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LACUSTRINE AND PALUSTRINE CARBONATES FROM THE MORRISON FORMATION (UPPER JURASSIC), EAST-CENTRAL COLORADO, USA: IMPLICATIONS FOR DEPOSITIONAL PATTERNS, PALEOECOLOGY, PALEOHYDROLOGY, AND PALEOCLIMATOLOGY

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Stan Porter Dunagan

August 1998

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DEDICATION

This dissertation is dedicated to my family:

F. Culton (1912 - 1990) & **Sara J. Porter** (1912 - 1987),

Horace H. Dunagan, Jr. (1925 - 1987),

Sara Z. Dunagan,

and

David N. and Cathy P. Dunagan,

who loved me with all their hearts and
who taught me practically every important lesson in life;

and

Stephanie C. Dunagan,

who loved and supported me throughout this consuming project.

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ABSTRACT

The Morrison Formation accumulated in the broad, shallow back-bulge depozone (Western Interior) of the Cordilleran foreland basin system during the Late Jurassic (?Oxfordian/Kimmeridgian - Tithonian). In east-central Colorado, the alluvial plain deposits of the Morrison Formation are composed of a complex sequence of interbedded floodplain, fluvial, and lacustrine deposits with minor evaporite and marine deposits. Within this alluvial plain complex, a well-developed lacustrine succession is present, which consists of two distinct lacustrine facies associations – an open and a marginal lacustrine facies association.

The open-lacustrine facies association is composed of lacustrine carbonates (skeletal mudstone-wackestone and microbialites) and laminated mudstone. The marginal-lacustrine facies association consists of palustrine carbonates (carbonaceous packstone, intraclast wackestone-grainstone, peloid skeletal mudstone-wackestone, peloid skeletal packstone-grainstone, and micritic mudstone), ooid packstone-grainstone, green mudstone, siltstone, and sandstone. The paucity of well-laminated and organic-rich deposits indicates the water column of Morrison paleolakes was well-oxygenated, reflecting holomictic to polymictic conditions.

Facies and stratigraphic relationships suggest that Morrison paleolakes were characterized by a central open-lake settings that graded laterally and vertically into marginal-lacustrine and eventually into adjacent distal-alluvial environments. The open- and marginal-lacustrine facies associations display evidence for frequent subaerial exposure and modification resulting from pedogenic activity, pseudomicrokarst, and meteoric diagenesis. The abundance of these features indicates that Morrison lakes are

best characterized by low-gradient ('ramp'-type) margins that were subjected to periodic reworking by wind-driven currents, by storms and flood events, and where oscillations in lake level resulted in the exposure of large areas. High groundwater tables discharging into paleotopographic lows, with minor meteoric contributions, served as the primary water source for Morrison lakes.

A diverse biota was present in the carbonate lakes of the Morrison paleoecosystem. Charophytes, ostracodes, prosobranch and pulmonate gastropods, and unionid bivalves were commonly observed, with lesser amounts of spongillids, microbialites, and conchostracans. Bone fragments indicate fish, crocodiles, and dinosaurs also were present within and around the lakes and ponds. Trace fossils record the presence of insects, crayfish, plants, and dinosaurs within and along the margins of Morrison lakes and ponds. Wind-driven currents and periodic high-energy events as well as scavenging/oxidation of organic matter were the primary taphonomic processes acting on the fossil assemblages. The lacustrine carbonate deposits are dominated by disturbed and transported fossil assemblages, with minor mixed and in-place fossil assemblages. Paleontological data indicate Morrison lakes were primarily freshwater and were characterized by perennial to ephemeral, and hydrologically open to closed conditions.

Sedimentologic evidence indicates that a wide range of hydroperiods (15-325 days) characterized the lake settings. The major factors controlling carbonate sedimentation were the low clastic input, due to the distal alluvial setting and the presence of a clastic-filtering fringe of macrophytes along lake margins, and the abundance of a prolific carbonate-producing biota (i.e., charophytes).

The results of stable isotope geochemistry revealed a lack of strong covariant trends ($r = 0.1$ to 0.50), which indicates that Morrison lakes were primarily hydrologically open. Isotopically-depleted soil CO_2 due to pedogenic modification produced the heterogeneous $\delta^{13}C$ values associated with the marginal-lacustrine (i.e., palustrine) deposits. The abundance and type of pseudomicrokarst associated with the lacustrine carbonate succession indicates the Late Jurassic climate was characterized by a distinct wet and dry season that was intermediate between semi-arid and sub-humid conditions. Magadi-type cherts and minor evaporites indicate intervals within the lacustrine succession when the climate temporarily deteriorated to more semi-arid conditions and the water column was more alkaline-saline. However, the lack of evaporites capping lacustrine sequences suggests the lakes maintained primarily freshwater, and probably hydrologically-open, conditions during carbonate precipitation. Stable isotope compositions also point toward non-evaporated lake waters, at least during carbonate deposition, due to the lack of covariant trends. The evolution of Morrison lakes apparently was driven by filling of the accommodation space as open-lacustrine facies aggraded and marginal-lake facies prograded into the central portions of the lake.

Lacustrine deposition does not appear to have been continuous in space and time in east-central Colorado and distribution of the lakes probably represents variations in local and regional accommodation space. The lakes and ponds occupied paleotopographic lows which locally formed as a result of differential compaction of Morrison and underlying clastic sediments as well as regional subsidence associated with the Denver-Julesburg basin, which produced a slightly irregular depositional topography.

TABLE OF CONTENTS

Chapter **Page**

1. **INTRODUCTION** 1
   - PURPOSE AND SIGNIFICANCE 1
   - TECTONIC SETTING AND PALEOGEOGRAPHY 5
   - AGE OF THE MORRISON FORMATION 10
   - REGIONAL STRATIGRAPHY 10
     - Middle Jurassic Series 11
     - Upper Jurassic Series 13
     - Lower Cretaceous 15
   - PREVIOUS INVESTIGATIONS OF THE MORRISON FORMATION 15
     - Paleontology 16
     - Sedimentology and Stratigraphy 17
   - INVESTIGATIVE METHODS 22
   - DISSERTATION ORGANIZATION 23

2. **CONTROLS ON LACUSTRINE AND PALUSTRINE CARBONATE DEPOSITION WITHIN A LATE JURASSIC PALEOECOSYSTEM, THE MORRISON FORMATION (EAST-CENTRAL COLORADO, USA)** 24
   - INTRODUCTION 24
   - METHODS 27
   - PREVIOUS INVESTIGATIONS 28
   - LACUSTRINE FACIES ASSOCIATIONS 30
     - Facies Association A: Open Lacustrine 32
       - *Facies A_1 (lacustrine carbonates)* 32
       - *Facies A_2 (dark laminated mudstone)* 41

Interpretations 42

Facies Association B: Marginal Lacustrine 44

Facies B_1 (palustrine carbonates) 44

Facies B_2 (ooid packstone/grainstone) 58

Facies B_3 (green mudstone) 58

Facies B_4 (siltstone) 59

Facies B_5 (sandstone) 59

Interpretations 60

DISCUSSION 62

Lacustrine Deposition 62

Idealized Facies Models 66

Paleohydrology 68

CONCLUSIONS 70

3. PALEOSYNECOLOGY AND PALEOLIMNOLOGY OF LATE JURASSIC PERENNIAL TO EPHEMERAL CARBONATE LAKES AND PONDS (MORRISON FORMATION, COLORADO) 72

INTRODUCTION 72

METHODS 74

STRATIGRAPHIC AND SEDIMENTOLOGIC OVERVIEW 75

LACUSTRINE PALEONTOLOGY 75

Charophytes 75

Ostracodes 80

Conchostracans 81

Spongillids 82

Gastropods 86

Unionid Bivalves 90

Microbialites 91

Vascular Plants 94

Vertebrate Remains 96

Lacustrine Ichnology 97

DISCUSSION 102

PALEOLIMNOLOGICAL SYNTHESIS 104

CONCLUSIONS 105

4. INSIGHTS INTO LATE JURASSIC PALEOLIMNOLOGY AND HYDROGEOCHEMISTRY FROM MAGADI-TYPE CHERTS IN THE MORRISON FORMATION (COLORADO) 107

INTRODUCTION 107

METHODS 108

PREVIOUS INVESTIGATIONS 108

MORRISON MAGADI-TYPE CHERT 110

Distribution 110

Textural Features 112

Petrographic Characteristics 112

X-Ray Diffraction Characteristics 119

DISCUSSION 119

Evidence of a Magadiite Precursor for Morrison Cherts 119

Sources of Silica 123

Formation of Magadiite 125

Conversion of Magadiite to Chert 125

PALEOLIMNOLOGIC IMPLICATIONS 127

CONCLUSIONS 128

5. CONSTRAINING LATE JURASSIC PALEOCLIMATE WITHIN THE MORRISON PALEOECOSYSTEM: INSIGHTS FROM THE TERRESTRIAL CARBONATE RECORD (MORRISON FORMATION, COLORADO) 129

INTRODUCTION 129

PALEOCLIMATIC AND PALEOHYDROLOGIC INDICATORS 131

Sedimentologic Indicators 132

Palustrine Limestones and Pseudomicrokarst 132

Magadi-Type Cherts 136

Pedogenic Carbonates 137
Evaporite Deposits 137
STABLE ISOTOPE GEOCHEMISTRY 138
Methods 138
Sample Description 140
Stable Isotope Results 142
Diagenetic Carbonates 142
Primary Carbonates 146
Pedogenic Carbonates 149
INTERPRETATION AND DISCUSSION 149
IMPLICATIONS FOR LATE JURASSIC CLIMATE 152
CONCLUSIONS 156
6. DEPOSITIONAL SYNTHESIS AND SUMMARY 158
REFERENCES 162
APPENDICES 177
APPENDIX A: FIELD AND STRATIGRAPHIC DATA 178
APPENDIX B: STABLE ISOTOPE DATA 269
VITA 276

LIST OF TABLES

Table		Page
2.1	Examples of post-Silurian lacustrine systems containing prominent marginal-lacustrine (palustrine) carbonate facies.	25
2.2	Summary of lacustrine facies associations, facies, and depositional environments in the Morrison Formation.	31
2.3	Carbonate microfacies from the open lacustrine facies association in the Morrison Formation.	33
2.4	Carbonate microfacies from the marginal lacustrine facies association in the Morrison Formation.	45
3.1	Aquatic biota observed from the lacustrine carbonate deposits of the Morrison Formation.	76
5.1	Climatic regimes and associated palustrine features.	134
5.2	Summary of stable oxygen and carbon isotope compositions for the depositional and diagenetic components from lacustrine carbonate deposits of the Morrison Formation.	144
5.3	Summary of climate indicators from the Morrison Formation.	154

LIST OF FIGURES

Figure		Page
1.1	Map showing the: A) geographic distribution of the Morrison Formation Across the Western Interior of North America based on subsurface data and outcrop exposures; and B) the location of measured stratigraphic sections from the primary study area in east-central Colorado.	2
1.2	Generalized stratigraphic section of the Morrison Formation (Upper Jurassic), in east-central Colorado.	4
1.3	Paleogeography of A) the Late Tithonian world; and B) the Western Interior basin with major structural and tectonic features of the Jurassic.	7
1.4	Schematic chart illustrating the nomenclature of the Morrison Formation and associated stratigraphic units above and below the Morrison Formation across the Western Interior.	12
1.5	Stratigraphic relationships of the Morrison Formation on the Colorado Plateau along a north-south transect.	19
1.6	Stratigraphic relationships of the Morrison Formation in east-central Colorado along a north-south-southeast transect.	20
2.1	Symbols used with the sedimentary logs.	34
2.2	Sedimentary logs of the open and marginal lacustrine facies associations in the Morrison Formation.	35
2.3	Open lacustrine facies from the Morrison Formation.	39
2.4	Field relationships and observations from marginal lacustrine facies of the Morrison Formation.	47
2.5	Marginal lacustrine carbonate facies from the Morrison Formation.	50
2.6	Calcite pseudomorphs after evaporites from the marginal lacustrine carbonate facies.	53
2.7	Pseudomicrokarst, calcrete, root traces, and other exposure features from the marginal lacustrine carbonate facies from the Morrison Formation.	55

2.8 Schematic block diagram of the lacustrine facies relationships for the Morrison Formation. 64

3.1 Common aquatic components of the biota associated with the lacustrine carbonate deposits in the Morrison Formation. 77

3.2 Spongillid remains from the Morrison Formation. 83

3.3 Gastropods, unionid bivalves, microbialites, and plant remains from the Morrison Formation. 87

3.4 Trace fossils associated with the lacustrine carbonate deposits of the Morrison Formation. 99

4.1 Magadi-type chert localities in the Morrison Formation superimposed on the paleogeographic reconstruction of the Morrison paleoecosystem during deposition of the Salt Wash Member. 111

4.2 Typical field occurrences of Magadi-type chert from the Morrison Formation. 113

4.3 Petrographic features associated with the Magadi-type cherts from the Morrison Formation. 115

4.4 Pseudomorphs after evaporites associated with Morrison Magadi-type cherts. 117

4.5 Randomly oriented to rectilinear or gridwork extinction patterns in the chalcedonic groundmass of Magadi-type cherts. 120

4.6 X-ray diffractometer patterns of three Morrison chert specimens from Horsetooth Reservoir. 122

4.7 Schematic illustration showing the evolution of alkaline-saline lacustrine waters in some Morrison lakes. 126

5.1 Estimated hydroperiod and exposure index for Morrison lacustrine environments, based upon features observed from the lacustrine facies associations. 135

