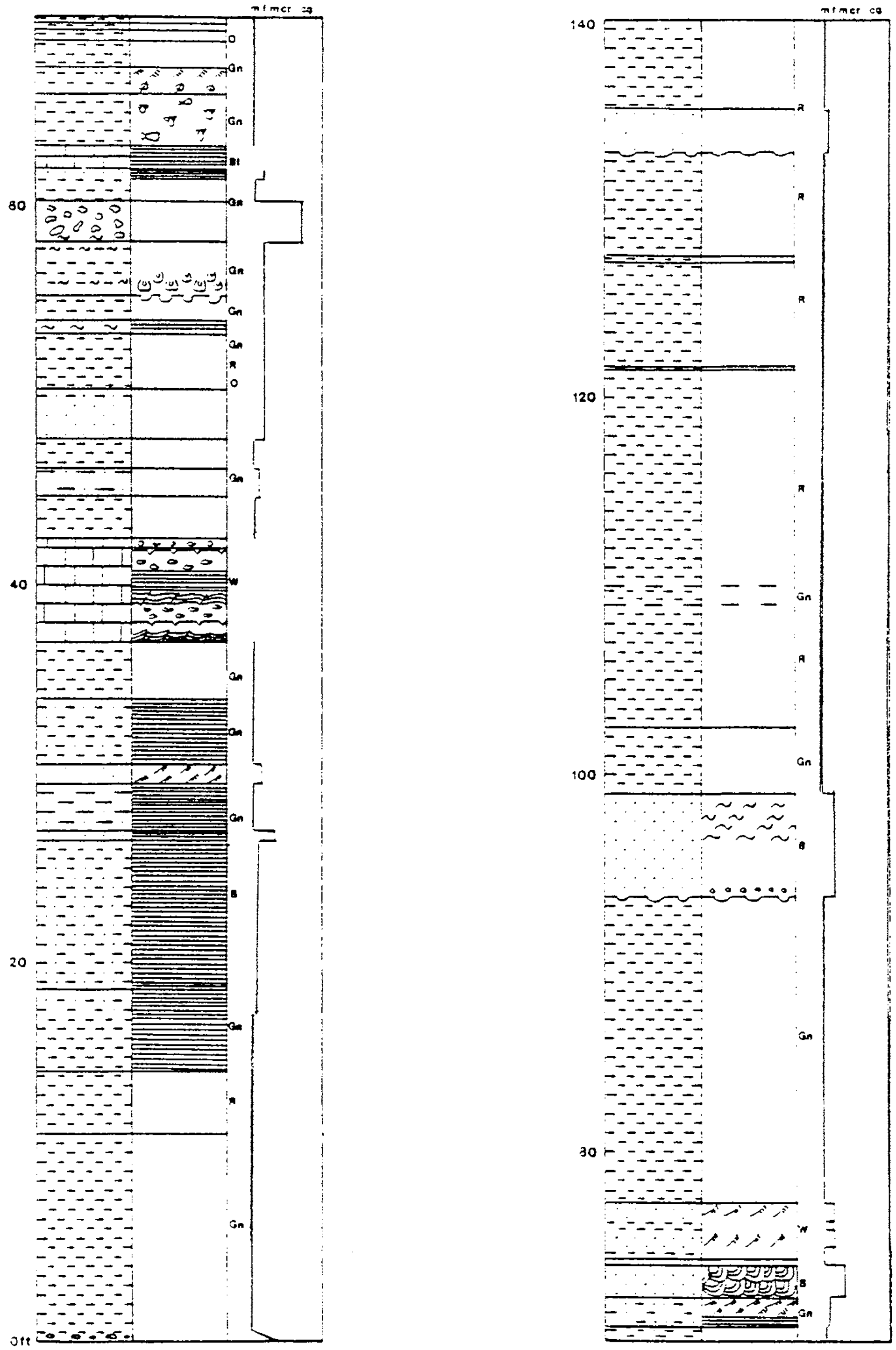
Wilson, M. D. and Pittman, E. D., 1977, "Authigenic Clays in Sandstones: Recognition and Influence on Reservoir Properties and Paleoenvironmental Analysis: Jour. of Set. Pet., Vol. 47, No. 1, pp. 3-31.

Yen, T. C., 1952, Molluscan Fauna of the Morrison Formation: U.S. Geol. Survey Prof. Paper 233B.