5.2 Stable isotopic compositions of the primary depositional and diagenetic phases from the Morrison Formation. 143

5.3 Stable isotopic compositions of the diagenetic phases from the Morrison Formation. 145

5.4 Stable isotopic compositions of the primary depositional components from the Morrison Formation. 148

A.1 Stratigraphic section measured at the Park Creek Reservoir outcrop. 179

A.2 Stratigraphic section measured at the Park Creek Spillway outcrop. 188

A.3 Stratigraphic section measured at the Highway 287 outcrop. 193

A.4 Stratigraphic section measured at the Horsetooth Reservoir outcrop. 204

A.5 Stratigraphic section measured at the Interstate 70 outcrop. 213

A.6 Stratigraphic section measured at the West Alameda Parkway outcrop. 224

A.7 Stratigraphic section measured at the Marsh-Felch Quarry outcrop. 233

A.8 Stratigraphic section measured at the Cope's Nipple outcrop. 238

A.9 Stratigraphic section measured at the Skyline Drive outcrop. 248

A.10 Stratigraphic section measured at the Purgatoire outcrop. 257

A.11 Stratigraphic section measured at the Purgatoire Trackway outcrop. 265

CHAPTER 1 -

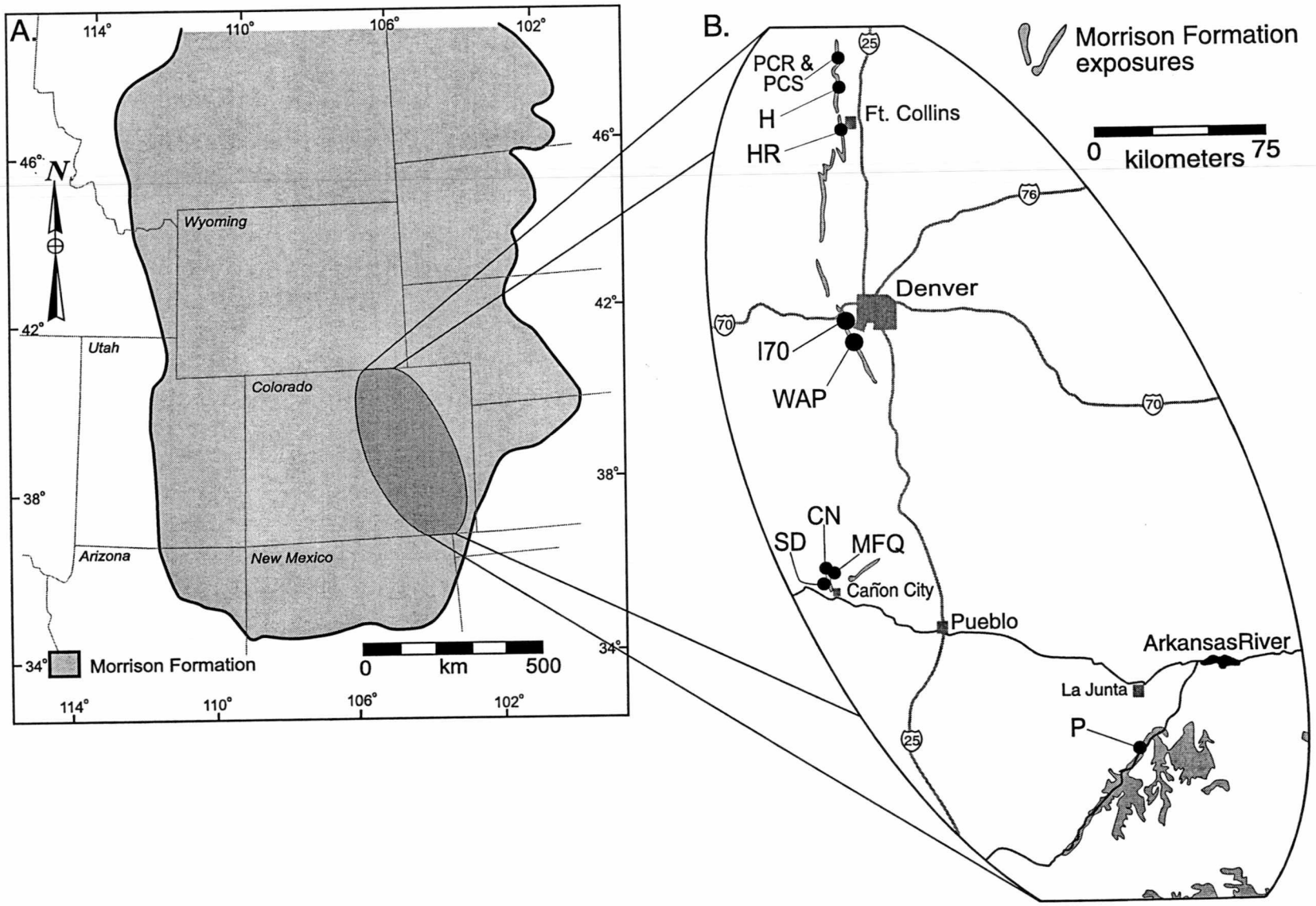
INTRODUCTION

The Upper Jurassic strata of the Morrison Formation record epicontinental sedimentation across much of the Western Interior of North America (Figure 1.1). These deposits reflect a wide spectrum of terrestrial and even marine environments that were present within the Morrison paleoecosystem. The sedimentary record of this paleoecosystem consists of alluvial-plain, eolian, fluvial, lacustrine, and marine deposits (Peterson and Turner-Peterson, 1987; Peterson, 1994) that accumulated within the Cordilleran foreland basin. Despite more than a century of study, critical aspects of the Morrison sedimentary and stratigraphic record are still poorly understood, especially as the carbonate lacustrine depositional systems. In the Morrison Formation, carbonate lacustrine strata are present in varying quantities throughout much of the Western Interior, from Montana to Arizona and from Colorado to Utah. One of the best exposures of the carbonate deposits is in east-central Colorado (Figure 1.1), where a well-developed carbonate lacustrine succession, the subject of this study, is present and occupies a significant part of the stratigraphic record (Figure 1.2).

PURPOSE AND SIGNIFICANCE

The objectives of this study are: (1) examination of the regional stratigraphic relationships between the carbonate and siliciclastic lithofacies; (2) reconstruction of the depositional environments with emphasis primarily on understanding the dynamics of

Figure 1.1. Map showing the: A) geographic distribution of the Morrison Formation across the Western Interior of North America based on subsurface data and outcrop exposures (based on Peterson, 1972); and B) the location of measured stratigraphic sections from the primary study area in east-central Colorado. The abbreviations are: PCR (Park Creek Reservoir), PCS (Park Creek Spillway), H (Highway 287), HR (Horsetooth Reservoir), I70 (Interstate 70 roadcut), WAP (West Alameda Parkway), MFQ (Marsh-Felch Quarry), SD (Skyline Drive), CN (Cope's Nipple), and P (Purgatoire River area). The specific location of stratigraphic sections are given in Appendix A-1.


A.
114°
110°
106°
102°
46°
42°
38°
34°
N
Wyoming
Utah
Colorado
Arizona
New Mexico
Morrison Formation
0 km 500
B.
Morrison Formation exposures
0 kilometers 75
PCR &
PCS
H
HR
Ft. Collins
25
76
Denver
70
I70
WAP
CN
SD
MFQ
Cañon City
Pueblo
ArkansasRiver
La Junta
P

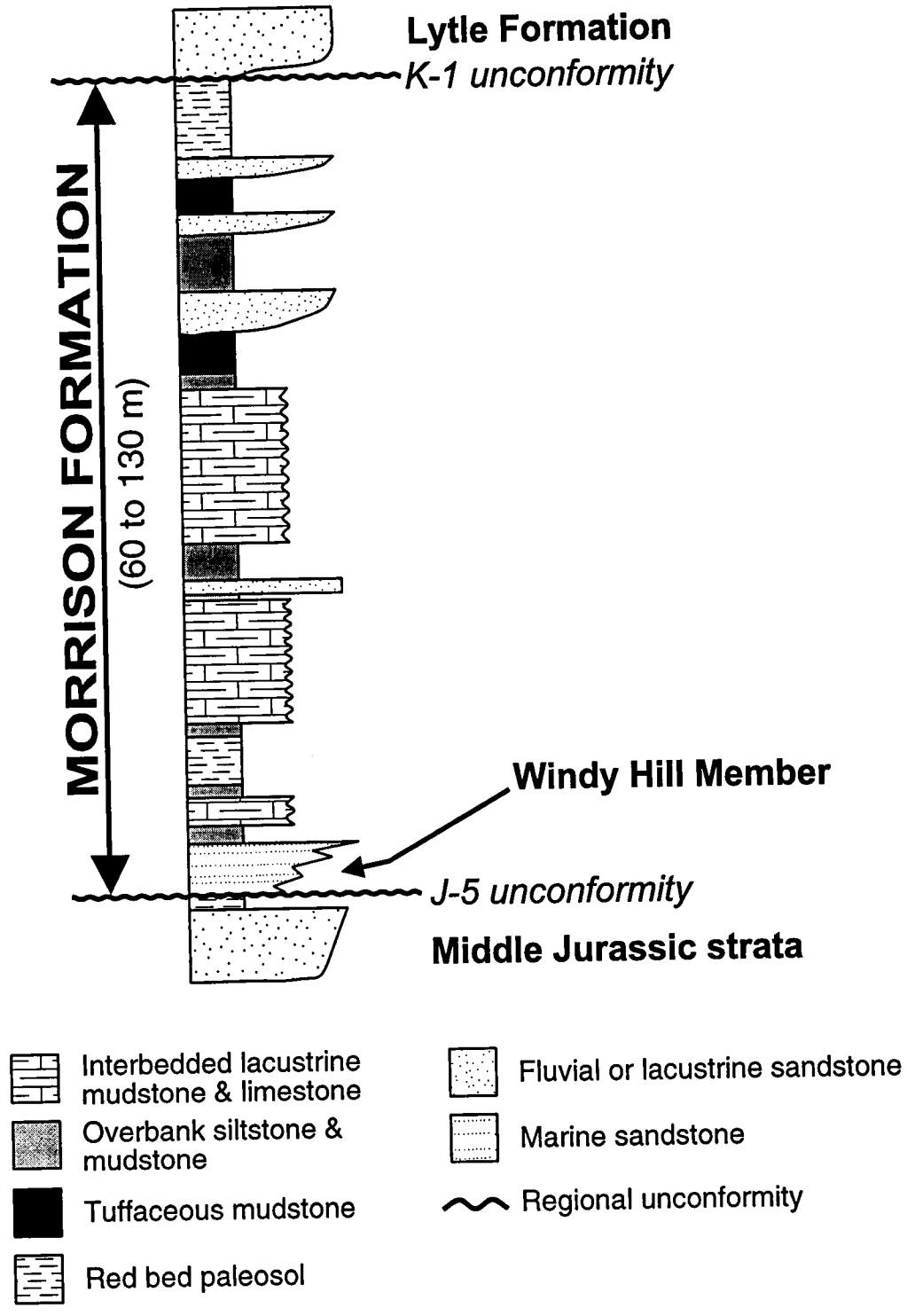


Figure 1.2. Generalized stratigraphic section of the Morrison Formation (Upper Jurassic), in east-central Colorado.

carbonate lacustrine sedimentation; (3) interpretation of the paleoecological relationships of the biota associated with the carbonate lacustrine systems; (4) interpretation of the Magadi-type cherts associated with the lacustrine carbonates; and (5) characterization of Morrison lacustrine paleohydrology and the Late Jurassic paleoclimate in east-central Colorado.

Carbonate lacustrine successions serve as valuable archives of information on continental hydrogeochemistry, paleoclimatology, paleogeography, paleontology, and sedimentation on a temporal scale analogous to a geologic snapshot. The fine temporal resolution and the wealth of geologic data associated with lake deposits makes this study significant for two reasons: 1) it will enhance our knowledge and understanding of the dynamics of carbonate sedimentation and diagenesis in shallow lacustrine environments; and 2) it will provide important insights into the spatial and temporal changes in sedimentation and paleoclimate in the Western Interior through the Late Jurassic.

TECTONIC SETTING AND PALEOGEOGRAPHY

Mesozoic basin development resulted from subduction along the western margin of the North American craton, which is reflected in the Mesozoic stratigraphy in the Rocky Mountain region (Lawton, 1994). The Mesozoic deposits record the development of a succession of sedimentary basin-fills that were separated by regional unconformities (Pipiringos and O'Sullivan, 1978; Lawton, 1994). Four major structural features influenced basin development and depositional patterns in the Western Interior during the

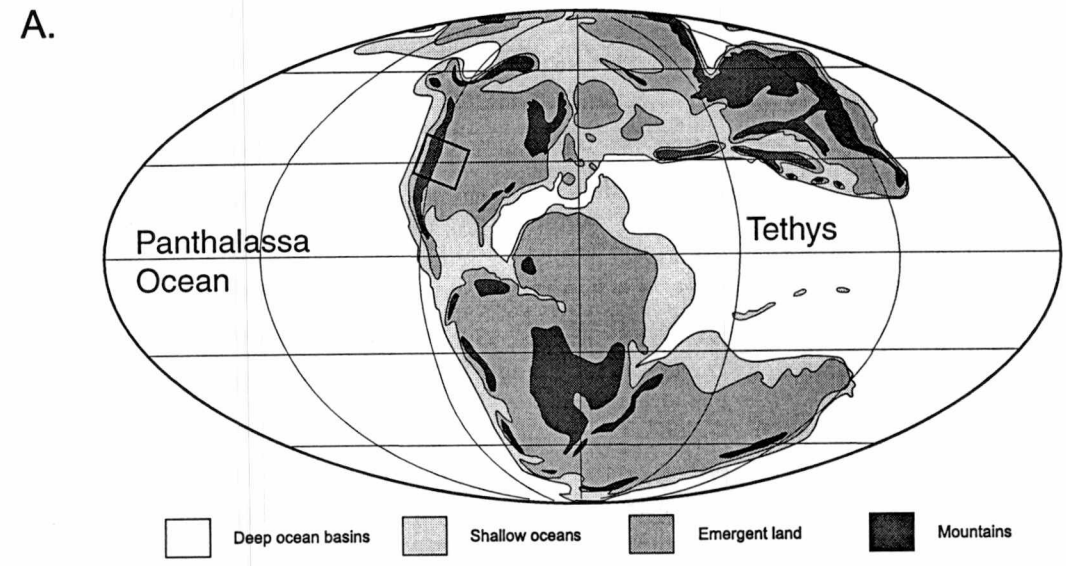
Jurassic: a continental magmatic arc, the Elko orogenic belt and highlands, the Utah-Idaho trough, and the ancestral Front Range and Uncompahgre uplifts (Figure 1.3).

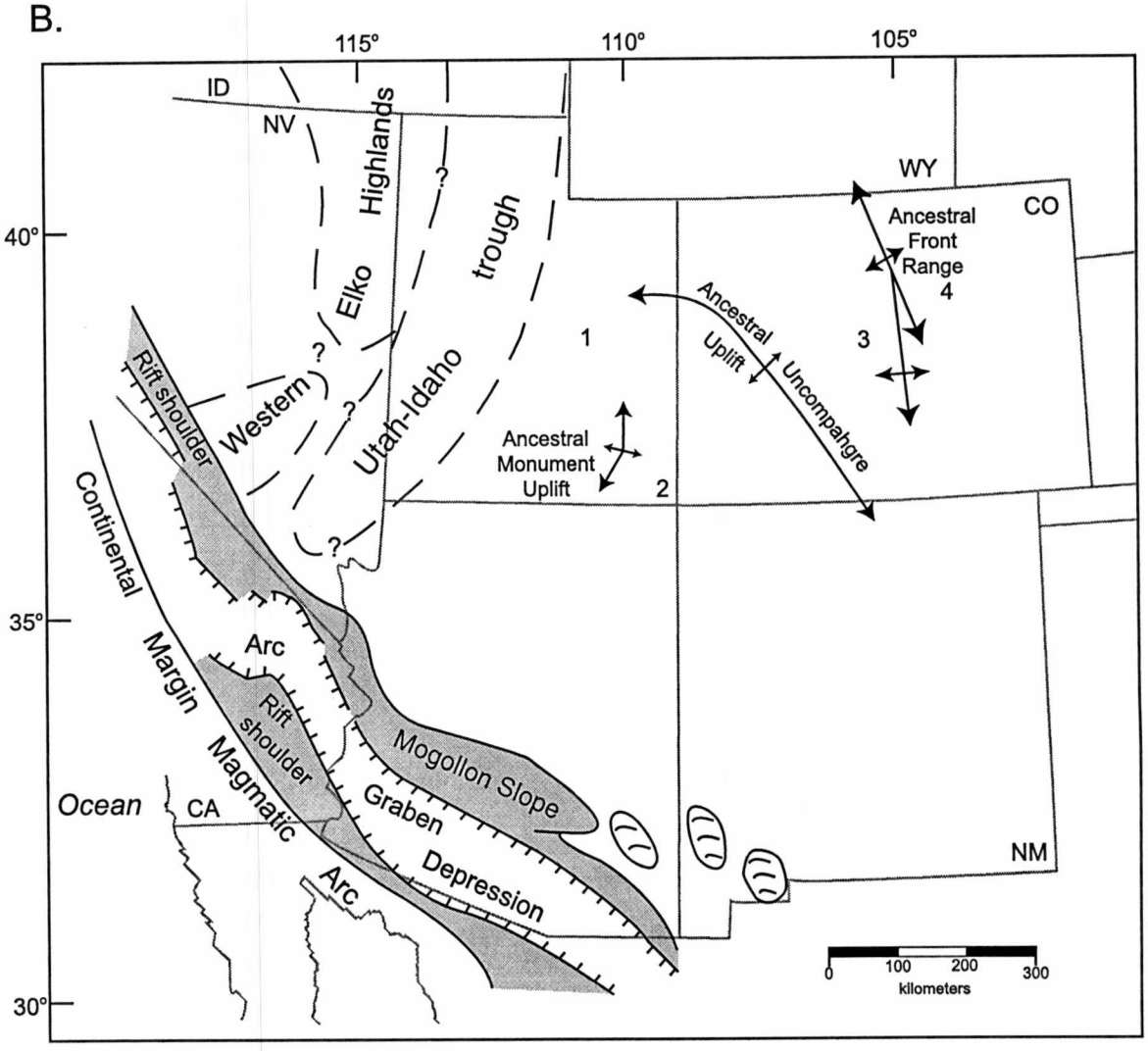
The continental magmatic arc that bordered the western margin of the North America craton contributed to the sedimentary budget via 1) the deposition of volcanic ash and ash-rich deposits as pyroclastic fall across much of the Western Interior (Christiansen *et al.*, 1994) and 2) through the shedding of clastic detrital material from topographically positive features during much of the Jurassic. The development of an arc graben produced a flanking topographic high, termed the Mogollon slope, on the southwestern margin that furnished clastic material to the Colorado Plateau (Peterson, 1994).