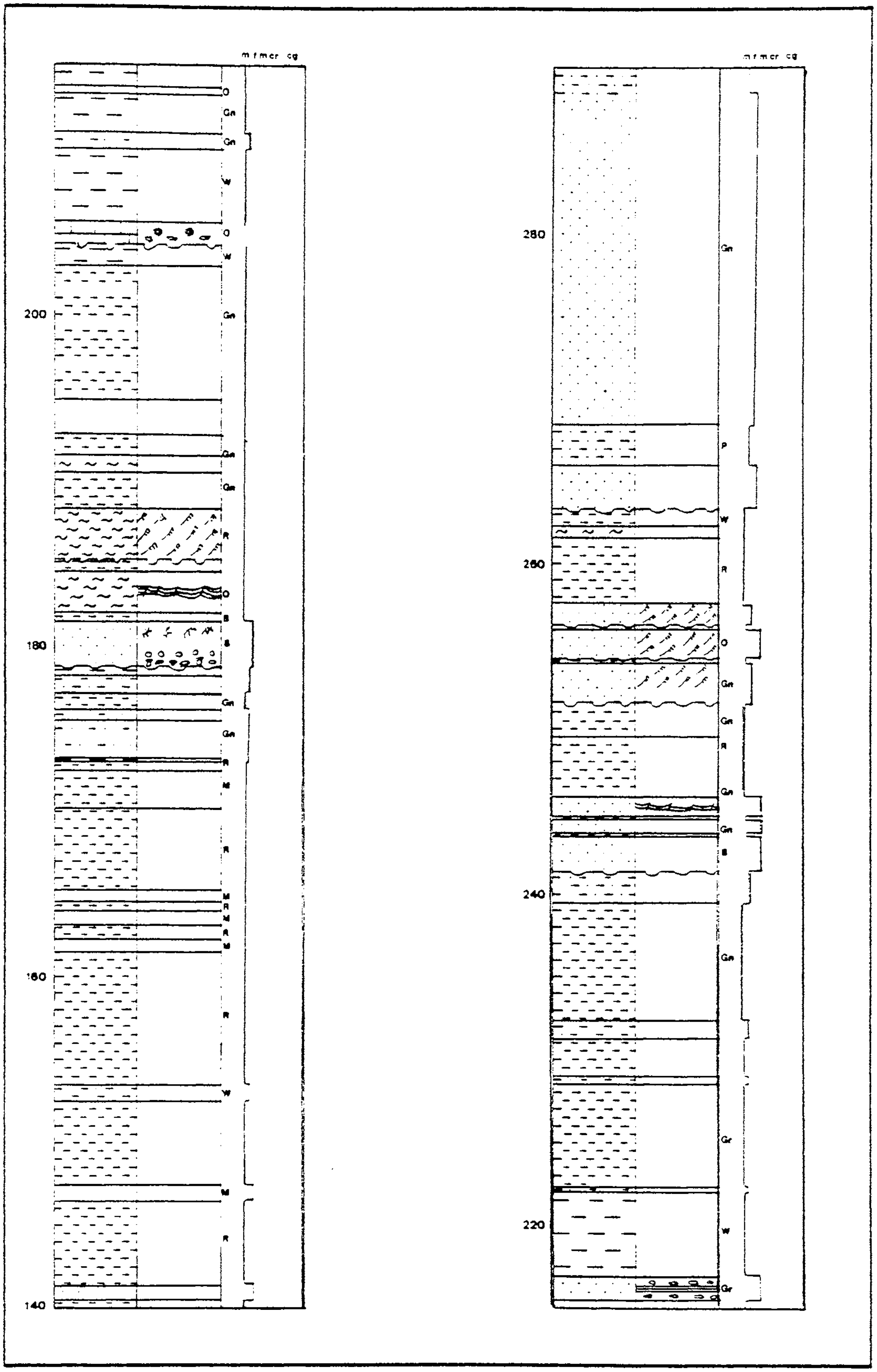
APPENDIX

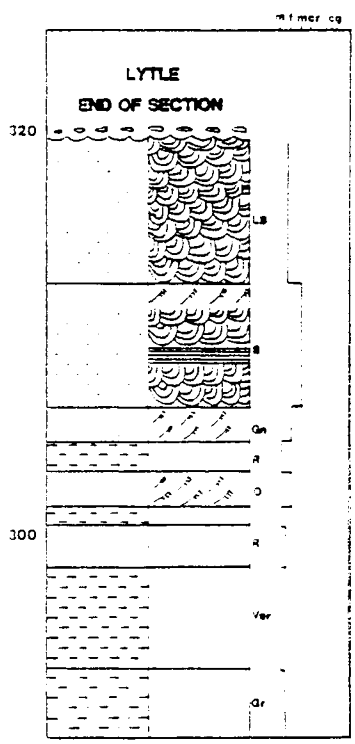
APPENDIX A

LOG OF THE MORRISON FORMATION AS IT IS EXPOSED AT GRAPE CREEK



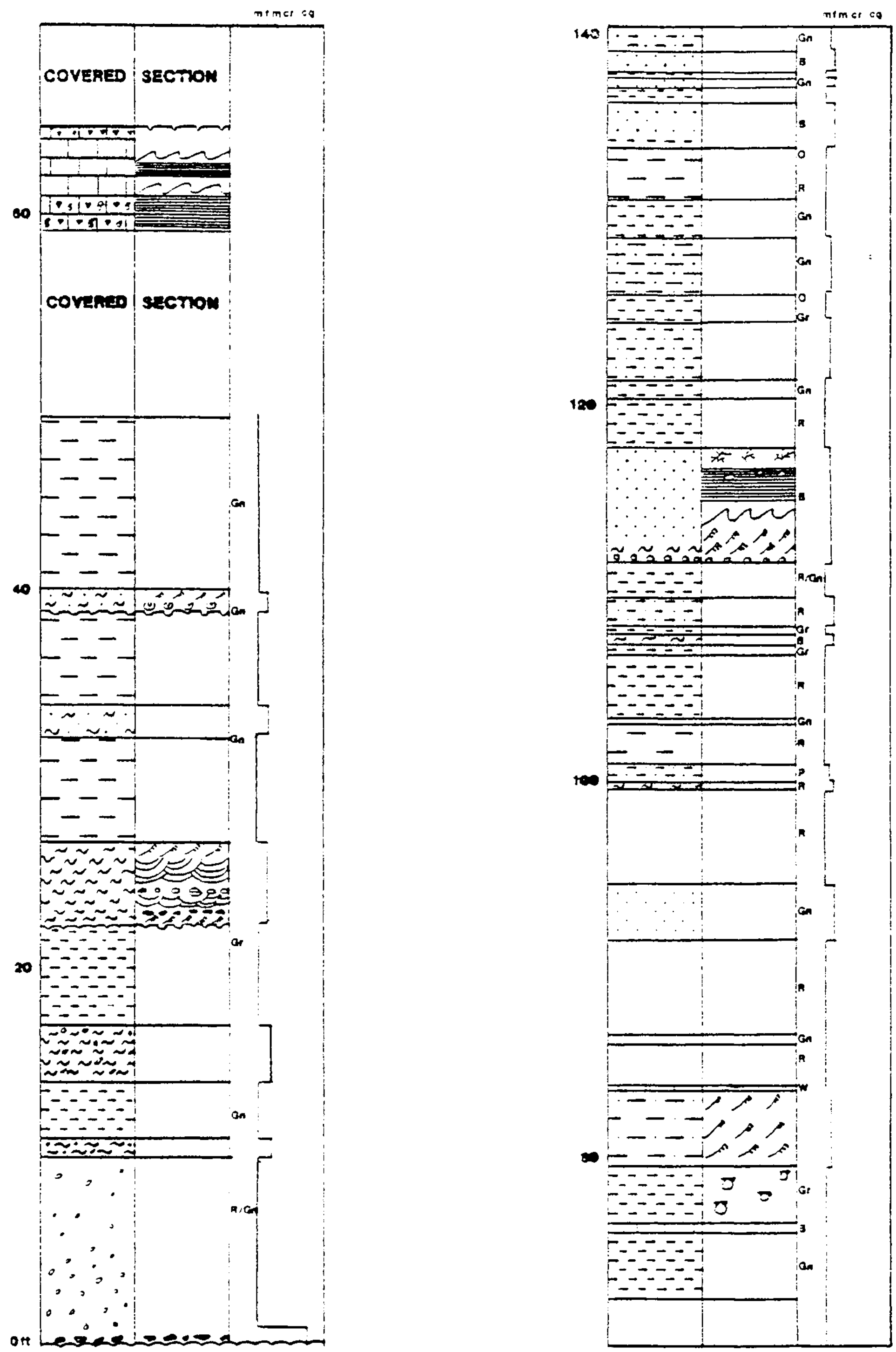
SEDIMENTARY LOG OF THE MORRISON FORMATION AS MEASURED AT GRAPE CREEK, CANON CITY, COLORADO