The Elko orogenic belt and related highlands came into existence by the early Middle Jurassic in eastern Nevada and Idaho (Peterson, 1994), and two subdivisions of the Elko highlands are recognized. The western Elko highlands were active during early Middle through Late Jurassic time and the eastern Elko highlands were active from latest Middle to Late Jurassic time (Peterson, 1994). The western Elko highlands are the equivalent of the Mesocordilleran high (Stokes, 1979) and was renamed for greater definition because it was the primary site of the Elko orogenic belt that was active during the Middle and Late Jurassic (Peterson, 1994).

The Utah-Idaho trough is genetically related to the Elko highlands in that this subsiding depression during the Middle Jurassic was inverted to a positive structure by the latest Middle Jurassic and remained a topographically positive feature through the Early Cretaceous (Peterson, 1994). The topographically positive structure represented by

Figure 1.3. Paleogeography of A) the Late Tithonian world (from Scotese, 1994); and B) the Western Interior basin (box in A) with major structural and tectonic features of the Jurassic (Peterson, 1994, Figure 2, p. 236). DJB, refers to the Denver-Julesburg Basin. Note that latitude and longitude are present-day coordinates. The numbers 1, 2, 3, and 4 in Utah and Colorado refer to localities discussed in Figure 1.4.


A.
Panthalassa Ocean
Tethys
Deep ocean basins
Shallow oceans
Emergent land
Mountains


B.
115°
110°
105°
40°
35°
30°
ID
NV
WY
CO
NM
CA
Ocean
Highlands
Elko
trough
Utah-Idaho
Western
Rift shoulder
Continental Margin
Arc
Rift shoulder
Magmatic Arc
Mogollon Slope
Graben
Depression
Ancestral Front Range
Ancestral Uplift
Uncompahgre
Ancestral Monument Uplift
1
2
3
4
0
100
200
300
kilometers

the inverted trough is referred to as the eastern Elko highlands.

The ancestral Rocky Mountains were composed of the Front Range and Uncompahgre uplifts and although the ancestral Rocky Mountains were elevated at times, the uplifts apparently did not contribute much clastic material, except during part of the Early Jurassic and locally during the Late Jurassic (Brady, 1969; Peterson, 1994). The highlands of the Middle Jurassic arc and backarc region in Idaho, Nevada, and Utah were the source of the majority of the clastic material for the Morrison Formation (Lawton, 1994).

During the Late Jurassic, the Morrison Formation was deposited as part of the thick Middle Jurassic-early Eocene succession in the back-bulge depozone of the Cordilleran foreland basin system (DeCelles and Currie, 1996). This back-bulge depozone was a broad, shallow sedimentary basin that was present across a wide expanse of the Western Interior from Arizona to Montana and Kansas to Utah (Figure 1.1). In east-central Colorado, a fluvial-lacustrine complex accumulated within the Denver-Julesberg basin, a shallow structural basin east of the Ancestral Rocky mountains (Figure 1.1). This structural basin covered an area within Colorado and Kansas of at least 80,000 km^2 and likely extended into southern Wyoming, southwestern Nebraska, Oklahoma, northeastern New Mexico. The bounding structural elements were not topographically high at the time of deposition (Merriam, 1955; Ahlbrandt and Groen, 1987; F. Peterson, personal communication, 1997), but controlled the overall geometry of the sedimentary facies. These structural elements included the Ancestral Rocky mountains to the east and the Oakley anticline and Cambridge-Chadron arch to the west (Merriam, 1955).

Subsidence and accommodation development in the Denver-Julesburg basin was a product of larger accommodation trends in the backbulge depozone of the Cordilleran foreland basin that resulted from dynamic subsidence (Currie, 1997).

AGE OF THE MORRISON FORMATION

The Morrison Formation has been dated by isotopic and biostratigraphic methods. Datable bentonite beds are present near the base and top of the formation on the Colorado Plateau (Peterson, 1994). Single-crystal $^{40}Ar/^{39}Ar$ isotopic dates from multiple bentonite beds indicate an age for the Morrison Formation ranging from about 155 to 148 Ma (Kowallis *et al.*, 1991). Fossil charophytes, ostracodes, and palynomorphs indicate that the Morrison Formation is primarily Kimmeridgian in age and that the upper approximately one-quarter of the formation is Tithonian (Schudack *et al.*, in press; Litwin *et al.*, in press). However, because neither microfossils nor isotopically datable material were found in the lower approximately 3 m of the formation, these basal beds could, conceivably, be latest Oxfordian in age (F. Peterson, personal commun., 1997). According to geologic time scale of Harland *et al.* (1990), the Morrison Formation ranges from Oxfordian/Kimmeridgian to Tithonian in age.

REGIONAL STRATIGRAPHY

In the Rocky Mountain region, the stratigraphic units east of the Colorado Front Range associated with the Morrison Formation are subdivided into the Middle Jurassic,

Upper Jurassic, and Lower Cretaceous Series. A summary of the associated stratigraphic units from each series is presented in Figure 1.4.

Middle Jurassic Series

The Middle Jurassic Series, specifically the upper Middle Jurassic (Callovian), is primarily characterized by three formations in the study area - the Bell Ranch, Entrada, and Wanakah Formations. Portions of the Sundance Formation are also represented in the uppermost Middle Jurassic series, but in the study area the Sundance is primarily lower Upper Jurassic (Oxfordian) and is described here in the Upper Jurassic Series. The upper Middle and lower Upper Jurassic units are separated from the Morrison Formation by a regional erosional surface, the J-5 unconformity, interpreted to represent a depositional hiatus of approximately 3 Ma (Pipiringos and O'Sullivan, 1978).

The Bell Ranch and Wanakah Formations are recognized in the southernmost portions of the study area, in the Purgatoire River area and in the Garden Park Paleontological Area, near Cañon City, respectively. Peterson (1994) noted that the Bell Ranch and Wanakah Formations were correlative from New Mexico to the southern Colorado Plateau, and preliminary interpretation of stratigraphic relationships in the study area also suggests that these two units are correlative (Figure 1.4). In the study area, the Bell Ranch and Wanakah consist of dark, and commonly mottled, red siltstone, sandstone and coarse conglomeratic sandstone. The Wanakah primarily has been examined in New Mexico and on the Colorado Plateau, where it has been interpreted to represent mudflat, eolian and interdune, hypersaline lacustrine, and sabkha environments (Condon and

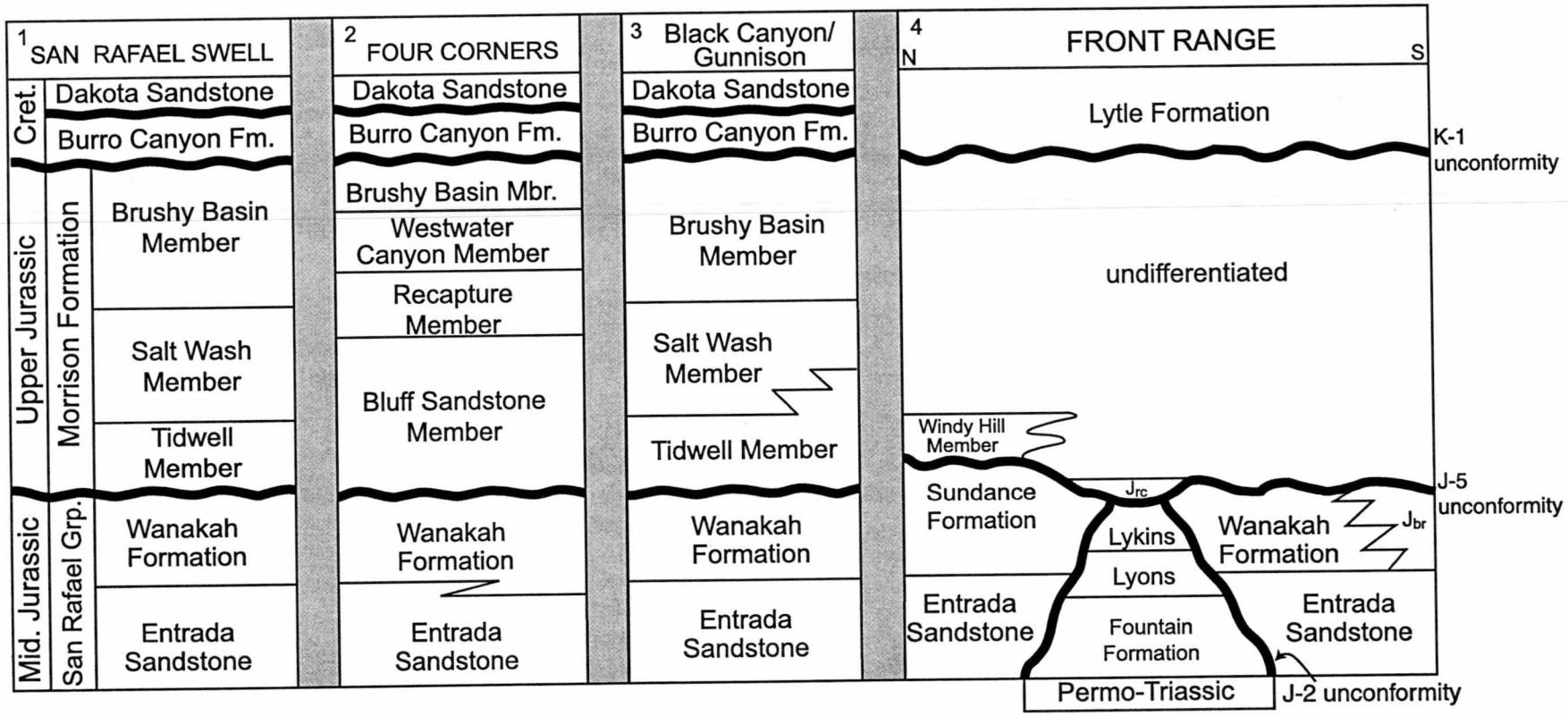


Figure 1.4. Schematic chart illustrating the nomenclature of the Morrison Formation and associated stratigraphic units above and below the Morrison Formation across the Western Interior. The general location of the stratigraphic sections 1, 2, 3, and 4 are shown in Figure 1.3. 1 - San Raphael Swell, Utah (Peterson and Turner-Peterson, 1987); 2 - Four Corners Area, southeastern Utah (Peterson, 1994); 3 - Black Canyon/Gunnison area, Colorado (O'Sullivan, 1992); 4 - from the primary study area, this generalized north-south section is in east-central Colorado. J_{rc} refers to the Ralston Creek Formation and J_{br} refers to the Bell Ranch Formation.

Peterson, 1986). In east-central Colorado, the Wanakah and Bell Ranch both represent deposition in mudflat, fluvial, and sabkha environments (Peterson, 1994).

The Entrada Formation is present in the northernmost and southernmost parts of the study area. The Entrada is composed of cross-bedded eolian sandstone with minor irregularly bedded, red sandstone and silty sandstone (Peterson, 1994), and is locally characterized by large mottles interpreted as root traces where the J-5 unconformity directly overlies this formation (Demko *et al.*, 1996). Kocurek (1981) and Crabaugh and Kocurek (1993) interpreted the Entrada Sandstone as representing deposition in a wet eolian system, which was characterized as an extensive erg with minor sabkha deposition.

Upper Jurassic Series

The Upper Jurassic Series consists primarily of the Morrison Formation, but also includes the uppermost members of the Sundance Formation and the Ralston Creek Formation. It is important to note that the J-5 unconformity separates the Sundance from the Ralston Creek and Morrison Formations (Figure 1.3). This stratigraphic relationship is particularly well-expressed in the area of the Morrison Formation type locality, where Ralston Creek mudstone and sandstone lie above the J-5 unconformity that has eroded down to Permo-Triassic units. However, throughout most of the study area, the only stratigraphic unit between the J-5 and K-1 unconformities is the Morrison Formation.

Deposition of the Sundance Formation spanned the late Middle Jurassic to early Late Jurassic and the Sundance underlies the Morrison Formation throughout the northernmost portion of the study area. The Sundance is characterized by calcareous and

gypsiferous sandstone, siltstone, and mudstone deposits that have been interpreted as representing deposition under normal to restricted marine conditions in northern Colorado (Peterson, 1994).

The Ralston Creek Formation was observed only in the middle part of the study area, near Morrison, Colorado, where it is composed of red to gray mudstone beds, and thin sandstone beds conformably overlain by the Morrison Formation. Yellow marlstone beds and rare thin limestone or gypsum beds also have been reported from the Ralston Creek Formation and these deposits record sedimentation in mudflats, evaporative basins, and rare lacustrine environments (Donovan and Richardson, 1989; Peterson, 1994).

In the study area, the Morrison Formation is largely undifferentiated, except for the presence of nearshore marine deposits of the Windy Hill Member in the northern portions of Colorado. The undifferentiated Morrison Formation is characterized by an extensive succession of interbedded mudstone and carbonate deposits with local sandstone and siltstone units (Figure 1.2; Dunagan *et al.*, 1996). Red bed paleosols and siltstones are also present. The well-developed lacustrine carbonate succession is common in Morrison Formation outcrops in east-central Colorado. Interpretations of the depositional environments in east-central Colorado have suggested that Morrison sedimentation patterns were primarily within a distal alluvial setting dominated by lacustrine and fluvial sedimentation (Brady, 1969; Jackson, 1979; Johnson, 1991; Peterson, 1994; Dunagan *et al.*, 1996; Dunagan, in review).

Lower Cretaceous

The Morrison Formation is separated from overlying Lower Cretaceous units by the K-1 unconformity, which is another prominent regional erosional surface in the Western Interior. However, interpretations concerning the length of the depositional hiatus have ranged from negligible by Johnson (1991, p. 104), who suggested the Morrison-Lytle contact was generally "conformable with" only "local disconformities," to estimates ranging from 3 Ma (Pipiringos and O'Sullivan, 1978) to 30 Ma (Heller and Paola, 1989). The longer depositional hiatus estimates are based on extensive paleosol development and erosive scour of the overlying Lower Cretaceous units. The immediately overlying Cretaceous unit in the study area is the Lytle Formation, which is composed predominately of fine to conglomeratic, quartzose sandstone. Cross-stratification is common and fine-grained mudstone and siltstone deposits are also locally present. The Lytle Formation has been interpreted as representing shallow marine and marginal-marine environments (MacKenzie, 1971).

PREVIOUS INVESTIGATIONS OF THE MORRISON FORMATION

The Morrison Formation is one of the "classic" stratigraphic successions in North American geology, having been studied intensely for over 100 years. Cross (1894, p. 2) was the first to publish the name "Morrison" to describe marl, limestone, and sandstone strata in the Garden Park area, near Cañon City, Colorado, and he stated that the name is taken from the locality at Morrison, Colorado. Cross (1894) is not, however, typically given credit for defining the Morrison Formation. Eldridge (in Emmons *et al.*, 1896, p.