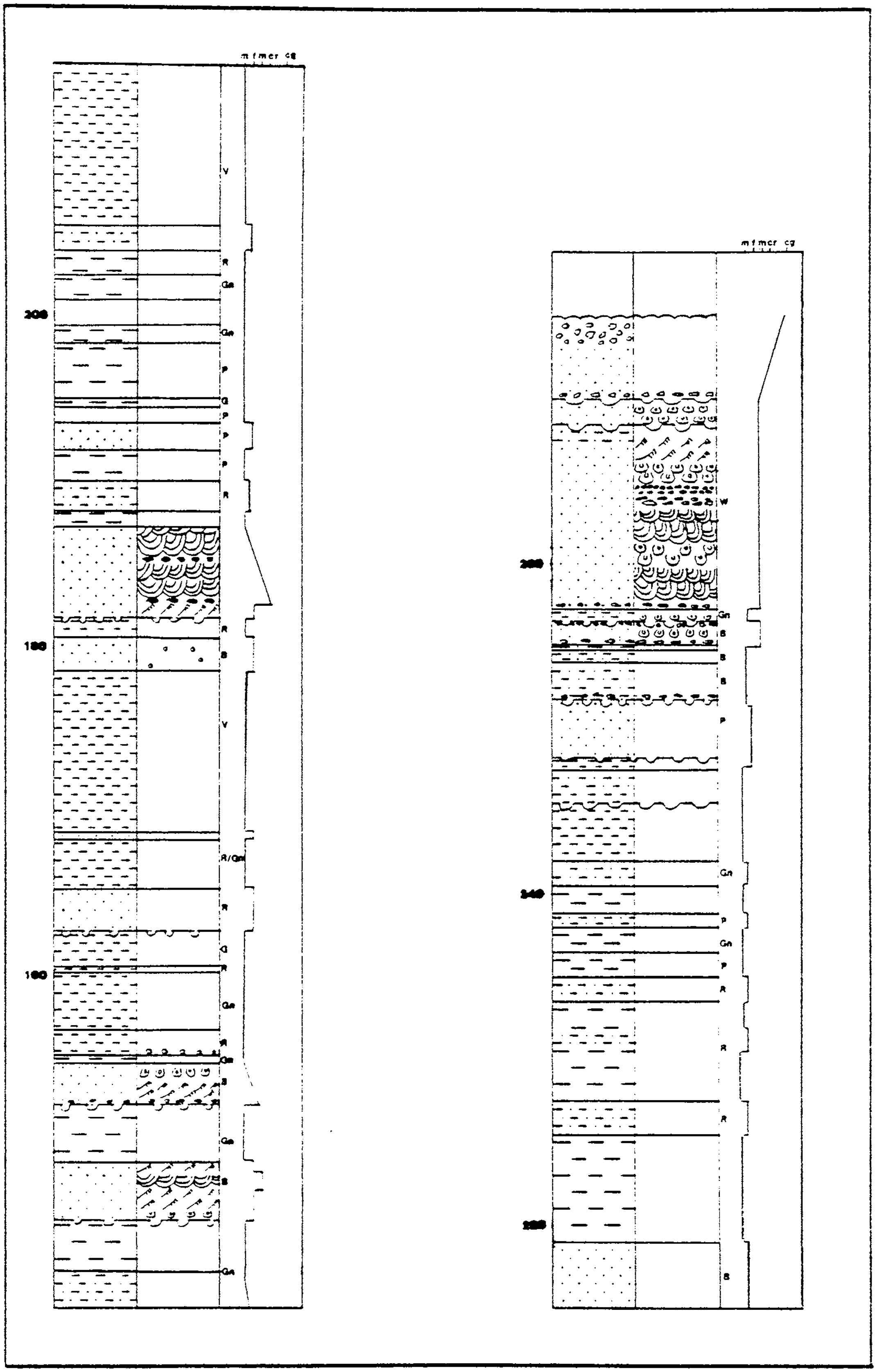

m f mcr cg
LYTLE
END OF SECTION
320
LS
Gn
R
300
R
Ver
Gr

APPENDIX B

LOG OF THE MORRISON FORMATION AS IT IS EXPOSED ALONG SKYLINE DRIVE

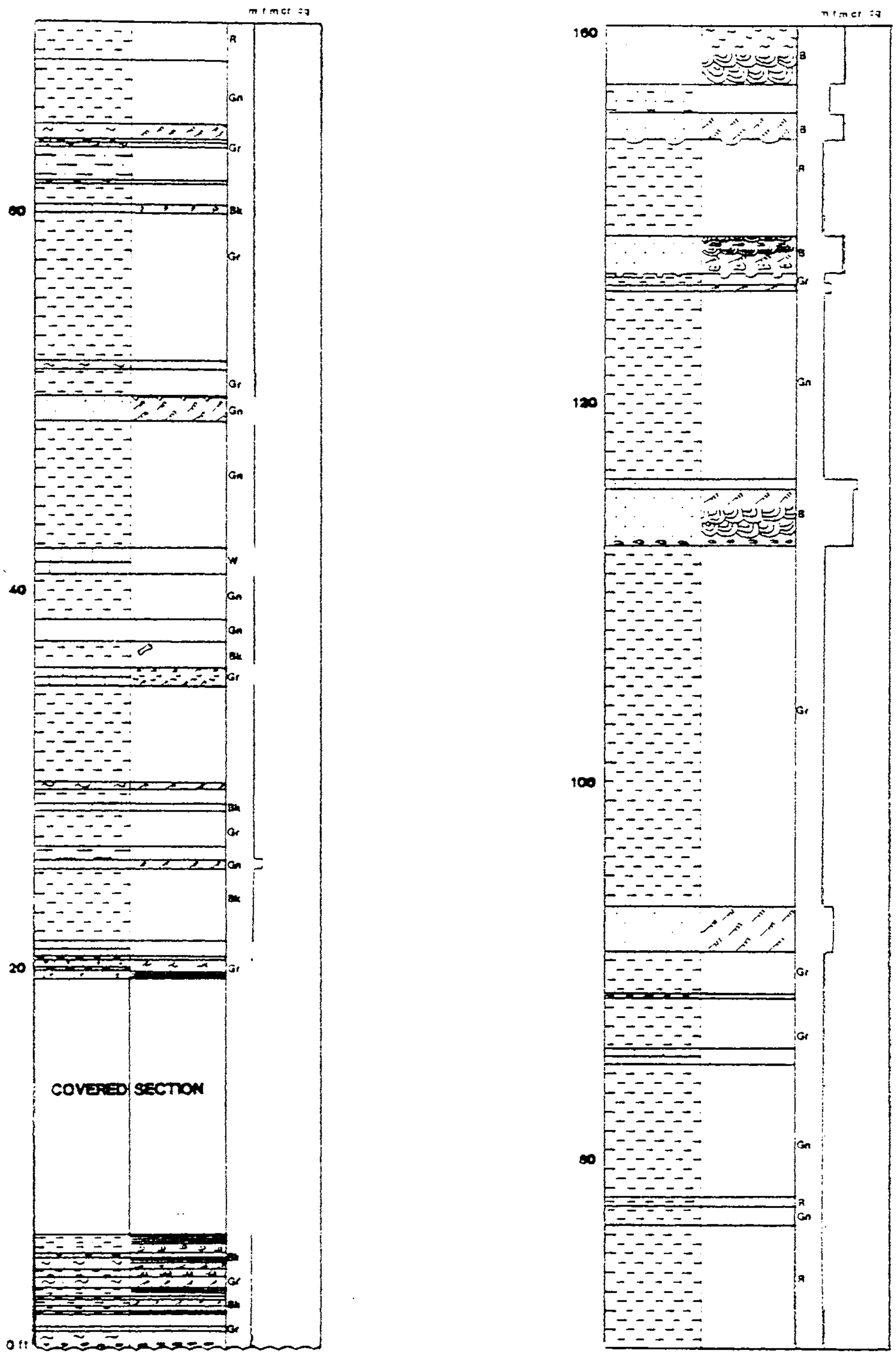


SEDIMENTARY LOG OF THE MORRISON FORMATION AS MEASURED ALONG SKY LINE DRIVE, CANON CITY, COLORADO


m f m c r cg
200
180
160
m f m c r cg
260
240
220

APPENDIX C

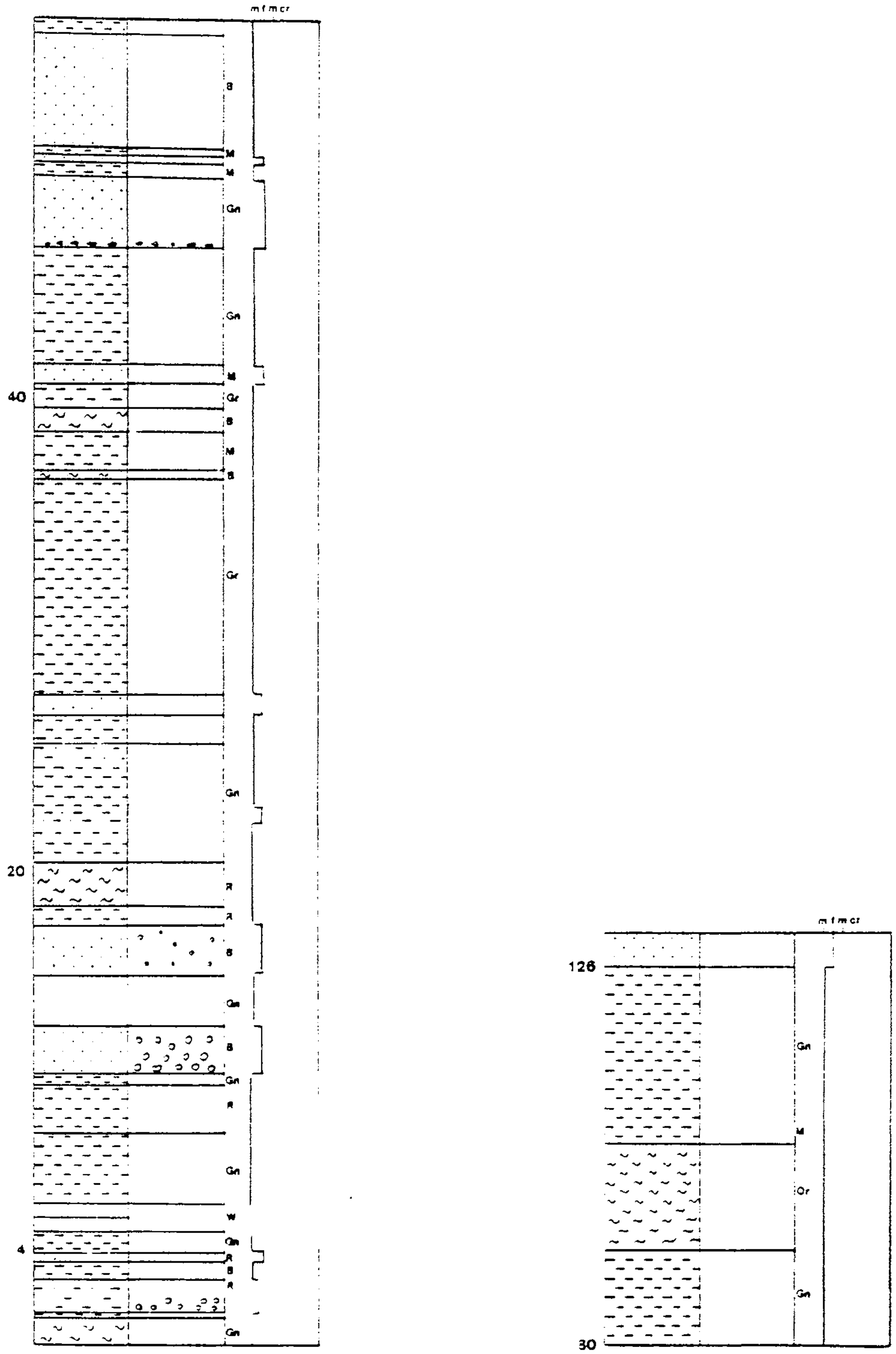
LOG OF THE MORRISON FORMATION AS IT IS EXPOSED AT GARDEN PARK



SEDIMENTARY LOG OF THE MORRISON FORMATION AS MEASURED AT GARDEN PARK , CANON CITY, COLORADO

APPENDIX D

LOG OF THE MORRISON FORMATION AS IT IS EXPOSED ALONG SIX MILE CREEK

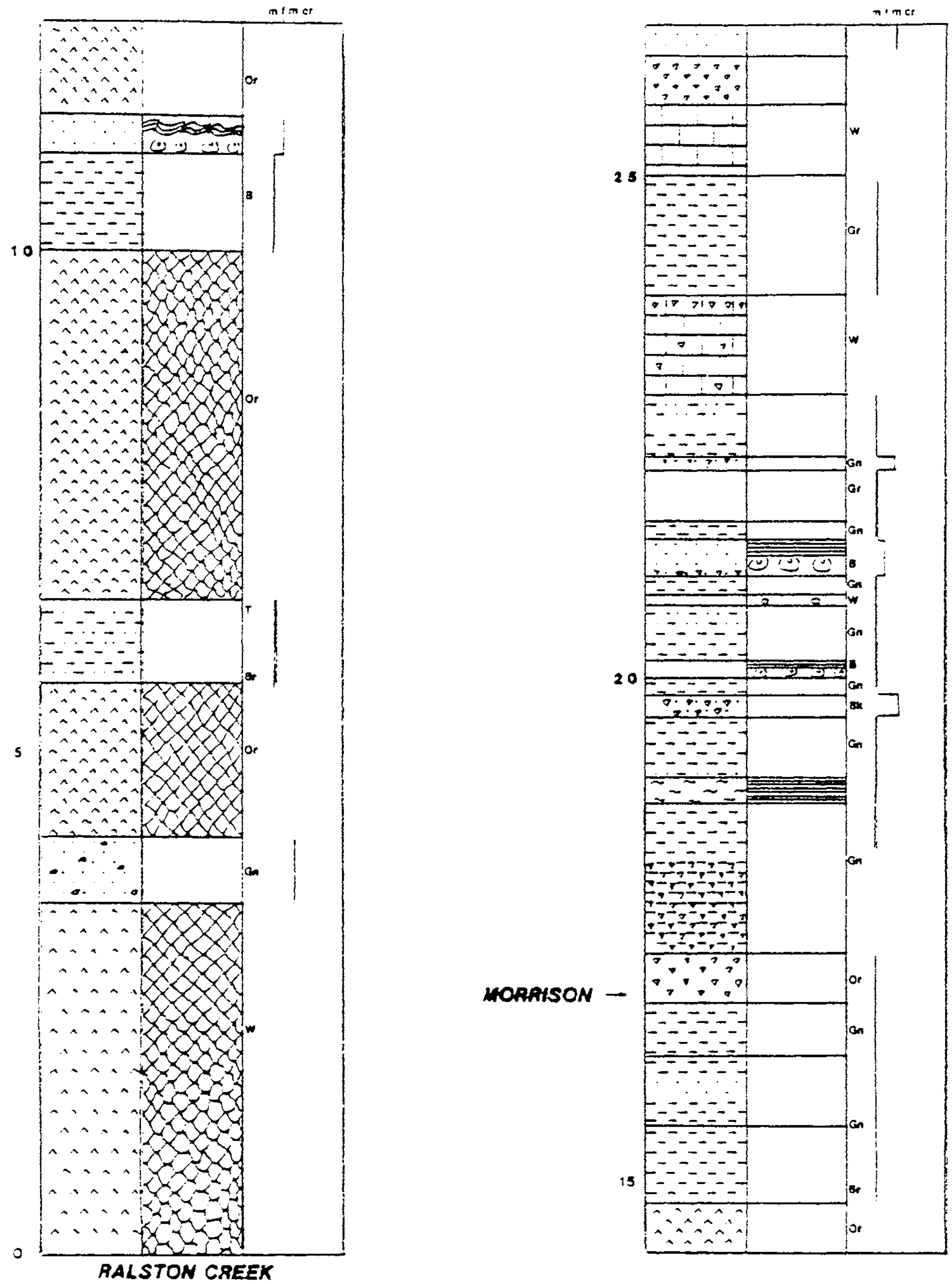


SEDIMENTARY LOG OF THE MORRISON FORMATION AS MEASURED

AT SIX MILE CREEK, CANON CITY, COLORADO

APPENDIX E

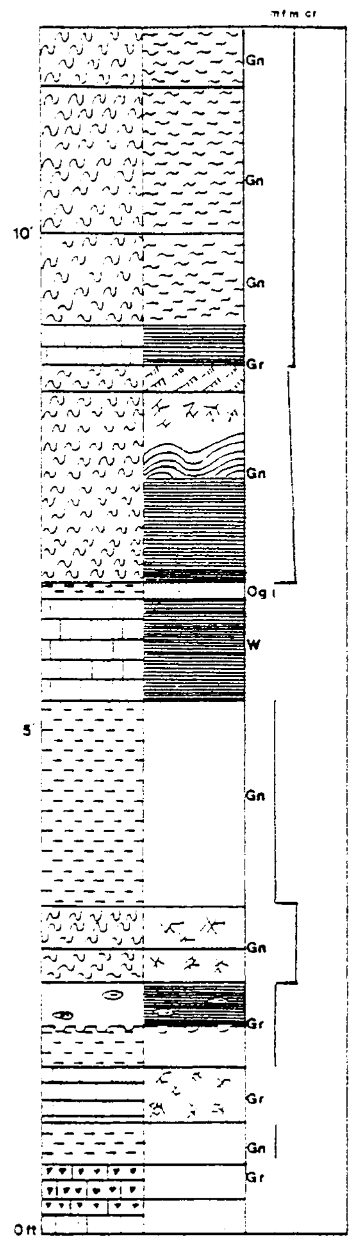
LOG OF THE BOC SECTION MEASURED EAST OF
THE BEAVER CREEK ROAD



SEDIMENTARY LOG OF THE MORRISON FORMATION FOR THE BOC SECTION MEASURED EAST OF BEAVER CREEK ROAD

APPENDIX F

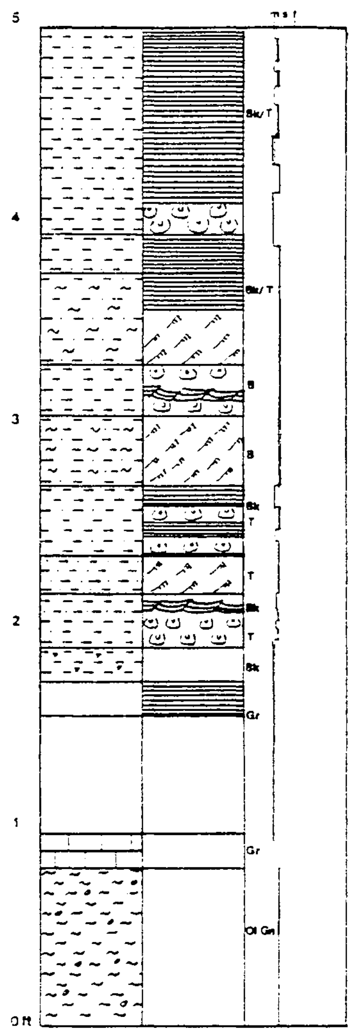
LOG OF THE DMC SECTION MEASURED EAST OF THE BEAVER CREEK ROAD



SEDIMENTARY LOG OF THE MORRISON FORMATION FOR THE DMC SECTION AS MEASURED EAST OF BEAVER CREEK ROAD

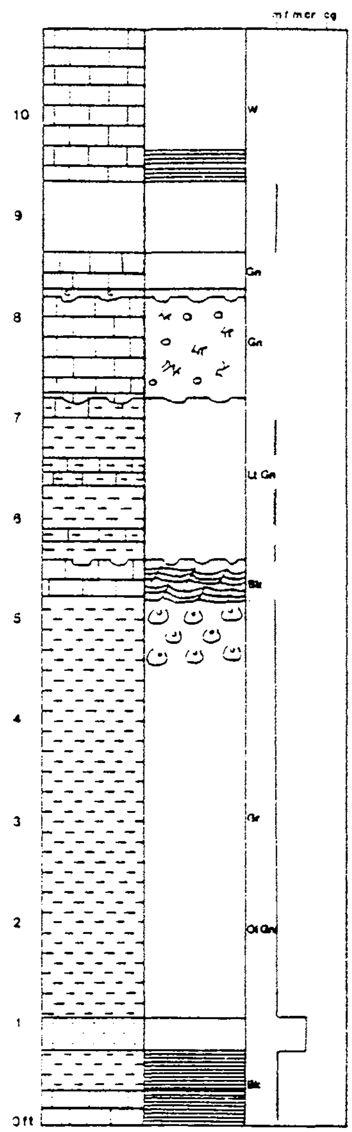
APPENDIX G

LOGS OF THE LACUSTRINE SEQUENCES MEASURED NEAR THE BASE OF THE FORMATION AT GARDEN PARK



LACUSTRINE SEQUENCE #1 LOCATED AT THE

BASE OF THE GARDEN PARK SECTION



LACUSTRINE SEQUENCE #2 LOCATED IN THE LOWER HALF OF GARDEN PARK AREA

APPENDIX H

THE ANATOMY OF A JURASSIC RIVER SYSTEM

THE ANATOMY OF A JURASSIC RIVER SYSTEM

R. Nowell Donovan and R. (Becky) Sweet

Introduction: The Setting

A few miles north of Canon City, Colorado, in the area known as Garden Park, a small and somewhat shabby monument pays tribute to two of the most famous and colorful scientists ever to wield a hammer and chisel. The more enduring aspect of their fame rests on their presentation to the (suitably impressed) world of 136 new species of