22-23, 60-62) first defined the Morrison Formation for freshwater marl, thin lenticular limestone, and sandstone deposits, and designated exposures near Morrison, Colorado, as the type section. Waldschmidt and LeRoy (1944) later reassigned the type locality to a better exposed section along West Alameda Parkway, north of Morrison, Colorado.

Paleontology

The earliest investigations of the Morrison Formation focused primarily on the collection and systematic description of vertebrate faunas during the late 19th century (see for review, Mook, 1918; Simpson, 1926). More recently, physiology, paleoecology, and taphonomy have been the focal point of dinosaurian research (Bakker, 1972; Dobson *et al.*, 1980; Lockley *et al.*, 1986) as well as documentation of mammalian faunas in the Morrison Formation (Engelmann and Callison, in press). Chure (1992) also reported the presence of sharks, bony fish, salamanders, frogs, turtles, lizards, sphenodontids, and crocodilians from Morrison continental deposits.

Morrison paleontological investigations have also included numerous systematic and paleoecological studies of freshwater algae and invertebrates in carbonate and siliciclastic lacustrine deposits, including charophytes (Peck, 1937, 1957; Ross, 1960; Schudack, 1993, 1995, 1996; Schudack *et al.*, in press), gastropods and unionid bivalves (Stanton, 1915; Branson, 1935; Holt, 1942; Yen, 1952; Evanoff *et al.*, in press), ostracodes (Schudack, 1993, 1995, 1996; Schudack *et al.*, in press), and sponges (Dunagan, 1997, in review).

The Morrison Formation also contains a diverse flora represented by numerous plant megafossils commonly preserved as petrifications or as casts, with few compressions (Tidwell, 1990b). The reported occurrences of plant megafossil remains have been limited to Utah, Wyoming, and Montana with only one locality in the four corners area of Colorado (Tidwell, 1990b, p. 3). These plant megafossils include conifers (Medlyn and Tidwell, 1975; Tidwell and Medlyn, 1992, 1993), cycads (Berry, 1915), cycadophytes (Delevoryas, 1960), pteridophytes (Tidwell and Rushforth, 1970; Tidwell, 1990a, Tidwell, 1994; Tidwell and Ash, 1994), fungi (Tidwell, 1990b), ginkgophytes (Brown, 1975; Tidwell, 1990b), and pteridophytes and sphenophytes (Tidwell, 1990b). In addition, previously unreported terrestrial plant fossils are also present in fluvial, lacustrine and paleosol deposits along the Colorado Front Range, including pyritized plant tissue from carbonate lacustrine deposits (this study).

Trace fossils are present throughout the Morrison Formation. Numerous dinosaur trackways have been described (Lockley *et al.*, 1986) as well as terrestrial and aquatic invertebrate traces (Hasiotis and Demko, 1996). Crocodilian tracks and tail drags have also been reported by Hatcher (1903) from the Garden Park paleontological area near Cañon City, Colorado, and more recently by Foster and Lockley (1997) from the La Sal area in Utah.

Sedimentology and Stratigraphy

The current stratigraphic and sedimentologic framework for the Morrison Formation was developed in response to the 1950's uranium boom on the Colorado

Plateau, which necessitated a better understanding of Morrison stratigraphic relationships as well as the mechanisms for uranium formation and distribution. The classic regional study of Craig *et al.* (1955) and subsequent works by Turner-Peterson *et al.* (1980), Peterson and Turner-Peterson (1987), and Turner and Fishman (1991) resulted in a better understanding of the stratigraphic relationships of the Morrison Formation and the sedimentologic and geochemical conditions that formed the sandstone-hosted uranium ore bodies found on the Colorado Plateau. Based on these studies, a detailed stratigraphic framework has been constructed, in which the Morrison Formation is subdivided into six members in parts of the Colorado Plateau (Figure 1.5). The sedimentary deposits within these members represent a wide variety of depositional settings including alluvial-plain, eolian, fluvial, lacustrine, and marine environments (Peterson and Turner-Peterson, 1987; Peterson, 1994).

Unfortunately, the detailed stratigraphic and sedimentologic framework developed for the Colorado Plateau is not applicable throughout the Morrison depositional system, and in east-central Colorado, the Morrison Formation is largely undifferentiated, except for the presence of nearshore marine deposits of the basal Windy Hill Member in northern Colorado (Figures 1.2 and 1.6). In east-central Colorado, the undifferentiated Morrison Formation is characterized by an extensive succession of overbank and lacustrine deposits interbedded with fluvial and lacustrine units (Figure 1.6; Dunagan *et al.*, 1996). Red bed paleosols and siltstones are also present. Recent investigations into the stratigraphic and sedimentologic relationships of the carbonate lacustrine and palustrine facies in the Morrison Formation suggests that these facies may be useful in

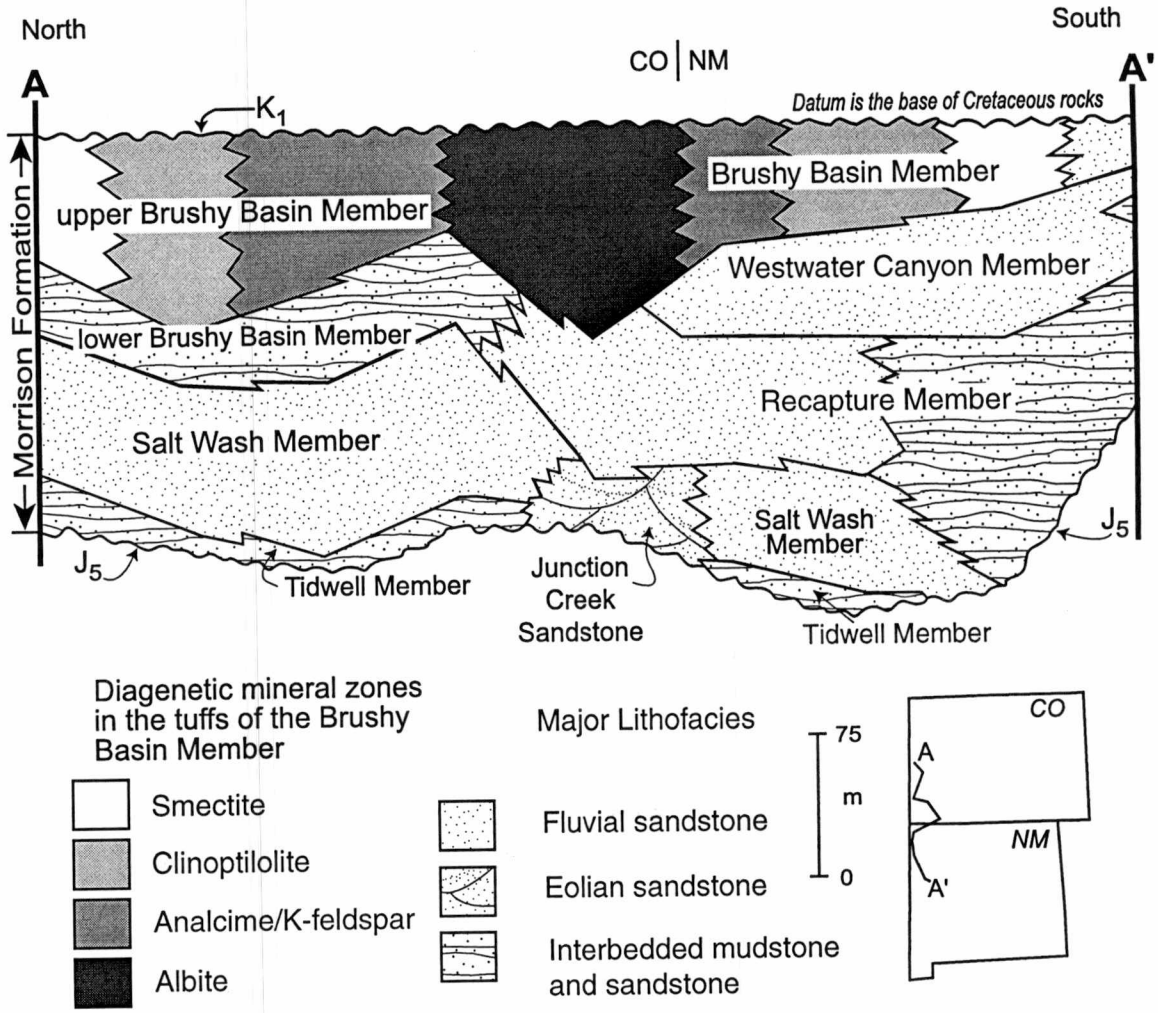


Figure 1.5. Stratigraphic relationships of the Morrison Formation on the Colorado Plateau along a north-south transect (see inset map). J_5 and K_1 are regional unconformities bounding the Morrison Formation on the Colorado Plateau. Modified from Turner and Fishman (1991, Figure 2, p. 540).

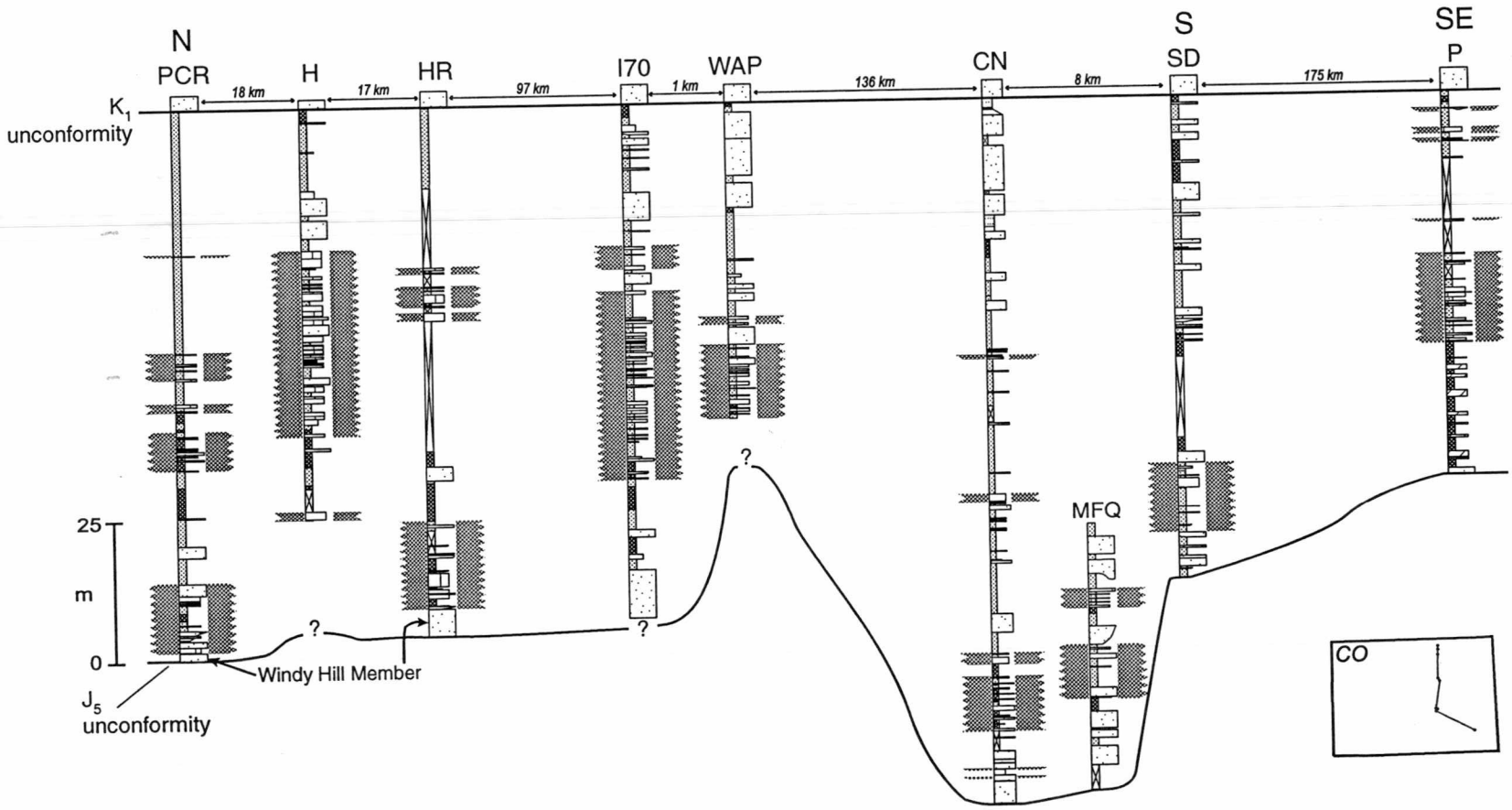


Figure 1.6. Stratigraphic relationships of the Morrison Formation in east-central Colorado along a north-south-southeast transect. Shaded stratigraphic intervals are characterized by deposits from the lacustrine facies associations. J_5 and K_1 are regional unconformities bounding the Morrison Formation. Note the shaded 'saw-tooth' pattern does not imply any sedimentologic or depositional trend and the horizontal spacing of sections is not to scale. See inset map for index; Figure 2.1 for lithofacies symbols and Appendix A for detailed stratigraphic sections. Section abbreviations: PCR (Park Creek Reservoir), H (Highway 287), HR (Horsetooth Reservoir), I70 (Interstate 70 roadcut), WAP (West Alameda Parkway), CN (Cope's Nipple), MFQ (Marsh-Felch Quarry), SD (Skyline Drive), and P (Purgatoire).

stratigraphic correlation. Dunagan *et al.* (1996) demonstrated that these facies are generally concentrated in the lower to middle undifferentiated Morrison (Tidwell and Salt Wash Members or equivalents on the Colorado Plateau), and present locally in the upper Morrison (Brushy Basin Member or equivalent on the Colorado Plateau).

While regional studies have provided insights into selected aspects of the depositional history of the Morrison, many of these sedimentologic and stratigraphic investigations have ignored the carbonate and siliciclastic lacustrine deposits common throughout the Morrison paleoecosystem. The other problem with previous lacustrine research in the Morrison Formation resulted from the lack of regional studies or the reconnaissance nature of the research. This has been problematic as investigators or other workers have often extrapolated interpretations from one particular lacustrine setting across the Western Interior. On the Colorado Plateau, lacustrine studies have included descriptions of the following: 1) sandstone, mudstone, and limestone deposits associated with a playa-lake complex in the Tidwell Member near Cache Valley, Utah (Malicse *et al.*, 1994); 2) minor lacustrine limestone associated with fluvial deposits of the Cleveland-Lloyd Dinosaur Quarry, Utah (Bilbey, 1993); and 3) in the Brushy Basin Member, the regional Lake T'oo'dichi' complex in the Four Corners area (Turner and Fishman, 1991) as well as smaller siliciclastic-dominated fluvio-lacustrine systems in west-central Colorado (Newell, unpublished data).

In east-central Colorado, Morrison lacustrine investigations have also been dominantly local in scope and included descriptions of: 1) playa-lake sedimentation in the Cañon City area (Sweet, 1984; Sweet and Donovan, 1988); 2) various carbonate and

siliciclastic lacustrine environments in the Purgatoire River area of southeast Colorado (Frazier *et al.*, 1983; Lockley *et al.*, 1986); 3) a reconnaissance description of stromatolite-bearing limestone and associated siliciclastic deposits near Park Creek Reservoir in north-central Colorado (Jackson, 1979); and 4) a broad overview of Morrison sedimentation along the Front Range by Johnson (1991), including a brief discussion of lacustrine deposition. The preliminary results from the first multidisciplinary regional scale investigation of the lacustrine systems in the Morrison Formation in east-central Colorado (Dunagan *et al.*, 1996) suggested that variations in lacustrine deposition may be tied to regional and temporal variations in paleohydrology, hydrogeochemistry, and paleoclimate.

INVESTIGATIVE METHODS

Detailed stratigraphic sections were measured with descriptions (Appendix A) and sampling focused primarily on the carbonate deposits in the Morrison Formation. Petrographic analysis included detailed conventional microscopy of 240 thin sections and examination of 98 polished slabs prepared from approximately 350 collected specimens. Based on the sedimentary structures, paleontology, and textural features, the general siliciclastic lithofacies and carbonate microfacies were determined and described in detail. From the lithofacies and carbonate microfacies observed, the depositional environments and facies associations were interpreted. Selected thin sections were also examined using cathodoluminescence (CL). Detailed petrographic and CL microscopy with the stable isotope compositions of primary depositional and diagenetic phases were

used to determine the degree of alteration in primary depositional phases. The details of the various analytical procedures used in the course of this study are presented in the respective chapters dealing with diagenesis and paleoclimatology. Lastly, data from previous and ongoing studies of the Morrison Formation from throughout the Western Interior are integrated with the data and results produced from the present study in order to broaden the perspective of carbonate lacustrine sedimentation and diagenesis to the entire Morrison paleoecosystem.

DISSERTATION ORGANIZATION

This dissertation contains six chapters including the introduction, which will focus on various aspects of the four objectives. In the second chapter, the focus is the dynamics of Morrison sedimentation, particularly carbonate deposition, as well as the facies associations and the environments of deposition. A model for carbonate sedimentation in a shallow, low-gradient lacustrine setting will also be described. The third chapter shifts emphasis to the paleoecological relationships interpreted from the biota present in the carbonate deposits, which are used to determine paleolimnological conditions. The fourth chapter centers on the origin of Magadi-type chert associated with the lacustrine carbonate deposits and their implications for hydrogeochemistry and paleolimnology. In the fifth chapter, the focus shifts to broader regional interpretations of paleoclimatology and paleohydrology within the Morrison paleoecosystem using an integrated database of paleontologic, sedimentologic, and geochemical evidence. The final chapter is a summary of the results and conclusions of this dissertation.

CHAPTER 2 -

CONTROLS ON LACUSTRINE AND PALUSTRINE CARBONATE DEPOSITION WITHIN A LATE JURASSIC PALEOECOSYSTEM, THE MORRISON FORMATION (EAST-CENTRAL COLORADO, USA)

INTRODUCTION

Basic summaries of carbonate sedimentation in lacustrine systems have included reviews by Picard and High (1972), Kelts and Hsü (1978), Eugster (1980), Dean and Fouch (1983), Eugster and Kelts (1983), and Allen and Collinson (1986). More recently, Tucker and Wright (1990) and Platt and Wright (1991) have synthesized existing data on lacustrine carbonate deposits and have proposed facies models based on hydrology, energy regime, and facies distribution. This previous research has demonstrated that the wide range of potential sizes, settings, facies distributions, hydrogeochemistries, and morphologies for lakes results from the interplay between extrinsic and intrinsic factors. Critical extrinsic factors include climate, hydrology, tectonics, geology, morphology, clastic input and geography (Glenn and Kelts, 1991); in contrast, the dominant intrinsic factors controlling carbonate sedimentation are the carbonate-producing biota. Understanding these extrinsic and intrinsic factors and their relationship to shallow-water lacustrine and marginal (palustrine) carbonate sedimentation has progressed significantly over the last twenty years with numerous post-Silurian examples documented from the sedimentary record and from a variety of tectonic settings (Table 2.1).

Table 2.1. Examples of post-Silurian lacustrine systems containing prominent marginal-lacustrine (palustrine) carbonate facies. Data partially derived from Platt and Wright (1992) and Armenteros *et al.* (1997, Table 1). References: (1) Dunagan and Driese, in press; (2) Weedman (1994), Valero Garcés and Gierlowski-Kordesch (1994), Valero Garcés *et al.* (1997); (3) Dunagan (unpublished data); (4) Toutin-Morin (1994); (5) Valero Garcés (1994a, b); (6) Dunagan *et al.* (1996); (7) Platt (1989, 1994); (8) Melendez *et al.* (1994); (9) Freytet (1973), Freytet and Plaziat (1982); (10) Floquet *et al.* (1994), (11) Stanley and Collinson, (1979), Wells (1983); (12) Armenteros *et al.* (1997); (13) Armenteros and Corrochano (1994); Mediavilla *et al.* (1994); (14) Anadón (1994); (15) Platt (1992); (16) Alonso Zarza *et al.* (1992); (17) Arlhac *et al.* (1994), (18) Platt and Wright (1992).

Example	Depositional systems	Basin setting	References
Appalachian Basin, Upper Devonian, New York, USA	Distal fluvial system	Foreland	1
Appalachian Basin, Middle Pennsylvanian, Pennsylvania, USA	Distal fluvial system	Foreland	2
Appalachian Basin, Upper Pennsylvanian, Ohio, USA	Distal fluvial system	Foreland	3
Bas-Argens and Estérel Basins, Permian, France	Distal alluvial plain	Extensional intermontane	4
Basque and Aragón-Béarn Basins, Middle-Upper Permian, Spain	Alluvial-fan system	Strike-slip	5
Western Interior Basin, Upper Jurassic, Colorado, USA	Distal alluvial system	Foreland	6
W. Cameros Basin, Early Cretaceous, Spain	Distal alluvial system	Extensional rift	7
La Serranía de Cuenca Basin, Lower Cretaceous, Spain	Alluvial system	Extensional rift	8
Languedoc Basin, Upper Cretaceous-upper Eocene, France	Alluvial and fluvial systems	Foreland	9
Santo Domingo de Silos/Arganza-Talveila Basins, Upper Cretaceous-lower Paleocene, Spain	Alluvial and fluvial systems	"proto-foreland"	10
Uinta Basin, upper Paleocene- lower Eocene, Utah, USA	Alluvial-lacustrine system	Foreland	11
Hampshire Basin, Eocene, England	Paralic to transitional environments	Subsiding	12
Duero Basin, Eocene, Spain	Alluvial to fluvial systems	Intraplate	13
Ebro Basin, Eocene, Spain	Distal alluvial	Foreland	14
Molasse Basin, Upper Oligocene to Lower Miocene, Switzerland	Distal alluvial to open lake	Foreland	15
Madrid Basin, Miocene, Spain	Distal alluvial to open lake	Intracratonic	16
Marseilles Basin, Plio-Pleistocene, France	Fluvial and tufa/marsh	Synrift	17
Florida Everglades, Holocene, USA	Distal fluvial to brackish marsh-lagoon	Low-lying marsh	18

In east-central Colorado, the Morrison Formation consists of a complex sequence of interbedded floodplain, fluvial, and lacustrine deposits with minor evaporitic and marine deposits (Figure 1.2). In the study area, the Morrison Formation contains a particularly well-developed lacustrine carbonate complex (Figure 1.6). This complex is different from the large alkaline-saline lake complex typically associated with Morrison Formation, which was described from the Colorado Plateau; the differences result from variations in the extrinsic and intrinsic factors mentioned above.

This chapter documents the first detailed, regional-scale sedimentologic and stratigraphic investigation of the Morrison lacustrine carbonate succession in east-central Colorado. The results of this multidisciplinary study include: (1) a detailed description and interpretation of the open and marginal lacustrine facies associations; (2) a summary of the controls on Morrison carbonate sedimentation, (3) a reconstruction of the lacustrine depositional environments and an idealized facies model; and (4) a discussion of the paleohydrologic conditions. The results of this systematic investigation should provide a framework for future studies and interpretations of the Morrison Formation throughout the Western Interior, wherever lacustrine carbonate deposits occur.

METHODS

Detailed stratigraphic sections were measured from ten localities in east-central Colorado, with descriptions and sampling focused primarily on the carbonate units in the Morrison Formation (Figure 1.1; Appendix A). Petrographic analysis included conventional microscopy of 240 thin sections and examination of 98 polished slabs prepared from approximately 350 collected specimens. Open- and marginal-lacustrine

carbonate microfacies were determined from sedimentary structures, paleontology, and textural features. From the detailed lithofacies descriptions, the depositional environments and facies associations were interpreted.

PREVIOUS INVESTIGATIONS

In the study area, previous studies have focused primarily on the general sedimentologic characteristics of the Morrison Formation (Waldschmidt and LeRoy, 1944; Jackson, 1979; Weimer and LeRoy, 1987; Johnson, 1991), on the siliciclastic deposits (Keller, 1953; Brady, 1969), or on the lacustrine deposits within a local context (Frazier *et al.*, 1983; Sweet, 1984; Lockley *et al.*, 1986; Sweet and Donovan, 1988). The purpose of this section is to discuss the results of previous sedimentologic studies as well as data collected from this study that are pertinent to the distal alluvial, evaporite, and marine lithofacies observed in the Morrison Formation in east-central Colorado.

Distal alluvial sandstone, red-clayey mudstone, and tuffaceous mudstone deposits were present at all localities. Sandstone deposits are non-calcareous to strongly calcareous, fine- to coarse-grained, quartzarenites or subarkoses with minor sublitharenites (Brady, 1969) that are locally conglomeratic (MFQ, CN, SD) and contain granule- to cobble-sized lithic fragments (igneous, metamorphic, and synsedimentary) and bone clasts. Sandstone deposits form extensive sheet-like lenses (0 to 4.8 m thick) to laterally discontinuous channels (25 cm to 5.6 m thick) characterized by basal scour surfaces and marked by mudstone rip-up clasts. The channels commonly exhibit sharp and erosive contacts with underlying and laterally adjacent siltstone, mudstone, or carbonate units. Sandstone deposits, as a whole, are coarser in the basal Morrison

Formation and generally are finer grained upward. Lateral accretion sets, planar to trough cross-beds with local chert granules and pebbles along foresets, low-angle to flat laminations, and minor distorted to convoluted cross-bedding are present. Bioturbation by invertebrates, dinoturbation, and bone lags are also locally present. Paleocurrent data indicated transport was primarily to the northwest, north-northeast, and northeast in the Fort Collins area (Jackson, 1979). Based upon the field relationships, sedimentary structures, and petrologic characteristics, these sandstone deposits represent elements associated with meandering fluvial systems (Brady, 1969; Jackson, 1979), including channels, point bar sequences, crevasse splays, and overbank deposits.

Red clayey mudstone (paleosol) deposits are very weakly calcareous to calcareous and characterized by pedogenic slickenslides, pedogenic carbonate nodules, and rare pseudoanticlines. Units are up to several decimeters in thickness and are commonly laterally continuous across an exposure. Pedogenic carbonate nodules occur as columnar, dispersed, or stacked nodules displaying septarian and circumgranular cracks, evidence for multiple cycles of nodular breaking, healing and recracking, and micro-nodules.

Tuffaceous mudstone deposits are massive, weather with a slight positive relief relative to other mudstones and contain rare biotite fragments. This lithofacies is similar to tuffaceous mudstones described from the Colorado Plateau (Turner and Fishman, 1991), which represent deposits of altered volcanic ash.

Bedded evaporite deposits are rare in the Morrison Formation; however, in southeastern Colorado (Purgatoire area), a prominent evaporite sequence approximately 25 m thick is present in the lower Morrison. This sequence is composed of 10-130 cm thick nodular-bedded gypsum with interbeds of reddish mudstone units, that is capped by

a silicified limestone. Thin interbeds of siltstone (<20 cm thick) and fine-grained sandstone are also present in the mudstone and gypsum interbeds. The sandstone and siltstone are both calcareous and commonly display crude horizontal laminations. This evaporite sequence is interpreted as evaporitic playa-lake deposits.

At the base of the Morrison Formation in the northern parts of the study area, the Windy Hill Member contains the only marine deposits of the formation. The marine deposits of the Windy Hill Member are composed of fine- to medium-grained, well-sorted quartzarenites that form laterally continuous sheet-like bodies (1.6 to 4.1 m thick). The sandstone units exhibit massive to flaggy, medium and thick beds, with faint planar laminations and low-angle cross-stratification. These deposits are also strongly calcareous and gypsiferous. Body fossils were not observed; however, individual beds in this facies are commonly bioturbated and vertebrate footprints 20-40 cm across are also locally present. The Windy Hill Member of the Morrison Formation represents primarily coarse siliciclastic deposition in a nearshore marine setting (Peterson, 1994).

LACUSTRINE FACIES ASSOCIATIONS

In the study area, Morrison lacustrine depositional facies are subdivided into two facies associations - open lacustrine (Facies Association A) and marginal lacustrine (Facies Association B). The open and marginal lacustrine facies associations are further subdivided into 7 microfacies based on field observations from 11 stratigraphic sections and detailed petrographic observations (see Table 2.2 for summary).

Table 2.2. Summary of lacustrine facies associations, facies, and depositional environments in the Morrison Formation.

Association	Facies	Depositional Environment
A: open lacustrine	A_1 - lacustrine carbonates	sub-littoral
	A_2 - dark laminated mudstone	sub-littoral
B: marginal lacustrine	B_1 - palustrine carbonates	littoral
	B_2 - ooid packstone/grainstone	moderate to high energy platform bench
	B_3 - green mudstone	lacustrine mudflat
	B_4 - siltstone	shallow ponds
	B_5 - sandstone	lacustrine delta, beach, and crevasse splay

Facies Association A: Open Lacustrine

This association is composed of two facies - lacustrine carbonates and dark laminated mudstone (clastic). The lacustrine carbonate facies (A_1) is composed of two primary microfacies (Table 2.3), which occur at the Park Creek Reservoir/Spillway, Horsetooth Reservoir, and Skyline Drive sections. The dark laminated mudstone facies (A_2) was observed only at the Marsh-Felch Quarry outcrop.

Facies A_1 (lacustrine carbonates)

This facies is characterized by skeletal mudstone to wackestone and microbialite deposits (15-200 cm thick) interbedded with marginal lacustrine green mudstone, sandstone, and palustrine carbonate (Figures 2.1 and 2.2). The skeletal mudstone to wackestone deposits are present at Skyline Drive and Horsetooth Reservoir, whereas microbialite deposits are present only at the Park Creek Reservoir/Spillway sections. Skeletal mudstone to wackestones consist of gyrogonites, ostracodes, and gastropods (10-15 mm in size) in a faintly bioturbated micritic matrix (Figure 2.3). Faint laminations locally occur as a doublet of 1) a light microsparitic and peloidal layer and 2) a dark micritic layer. Magadi-type cherts (described in detail in Chapter 4) are also associated with this microfacies. Rare charophyte stems and oncoids were also present. This microfacies exhibits exposure indicators such as minor to moderate intensity pseudomicrokarst, which occurs as vertical to horizontal, "Y"-shaped pores (<5-10 mm diameter; up to 40 mm in length) infilled with vadose silt, micritic clasts, and calcite cement.

Table 2.3. Carbonate microfacies from the open lacustrine facies association in the Morrison Formation.