animals, including such saurian behemoths as Brontosaurus and Allosaurus. Less endearing is the mutual hostility and venom which poisoned their personal relationship. If we award the laurels for geological argumentativeness to Sedgewick and Murchison, then we must in all fairness grant Marsh and Cope second place.

The one-time jealously-guarded excavations of both men can still be found and, with luck, it is still possible to find quite substantial bits of disarticulated dinosaur carcasses. The land across which the giant lizards roamed differed greatly from that seen in the area today. Few hills would have broken the skyline; the climate was warm and seasonal (latitude was c. 25-30°N). The dinosaurs lived in a world of sluggish meandering rivers, broad flood plains and (mostly) shallow lakes. The latter varied greatly in character; some were fresh and were home to large numbers of fish, gastropods and pelecypods, all of which were supported by prolific growths of algae. Other lakes, reflecting long-term changes in climate, were saline. There appears to have been two basic types of playa lake; those in which sulphates formed and those in which unusual sodium carbonate salts (trona and gaylussite) precipitated.

Here we will examine a single unit of sandstone which outcrops a mere 150 meters from the Marsh and Cope memorial. Our purpose is to quantify one of the components of the dinosaurs' habitat by determining the size and character of a river system which traversed the landscape which would eventually be preserved as the Upper Jurassic Morrison Formation.

The Rocks: Evidence for a Meandering River

The exposure, which is illustrated in Figure 70, is a steep cliff with a face which trends east-west. The lower part of the cliff consists of green mudstones and thin light grey limestones interpreted as recording the existence of shallow lakes and floodplains. These are overlain by a unit constructed of fine-coarse grained sandstones which has a spectacularly erosive base. Intraformational conglomerates