Microfacies	Paleontology	Exposure Indicators	Other depositional Features	Paleoenvironment
Skeletal mudstone-wackestone	gyrogonites, ostracodes, gastropods (prosobranch and pulmonate), fish bone, algal and cyanobacterial filaments	minor to moderate pseudomicrokarst	Minor intraclasts and detrital quartz; Magadi-type cherts; diffuse to bioturbated laminations	Holomictic to polymictic, oxygenated, low-energy littoral setting on low-gradient ramp
Microbialites	stromatolites, algal and cyanobacterial filaments, oncoids, gyrogonites, ostracodes, fish bone fragments	minor to moderate pseudomicrokarst; minor desiccation cracks	Minor intraclasts and detrital quartz; Magadi-type cherts; diffuse to bioturbated laminations; composite microbial biostromes (planar, wrinkled, laterally-linked, and columnar stromatolites	Holomictic to polymictic, oxygenated, low- to moderate-energy littoral setting on low-gradient ramp

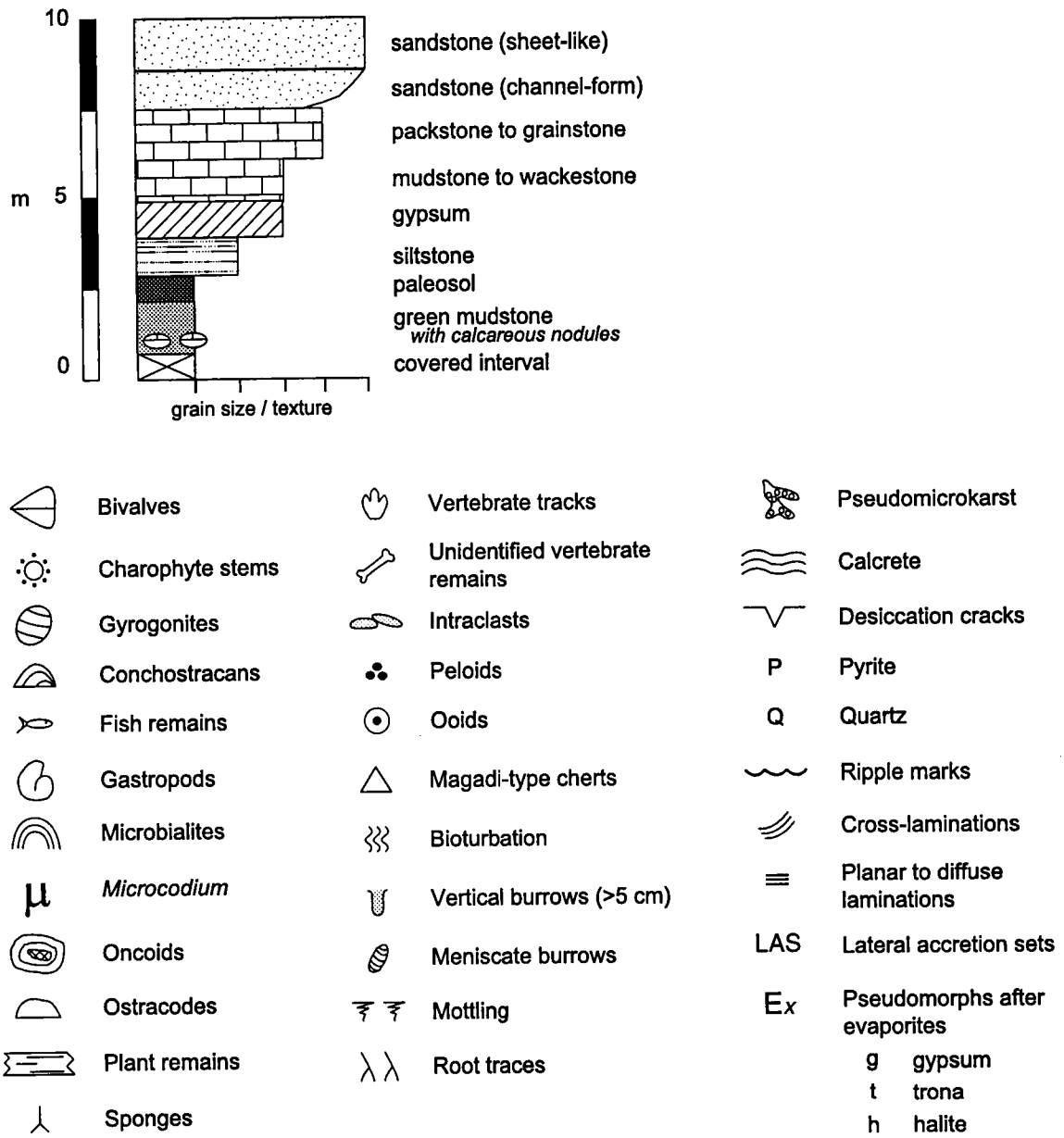


Figure 2.1. Symbols used with the sedimentary logs.

Figure 2.2. Sedimentary logs of the open and marginal lacustrine facies associations in the Morrison Formation. A, B, and C, open lacustrine facies from Park Creek Reservoir (units 1-19), Marsh-Felch Quarry (units 9-22), and Horsetooth Reservoir (units 2-17), respectively. Open lacustrine facies (OL) denoted with arrows. D and E, wave-influenced, marginal lacustrine facies from Highway 287 (units 1-2) and Purgatoire trackway (units 1-13). Specific locations and descriptions are noted in Appendix A. See Figure 2.1 for symbols.

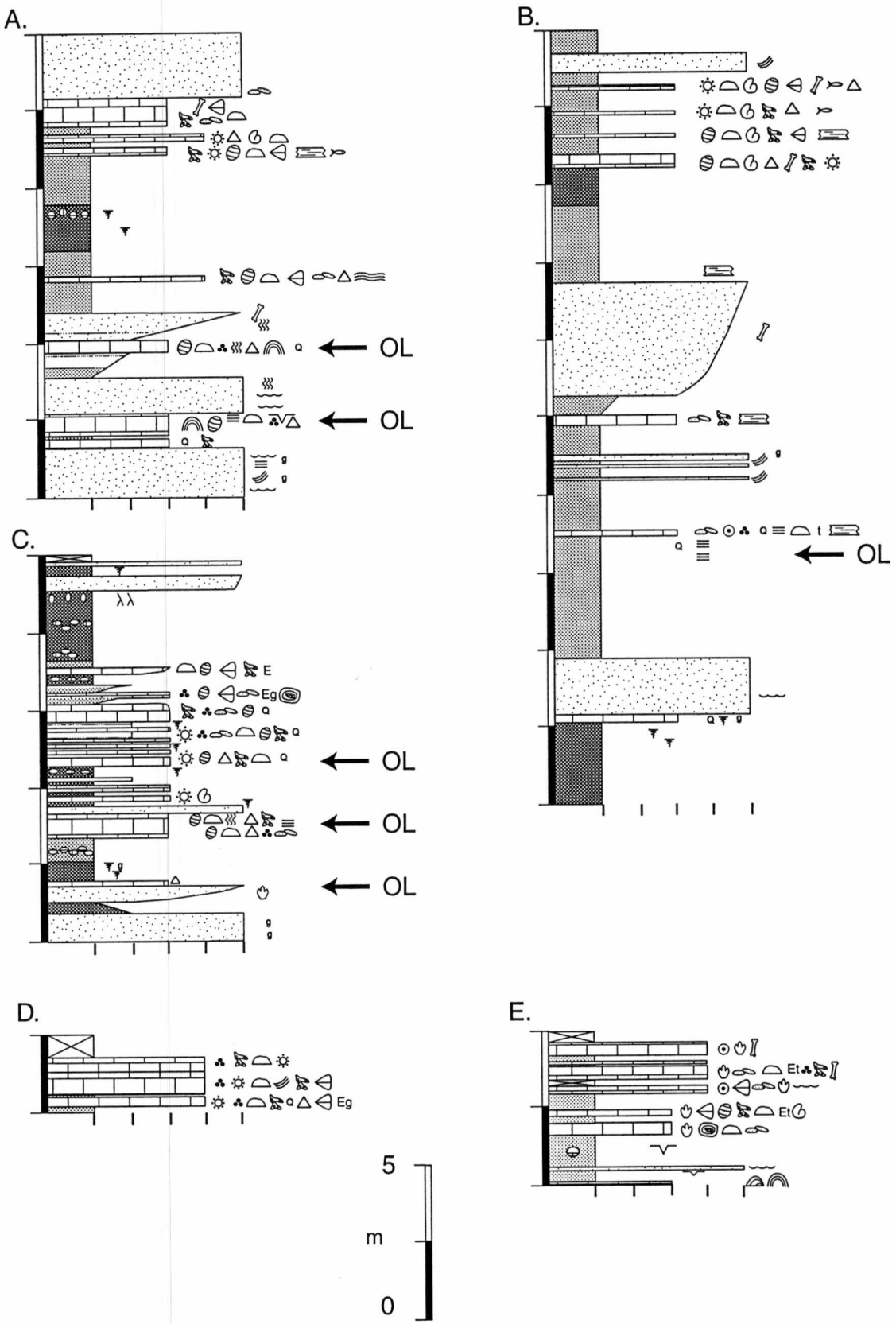

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Figure 2.2. (continued)
Sedimentary logs of the open and marginal lacustrine facies associations in the Morrison Formation. F, G, H, I, and J, low-energy, marginal lacustrine facies for West Alameda Parkway (units 1-26), Highway 287 (units 23-43), Skyline Drive (units 8-19), Park Creek Reservoir (units 40-53), and Horsetooth Reservoir (units 29-40), respectively. H, open lacustrine facies (OL). Specific stratigraphic locations for the sedimentary logs are noted in Appendix A. See Figure 2.1 for symbols.

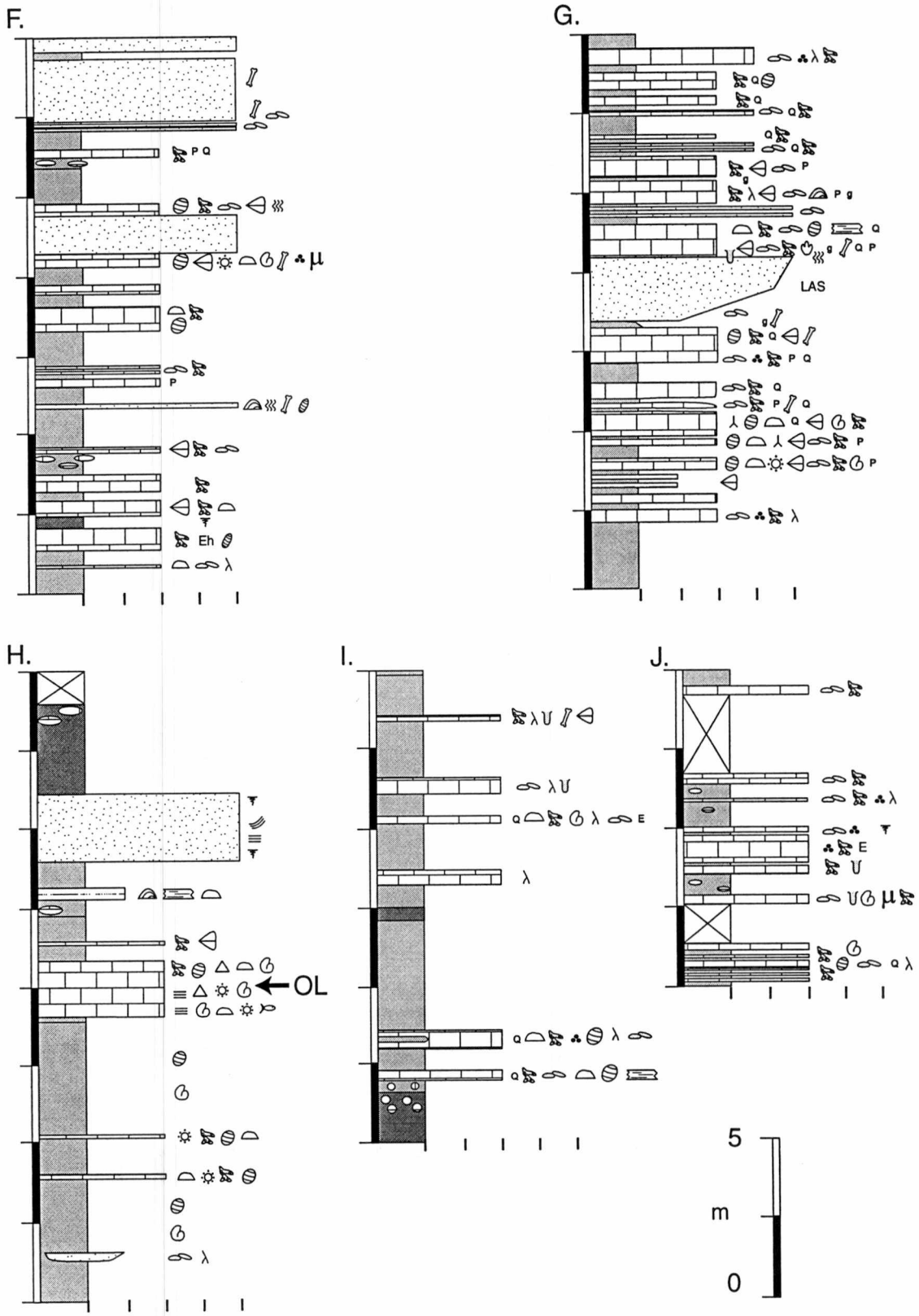
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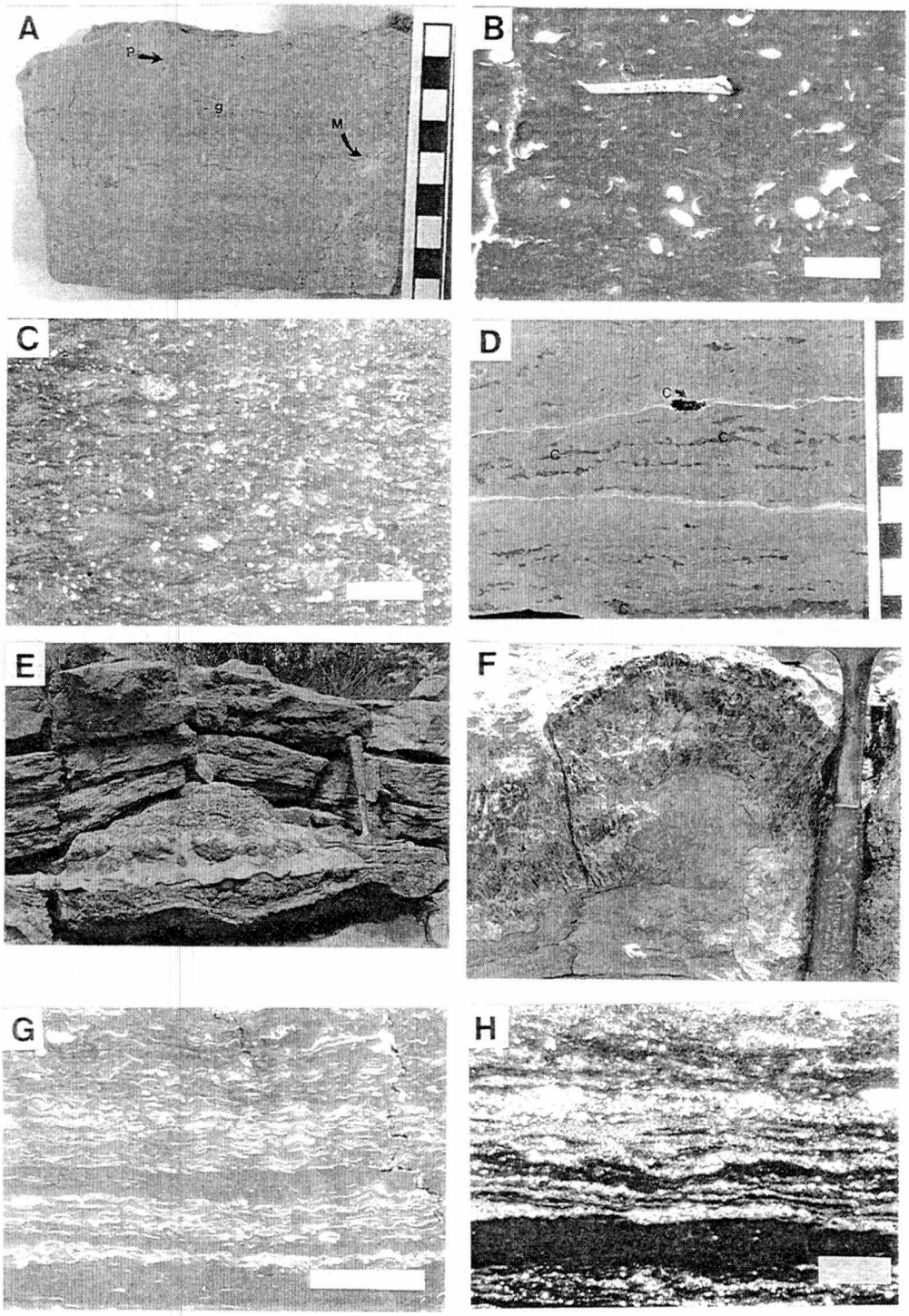
Figure 2.3. Open lacustrine facies from the Morrison Formation. A, D, photograph of polished slabs; B, C, G, H, photomicrographs (plane-polarized light); and E, F, field photographs. A, Skeletal mudstone showing faint laminations within bioturbated fabric. Note the presence of gastropods (g) and both microkarst (M) and pseudomicrokarst (P). Scale is in centimeters. B, Skeletal mudstone with bone and disarticulated ostracode fragments within bioturbated fabric. Scale bar = 1 mm. C, Bioturbated micritic mudstone with detrital quartz. Scale bar = 1 mm. D, Skeletal mudstone displaying a faint laminated fabric and Magadi-type cherts (C). Scale is in centimeters. E, Partially silicified microbialite buildup with lenticular geometry that is onlapped by microbialite laminates and weakly laminated skeletal mudstones. F, Partially silicified stromatolite head composed of basal microbial laminates and grading up into digitate and columnar stromatolites. G, Alternating laminae of skeletal mudstone and ostracode packstone. Scale bar = 4 mm. H, Dark mudstone (clastic) with detrital quartz silt along laminations. Scale bar = 1 mm. A, B, Skyline Drive; C, D, Horsetooth Reservoir; E, F, G, Park Creek Reservoir; and H, Marsh-Felch Quarry.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Open lacustrine microbialite deposits crop out as a biostromal unit covering at least 3 km^2. The biostromal unit is composed of a composite microbialite structure of basal oncoids and planar to wrinkled stromatolites that grade rapidly upward into lateral-linked hemispheroids and club-shaped columnar stromatolites (Figure 2.3); the composite microbialites are onlapped and covered by microbial laminates (Figure 2.3). Thrombolitic fabrics composed of algal and cyanobacterial filaments, and clotted to stacked peloids are also common. Other skeletal components include ostracodes, gyrogonites, and bone fragments. The ostracode accumulations, with minor detrital quartz silt, define 0.5 to ~4.0 mm thick laminae that overly the microbialites and the microbial laminates. The ostracodes occur as crushed articulated, partially articulated, and disarticulated valves that are commonly oriented in a hydrodynamically stable, convex upward position. Magadi-type cherts are also associated with the microbial deposits.

Minor to moderate intensity pseudomicrokarst is present as indicated by inverted vertical to horizontal, cylindrical-shaped pores infilled with vadose silt, micritic clasts, and calcite cement; minor desiccation cracks (depth <5 mm) are also present.

Facies A_2 (dark laminated mudstone)

This facies is characterized by a 25 cm thick dark brown, smectitic mudstone. The mudstone is calcareous and laminated, with individual laminae (0.2 to 1 mm) composed of a lenticular basal quartz silt and an upper dark mudstone component (Figure 2.3). Other features include soft-sediment deformation and a possible burrow or desiccation crack (~ 15 mm in depth) that is infilled with a disturbed mudstone infill.

This facies is interbedded with marginal lacustrine carbonates and green-gray mudstones (Figures 2.1 and 2.2); however, poor lateral control limits understanding of its distribution. No fossils, evaporites or pseudomorphs after evaporites were observed.

Interpretations-The definition of these deposits as open lacustrine facies does not imply deposition in a deep-water body with a permanently stratified water column even though this facies association occupied the most distal portion of the lacustrine system. On the contrary, Morrison lacustrine carbonates locally display pseudomicrokarst, karst-like features resulting from pedogenesis and plant rooting activity, and desiccation cracks, which were observed in the lacustrine carbonates and possibly the dark laminated mudstone. This suggests deposition in lakes that were extremely shallow even in their open areas. The relatively shallow nature and associated features of the Morrison open lacustrine facies are similar to those described from the Lower Cretaceous Rupelo Formation of Spain (Platt, 1989), the Upper Cretaceous-Lower Tertiary of southern France (Freytet and Plaziat, 1982) and Bolivia (Camoin *et al.*, 1997), the Paleocene-Eocene Flagstaff Formation (Wells, 1983), the Middle Eocene of Spain (Alonso Zarza *et al.*, 1992), and the Oligocene Lower Freshwater Molasse (Platt, 1992).

The general paucity of well-defined laminations suggests oxygenated bottom waters and indicates that thermal and/or anoxic stratification of the lake waters was not permanent, and that the lakes were probably polymictic to holomictic. The general absence of definitive fish remains is also a good indicator of holomictic lakes (Freytet and Plaziat, 1982; Elder and Smith, 1988). The presence of Magadi-type cherts associated with the open lacustrine carbonates suggests that Morrison "freshwater" lakes

experienced periodic episodes of increased alkalinity, possibly due to evaporative concentration. Episodic input of freshwater into the alkaline lakes resulted in temporary stratification, with magadiite precipitation. The mudstone and wackestone textures suggest predominantly low-energy sedimentation.

Deposition of the open lake facies was primarily associated with carbonate production derived from biogenic and bio-induced sources. The degradation of calcified charophyte stems as well as gyrogonites, ostracodes, and unionid bivalves served as major sources of biogenic carbonate. Modern charophytes commonly live in shallow waters, typically at depths of <10 m (Cohen and Thouin, 1987). Charophyte stems are delicate structures; the paucity of intact stems suggests periodic reworking of lake bottoms by storms or wind-generated currents, which would have transported significant quantities of carbonate mud produced in marginal lacustrine environments to the central parts of the lake.

Biogenically induced inorganic calcite precipitation resulted from photosynthetic activities of charophytes and microbial buildups that removed CO_2 and HCO_3^- from the lake waters, thereby significantly decreasing the CO_2 pressure, and resulting in calcite precipitation. The scarcity of trapped detrital particles in the microbialites suggests that growth was due to biogenically induced inorganic calcite precipitation related to microbial activity (Camoin *et al.*, 1997). Seasonal temperature increases may have also contributed by increasing the degree of calcite supersaturation.

Clastic sedimentation in the open lake facies is restricted to the Marsh-Felch Quarry locality, which is near the Ancestral Rockies, and hence, a ready source of clastic

material. The preservation of laminated deposits may reflect periods of higher organic productivity and local reducing or temporary polymictic conditions within the lake.

Facies Association B: Marginal Lacustrine

The marginal lacustrine facies association is comprised of palustrine carbonates (B_1), ooid packstone/grainstone (B_2), green mudstone (B_3), siltstone (B_4), and sandstone (B_5). This association is found throughout the study area with palustrine carbonates and mudstone facies representing the majority of the marginal lacustrine deposits.

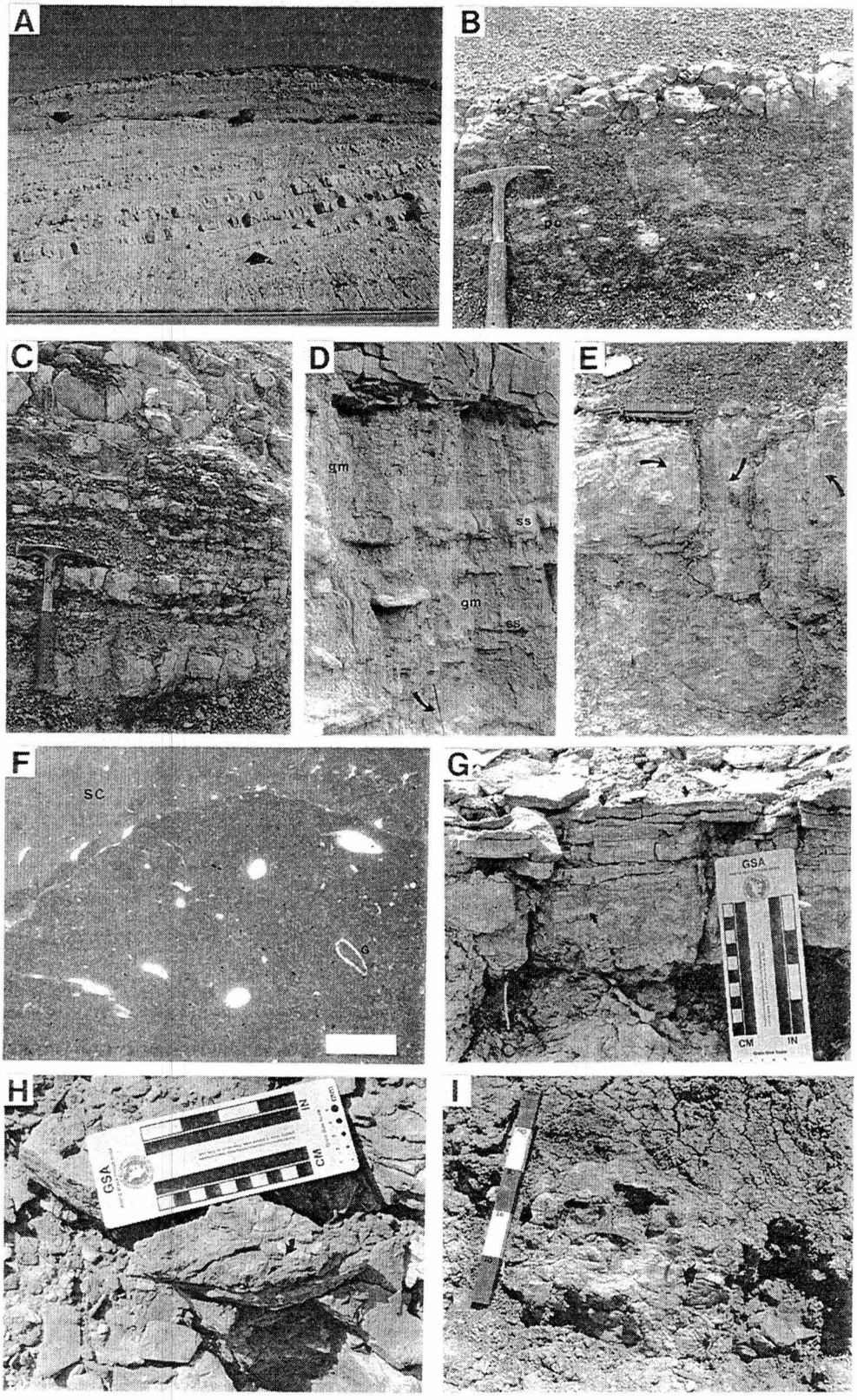
Facies B_1 (palustrine carbonates)

Palustrine carbonates display a variety of sedimentological and paleontological characteristics, yet these deposits are genetically related by the abundance of pseudomicrokarst. The palustrine carbonates occur as thin to thick beds (3-150 cm) that are laterally continuous for over 1.5 kilometers. Palustrine carbonates are composed of five primary microfacies, including carbonaceous packstone, intraclast wackestone/packstone, micritic mudstone, peloid skeletal mudstone/wackestone, and peloid skeletal packstone/grainstone (Table 2.4). The palustrine carbonates are interbedded with other marginal lacustrine facies, typically green mudstone, and distal alluvial deposits (Figures 2.1, 2.2, and 2.4). Laterally, palustrine carbonates become increasingly nodular, marly, brecciated, and pedogenically modified as they grade into clastic marginal lacustrine (green mudstone, siltstone, or sandstone) or alluvial plain deposits.

Table 2.4. Carbonate microfacies from the marginal lacustrine facies association in the Morrison Formation. Note that the presence of pseudomicrokarst as an exposure indicator indicates complex fills of vadose silt, micritic clasts, and calcite cement.

Microfacies	Biota	Exposure Indicators	Other depositional Features	Paleoenvironment
Carbonaceous packstone	plant fragments (xylem and cortical vascular tissue), minor gastropods	minor pseudomicrokarst	diffuse laminations, pyrite	nearshore lake margin to marsh, low energy, local reducing conditions
Intraclast wackestone - grainstone	gyrogonites, ostracodes	pseudomicrokarst (moderate to intense); brecciation, grainification, & circumgranular cracks; illuviated clays	peloids and green mudstone rip-up clasts; rare dark intraclasts; minor ooids and volcanic shards; chert; detrital quartz; pyrite	lake margin, moderate energy
Micritic mudstone	rare unionid bivalves, ostracodes, gyrogonites	pseudomicrokarst (moderate to intense); root traces; brecciation, grainification, & circumgranular cracks; calcrete	starved ripples of detrital quartz & peloids; pseudomorphs after halite, gypsum, and trona, plant fragments, detrital quartz, volcanic shards, pyrite	lake margin, generally low energy
Ooid packstone - grainstone	Bones (fish & reptile), unionid bivalves, ostracodes		minor ripples marks; dinoturbation & trackways; nuclei composed of quartz, bone, ooids, and bioclasts	lake margin, moderate to high energy
Peloid skeletal mudstone - wackestone	charophytes (stems & gyrogonites), ostracodes, unionid bivalves, sponges, gastropods	pseudomicrokarst (moderate to intense); root traces, alveolar texture, & circumgranular cracks; subaerial exposure surfaces	rare plant fragments, oncoids, and bone debris (fish & reptile); rounded to elliptical peloids and rare dark intraclasts; minor green mudstone rip-up clasts; Magadi-type cherts; pseudomorphs after gypsum; pyrite; detrital quartz	lake margin, low energy
Peloid skeletal packstone - grainstone	charophyte stems & gyrogonites, unionid bivalves, ostracodes	pseudomicrokarst (moderate to intense), illuviated clays	minor cross-laminations; laminae of alternating grainstone and packstone; pseudomorphs after gypsum; Magadi-type cherts; rounded to elliptical peloids; minor intraclasts; pyrite; detrital quartz	lake margin, moderate to high energy