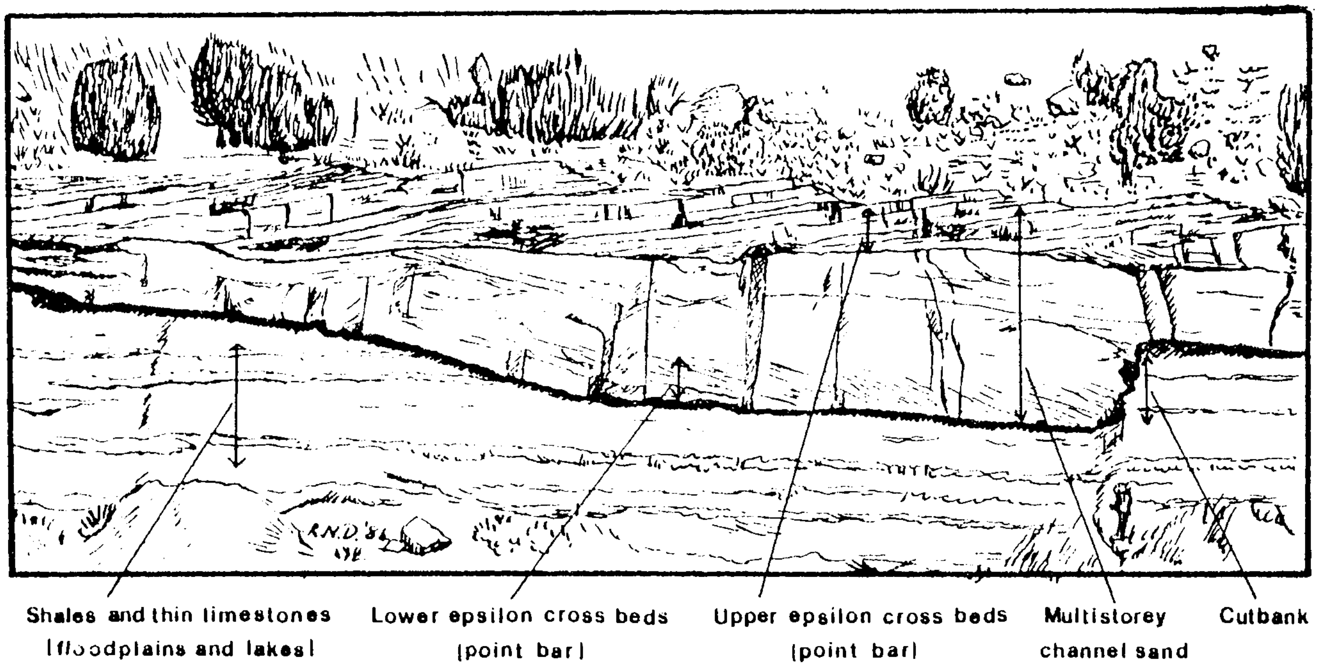


Figure 70. Schematic Diagram of the Point Bar Located at Garden Park

(which contain dinosaur bone fragments) are found at several levels in this unit and serve to define specific subunits (storeys).

Within each subunit, medium-scale trough cross beds indicate internally consistent current flow; however, a wide variability is seen to exist when several subunits are compared (Figure 58). Such a pattern suggests that the sandstone body as a whole has been constructed by a highly sinuous meandering stream with a general direction of flow to the south; each storey records the migration of a single meander.

Spectacular support for this interpretation is provided by the obviously asymmetric erosive profile of the base of the sandstone. The easiest explanation of this profile is that it records the incision of a meandering fluvial channel with a well-defined cut bank and point bar profile. This initial meander was migrating to the east before being abandoned.

A second line of support is the existence of two distinct horizons of epsilon crossbedding (Figure 70). Epsilon crossbedding, first defined by Allen (1965), records the lateral accretion of sediment as a result of episodic point bar migration. It is *prima facie* evidence for a meandering channel. The lower unit of epsilon crossbedding sits, with convenient exactitude, on the point bar profile of the lowest level of the sandstone. The upper epsilon unit occurs at the top of the sandstone and records the drawn-out and stilted farewell of a meander migrating to the west.

How "Big" Was the River?

Some estimate of the size of the river channels which moulded this particular Morrison sandstone can be deduced from three independent sources. These are (1) the cut bank/point bar profile at the bottom of the sandstone; (2) the lower set of epsilon cross beds; and (3) the upper epsilon cross beds. All three entities trend approximately perpendicular to the cliff and thus are suitably oriented for measurement. The lower epsilon cross beds are the weakest source; they are difficult of access, of limited extent and have been truncated by later meander migration. They are largely discounted in the following analysis. Table III gives appropriate dimensions.

By uniformitarian analogy, Allen (1965) has shown that the horizontal extent of an epsilon unit approximates to two-thirds of the channel bank full width. When applied to the upper epsilon cross beds, this approximation indicates a channel width of c. 25 m, a value which is in accord with the preserved channel profile.

TABLE III

DATA FOR POINT BAR LOCATED AT GARDEN PARK

Item	Thickness/ Depth	Width	Width/ Depth	Dip of Beds
Channel profile	2.52 m	28.1 m	11.2	
Lower epsilon beds	1.78 m	13.78m[a]	7.7	12^{o}[b]
Upper epsilon beds	2.67 m	16.67m[a]	6.2	12^{o}[b]

[a]Taken as the horizontal distance along which a distinct bedding surface can be traced.

[b]Dip values of the epsilon surfaces are typical of relatively small rivers and are well within the 95% confidence limit for rivers of the size indicated by the dimensions of the epsilon cross beds (Leeder, 1973).

Epsilon crossbedding is something of a rarity in the pantheon of hydrodynamic sedimentary structures. More usually students of fluvial geology simply assume that the thickness of the coarse member of a fining upward cycle is approximately equal to the bank full depth of the channel. Leeder (1973) has expressed the relationship between bank full depth (h) and channel width (w) observed in 57 modern rivers by the regression equation

$$w = 6.8\ h^{1.54} \qquad (1)$$

Using the formula (which has more general applicability than Allen's observation on epsilon cross beds) we obtain values as follows:

For the upper epsilon unit - $w = 28$ m
For the channel profile - $w = 26.4$ m

In both cases the derived values are compatible with the direct field observations which can be made at this site. Furthermore, the values fall well within the 95% confidence limits calculated by Leeder (1973).

Additional empirical equations allow us to further quantify our interpretation of the Morrison River. Free meander wavelength (Lm) is deduced as follows (from Leopold, Wolman and Miller, 1964)

$$Lm = 10.9\ w^{1.01} \qquad (2)$$

Using values obtained from equation (1) we get Lm = 308 m (upper epsilon cross beds) and Lm = 291 m (channel profile), i.e. meander wave length was c. 300 m.

Mean annual discharge ($\bar{Q}$) for a river of this size is given (by Carlton, 1965) as

$$Lm = 106\bar{Q}^{0.46} \qquad (3)$$

General values of $\bar{Q}$ obtained via equations (1), (2), and (3) indicate a mean annual discharge of c. 6 m^3 per second.

The various parameters determined here suggest that the particular Morrison River we are concerned with here was a modest-sized stream, perhaps comparable in size and behavior with the Washita River in the neighborhood of Pauls Valley.

Conclusions: The History of the River

The following history can be deduced from the data derived above, and from study of Figure 70. Four phases of development can be recognized. Phase one began with the entry of modest-size (flow c. 6 m^3/sec.) highly sinuous meandering river into the area. The initial incision of a channel into lacustrine limestones and floodplain mudstones was followed by some lateral migration to the east and the deposition of the lower epsilon cross beds. Phase two began with the channel abandonment (and the probable formation of an ox bow lake). This abandonment was not of long duration, for a clay plug did not develop. Instead the ox bow was filled with sand as the channel complex moved back into the area at the commencement of phase three, during which the river meandered back and forth within its meander belt. Multistoreyed sandstones demarcated by intraformational conglomerates record the journeys of individual meanders. The meanders were highly sinuous as is indicated by the wide variation of medium scale trough cross bedding modes (Figure 58). They had wave lengths of c. 300 m. In the fourth phase the final meander path to the west is indicated by the fully preserved epsilon cross bedding at the top of the sandstone. Subsequently terminal avulsion resulted in the complete abandonment of this meander belt.

References

Allen, J. R. L., 1965, The Sedimentation and paleogeography of the Old Red Sandstone of Anglescy, North Wales: Proc. Yorks. Geol. Soc., Vol. 35, pp. 139-85.

Carlston, C. W., 1965, The Relation of Free Meander Geometry to Stream Discharge and its Geomorphic Implications: Am. Jour. Sci., Vol. 263, pp. 864-85.

Leeder, M. R., 1973. Fluviatite Fining-Upwards Cycles and the Magnitude of Paleochannels: Geol. Mag., Vol. 110, pp. 265-276.

Leopold, L. B., Wolman, M. G. and Miller, J. P., 1966, Fluvial Processes in Geomorphology: Freeman, San Francisco, 522 pp.

APPENDIX I

LOCATIONS OF SECTIONS MEASURED IN THE VICINITY OF CANON CITY, COLORADO

LOCATIONS OF SECTIONS MEASURED

1. Grape Creek section:
   measured north of the municipal garbage dump
   C, SE, Sec. 1, T19S, R71W
   Fremont Co., Colorado

2. Skyline Drive section:
   measured 0.2 to 0.6 miles from turnoff on U. S. Highway 50
   W1/2, Sec. 20, T18S, R70W
   Fremont Co., Colorado

3. Garden Park section:
   measured 0.1 mile from the Garden Park Monument
   SE, SE, Sec. 28, T17S, R70W
   Fremont Co., Colorado

4. Six Mile Creek section:
   measured 100 feet west of the Phantom Creek Road
   C, SW, Sec. 9, T18S, R69W
   Fremont Co., Colorado

5. BOC section:
   measured approximately 750 yards east of the Beaver Creek Road
   NE, NE, SW, Sec. 11, T18S, R69W
   Fremont Co., Colorado

6. DMC section:
   measured approximately 450 feet east of the Beaver Creek Road
   C, SE, Sec. 20, T17S, R68W
   Fremont Co., Colorado

APPENDIX J

CATALOG OF REPRESENTATIVE THIN SECTIONS FROM THE MORRISON FORMATION

GRAPE CREEK

Approximate Location Above the Base of the Formation	Thin Section Number	Lithology
36'	GC 1	"White" Limestone
40'	GC 4	"White" Limestone
40'	WL S	"White" Limestone
40'	WL S	"White" Limestone
40'	WL 2	"White" Limestone
40'	WL 5	"White" Limestone
40'	NM 4	"White" Limestone
58' 4"	GC 12	"Black" Limestone
59' 4"	BL	"Black" Limestone
59' 4"	BL S	"Black" Limestone
59' 4"	BL 3	"Black" Limestone
59' 4"	BL S4	"Black" Limestone
59' 4"	16	"Black" Limestone
63' 3"	GC 14	Marl
81' 7"	GC 19	Quartz Pebble Cong.
87' 4"	GC 20	Sandstone
182'	GC 24	Marl
182'	GC 26	Marl
184' 5"	Chara	Limestone
188'	IFC	Conglomerate
191'	GC 29	Limestone
191'	GC 30	Limey Marl
240' 10"	GC 30	Sandstone
243' 10"	GC 39	Sandstone
248' 9"	GC 40	Sandstone
249' 9"	GC 41	Sandstone
289' 9"	GC 47	Sandstone
320'	Top of the Morrison	Conglomerate

SKYLINE DRIVE

25' 6"	SK 2	Sandstone
25' 6"	SK 2	Micrite
60' 8"	SK 4	Sandstone
112' 2"	SK 11	Marl
136' 2"	SK 18	Sandstone
136' 2"	SK 18	Sandstone
189' 9"	SK 29	Marl
225'	SK 37	Siltstone
251' 7"	SK 46	Sandstone
260'	SK 47	Sandstone
262' 5"	AXSKD-1	Sandstone
263' 5"	AXSKD-2	Conglomerate
?	RND-2	Conglomerate

BOC SECTION

Approximate Location Above the Base of the Formation	Thin Section Number	Lithology
3' 5"	BOC 4	Sandstone
4' 5"	BOC 5	Chert
4' 9"	BOC 6	Marl
5' 5"	BOC 8	Sandstone
7' 6"	BOC 10	Chert
________	BOC 10	Chert

DMC SECTION

30' 8"	DMC 1	Chert
31' 8"	DMC 2	Pseudomorphs
37'	DMC 6	Dolomite
38' 10"	DMC 7	Pseudomorphs
42' 6"	DMC 9	Sandstone

GARDEN PARK

Near the base	GP A	Sandstone
Near the base	GP F	Siltstone
Near the base	GP J	Dolomicrite
19' 6"	GP 1	Limestone
32' 5"	GP 5	Marl
32' 5"	GP 5	Marl
43'	GP 12	Limestone
46' 3"	GP 14	Sandstone
73' 8'	GP 16	Sandstone
91' 8"	GP Ch	Conglomerate
94' 8"	GP 17	Sandstone
115' 7"	GP 29	Sandstone

MISCELLANEOUS

	GH P	Siltstone
	S-12 (Six Mile Creek)	Sandstone
	DJM-2 (Bumback Gulch)	Limestone
	DJM J	Limestone
	Dino	Dinosaur Bone
	MO 3	Micrite
	MO 2	"Black" Limestone
	NM 6	Limestone
	NRC-1	Limestone
	NM 5	Limestone
	NM 7 (Skyline Drive)	"White" Limestone
	NM 2 (Skyline Drive)	"Black" Limestone

MISCELLANEOUS - Continued

Approximate Location Above the Base of the Formation	Thin Section Number	Lithology
	NM 11 (Grape Creek)	"Black" Limestone
	NM 1	Limestone
	RC	Chert
	DJM 4	Chert (White Limestone)
	Gastro	Chert
	NM 83	Chert
	NM 5	Chert

VITA

Rebecca Gail Sweet

Candidate for the Degree of

Master of Science

Thesis: A SEDIMENTARY ANALYSIS OF THE UPPER JURASSIC MORRISON FORMATION AS IT IS EXPOSED IN THE VICINITY OF CANON CITY, COLORADO

Biographical:

Personal Data: Born in Kermit, Texas, October 31, 1959, the daughter of Kenneth G. and Gail B. Sweet.

Education: Graduated from Putnam City High School, Oklahoma City, Oklahoma, in May, 1977; received Bachelor of Science degree in Geology from Oklahoma State University in December, 1981; completed requirements for the Master of Science degree at Oklahoma State University in May, 1984.

Professional Experience: Summer geologist for Grace Petroleum Corporation, Oklahoma City, Oklahoma, May to August, 1982 and from June to August, 1983; Graduate Teaching Assistant, Department of Geology, Oklahoma State University, August 1981 to December 1983.