Figure 2.4. Field relationships and observations from marginal lacustrine facies of the Morrison Formation. A-E and G-I, field photographs; and F, plane-polarized light photomicrograph. A, Typical exposure of marginal lacustrine facies with alternating limestone beds, weathering with positive relief, with green mudstone units. The arrows bracket approximately 18 m of exposure. Lateral accretion sets of sandstone are present above the lower arrow. B, Nodular and poorly indurated palustrine carbonate overlying a dark paleosol with minor pedogenic carbonate nodules (pc). C, Interbeds of thinly bedded, irregular marginal lacustrine carbonates with reddened paleosol mudstones (dark on photograph). D, Interbeds green mudstone (gm) with discontinuous, bulbous to nodular sandstone to siltstone beds (ss). Fluvial channel sandstone scours down into upper green mudstone. Hoepick (arrow) for scale is ~45 cm. E, Marginal lacustrine sandstone containing possible insect burrows (arrows). The burrows (<1 cm in diameter) penetrate up to 40 cm and are partially infilled with green mudstone. F, Carbonate nodule showing crushed gyrogonite, detrital quartz, and an outer secondary, carbonate rim (SC) with pseudomicrokarst. Scale bar = ~1 mm. G, Laminated lacustrine sandstone with minor interbeds of gypsum (arrows). H, Lacustrine sandstone with gypsum filled teepee structures (arrow). I, Typical poor exposure of laminated lacustrine siltstone, which commonly contains conchostracans, plant remains, and ostracodes. Scale in 10 centimeter intervals. A, E, Highway 287; B-C, Horsetooth Reservoir; D, Marsh-Felch Quarry; F, I, Skyline Drive; and G-H, Cope's Nipple.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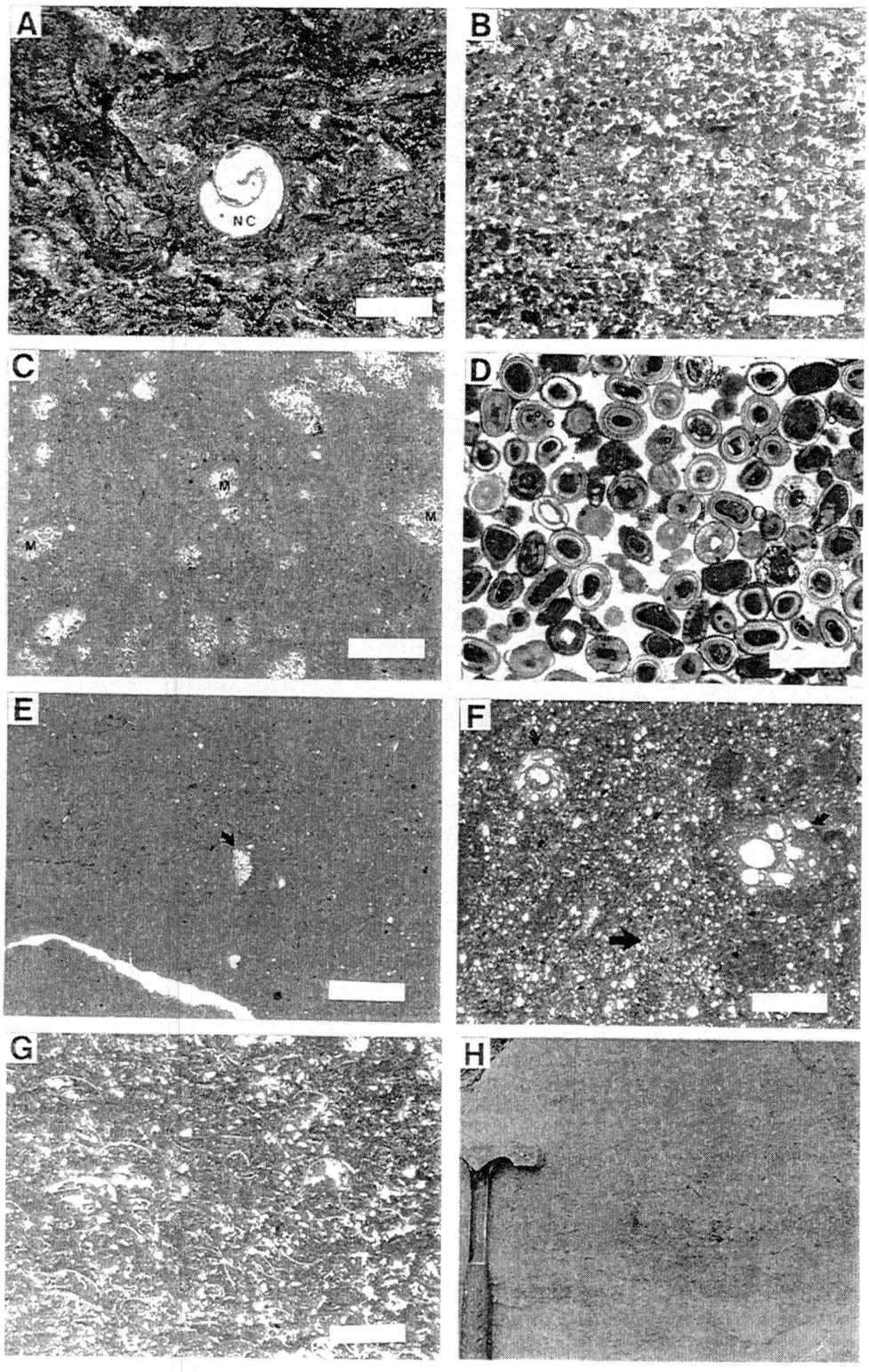
Carbonaceous packstones contain pyritized plant remains in a micritic to microsparitic matrix (Figure 2.5). This facies occurs as a thin bed (< 5 cm) at only one locality (MFQ). The plant fragments are oriented parallel to bedding and include both xylem and cortical fiber bands (identification by C. Hotton, 1997), possibly as a series of compressed fern stems or perhaps a very fine root mat. Other minor components within this facies include detrital quartz silt and sand and rare prosobranch gastropods.

Intraclast wackestone/packstones occur primarily as 0.5 to 10 cm interbeds within other marginal lacustrine facies (Figure 2.5; H, HR, I70, P, PCR/PCS). This microfacies was difficult to recognize in the field due to the lack of lithological contrast between the irregular and angular to weakly rounded micritic clasts and the micritic matrix. The clast component also included green mudstone rip-up clasts and lithoclasts (volcanic, siltstone, and chert). The interstices between clasts are filled primarily with micrite, peloids, and detrital quartz; minor amounts of illuviated clay, ooids, peloids, gyrogonites, ostracodes, and framboidal pyrite were also present.

Micritic mudstone is generally restricted to the uppermost portion of the lacustrine successions (WAP, PCR, I70), where it is dominated by a micritic to marly micrite matrix with minor framboidal pyrite, detrital quartz, volcanic shards, and fenestral pores with illuviated clays (Figure 2.5). This microfacies also contains rare meniscate burrows, plant fragments, *Microcodium*, unionid bivalve fragments, ostracodes, and gyrogonites as well as starved ripples of quartz silt and peloids.

Peloid-skeletal mudstone/wackestones are one of the most common microfacies, which is present at all sections, and may exhibit a significant marl component (Figure 2.5). Skeletal components include abundant charophyte stems, gyrogonites, unionid

Figure 2.5. Marginal lacustrine carbonate facies from the Morrison Formation. A-G, plane-polarized light photomicrographs; H, field photograph. A, Carbonaceous packstone with abundant pyritized plant fragments and gastropod. Non-ferroan equant drusy calcite (NC) fills the intragranular porosity of the gastropod. B, Peloid intraclast grainstone. Note the peloids and intraclasts are primarily subangular to subrounded and micritic. C, Intraclast wackestone with abundant green mudstone rip-up clasts (M). D, Ooid grainstone with broken, compound, superficial, and normal ooids. Coated grains are common. Note that the nuclei consist primarily of micritic peloids and intraclasts and detrital quartz. E, Micritic mudstone with detrital *Microcodium* (arrow) fragment and minor quartz. F, Peloid skeletal wackestone. Note the abundance of detrital quartz, calcified charophyte stems (small arrows), and partially disaggregated gyrogonite (big arrow). Intragranular porosity within the charophyte stems is filled with non-ferroan calcite. G, Peloid skeletal packstone with disarticulated ostracodes in a hydraulically stable position as well as fragmented gyrogonites. H, Skeletal (charophyte and ostracode) packstone to grainstone. Note the presence of faint cross-laminations and Magadi-type chert weathering with positive relief. A, Marsh-Felch Quarry; B, Purgatoire; C, E, West Alameda Parkway; D, Purgatoire Trackway; F, G, Cope's Nipple; and H, Highway 287. All photomicrograph scale bars = 1 mm.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bivalves, and ostracodes with lesser amounts of sponges, gastropods, plant fragments, oncoids, and bone debris (fish and reptile). Rounded to elliptical peloids, green mudstone rip-up clasts, Magadi-type chert, framboidal pyrite, and detrital quartz also are present. Subaerial exposure surfaces are locally present (for example, I70 locality).

Peloid skeletal packstone/grainstones were observed at several outcrops (H, HR, I70), where grainstone laminae and thin beds commonly occur within the packstone microfacies. The skeletal component of this microfacies includes abundant charophyte stems, gyrogonites, unionid bivalves, and ostracodes (Figure 2.5). Rounded to elliptical peloids, micritic intraclasts, crystallaria, Magadi-type cherts, framboidal pyrite, and detrital quartz also are present. Cross-laminations were locally observed in charophyte- and peloid-rich lithofacies (Figure 2.5).

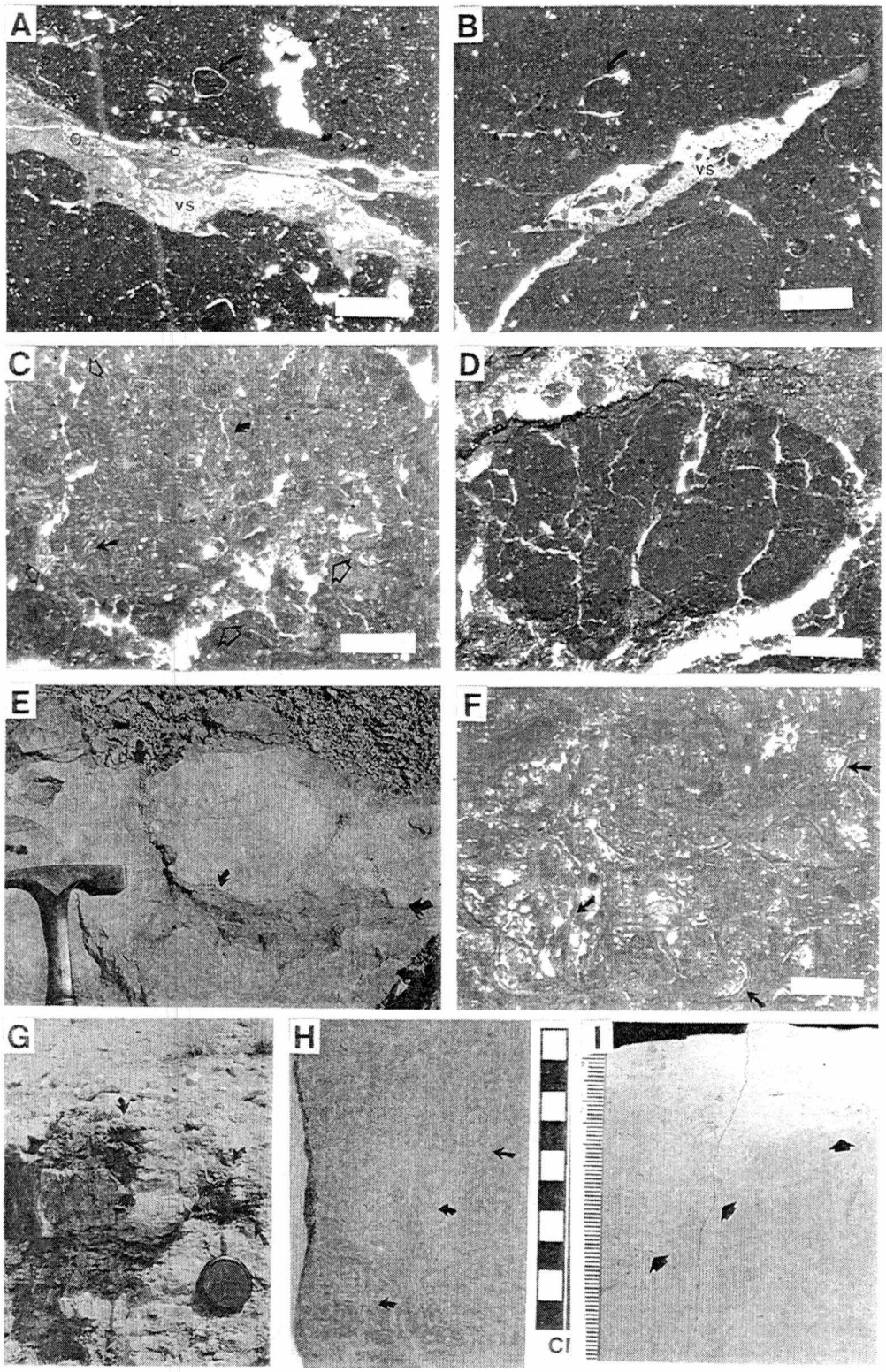
Pseudomorphs after evaporites were observed within these palustrine carbonate microfacies. Calcite pseudomorphs after gypsum (H, I70, MFQ), halite (WAP) and trona (HR, MFQ) were observed as well as replaced ellipsoidal gypsum nodules (up to 0.7 cm; WAP) (Figure 2.6).

Palustrine carbonates also display numerous exposure indicators. Mottling is common, typically black and purple-red to green (Figure 2.7), and all of the microfacies display pseudomicrokarst; palustrine units in the uppermost parts of the lacustrine succession generally display greater intensity and increased frequency of both mottling and pseudomicrokarst. Pseudomicrokarst features observed include: complex voids filled with vadose and internal sediment, micritic clasts, and calcite cement; root traces (mm to decimeter-scale), columnar and stacked rhizoconcretions, and *Microcodium*; circumgranular, desiccation, horizontal, and septarian cracks; and brecciation and

Figure 2.6. Calcite pseudomorphs after evaporites from the marginal lacustrine carbonate facies. A, Field photograph of lenticular gypsum rosettes. B, C, and D, plane-polarized light photomicrographs. B, Pseudomorphs after lenticular gypsum in micritic mudstone. Note pseudomicrokarstic cavity fill (center, far right) and floating breccia clasts. Scale bar = 1 mm. C, Pseudomorph after trona(?). The moldic porosity is filled with ferroan equant blocky calcite (fc). Scale bar = 0.5 mm. D, Pseudomorphs after halite. Scale bar = 200 μm. A, Highway 287; B, C, Marsh Felch Quarry; and D, West Alameda Parkway.

A
B
C
fc
D

Figure 2.7. Pseudomicrokarst, calcrete, root traces, and other exposure features from the marginal lacustrine carbonate facies from the Morrison Formation. A-E, plane-polarized light photomicrographs; F-G, field photograph; and H-I, polished hand specimens. A-B, Micritic mudstones with pseudomicrokarst voids infilled with angular micritic clasts spalled from the void walls, vadose silt, and non-ferroan equant drusy calcite cement (VS). Circumgranular cracks are also present (arrow). C, Micritic mudstone with extensive subvertical wispy tubules that occasionally bifurcate downward (solid arrows). Arcuate pseudomicrokarst void infilled with vadose silt, rounded micritic clasts, and calcite cement (outlined with open arrows). Note the apparent "grainy" texture resulting from the pseudomicrokarst. D, Curved and planar cracks around and within micritic mudstone showing incipient brecciation and grainification. E, Root trace starting at the top of the marginal lacustrine carbonate bed continues downward over several centimeters and then bifurcates (just below the level of the hammer's head) and levels off. Trace was partially infilled with green mudstone. F, Biogenic laminar calcrete (arrows) along the walls of voids. G, Palustrine limestone with dark gray-black clayey mottles (arrows). H, Alternating laminae of peloid intraclast packstone and grainstone with skeletal wackestone that is severely disturbed by subvertical to vertical root traces (arrows), which alters the original depositional fabric. I, Subtle subaerial exposure surface (outlined with arrows) with 5-6 cm of relief. Note similarity in carbonate lithofacies above and below, making identification difficult. Scale bar is in mm. A-B, Highway 287; C, Cope's Nipple; D, Horsetooth Reservoir; E, G, Park Creek Reservoir; F, I, I-70; and H, Purgatoire. All photomicrograph scale bars = 1 mm.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grainification (Figure 2.7). Pseudomicrokarst also generates peloid and intraclast-size particles, that may be subsequently reworked.

Erosional surfaces, desiccation cracks and bedding planes with root traces also characterize subaerial exposure surfaces. Carbonate-on-carbonate erosional surfaces are difficult to recognize in the field due to similarities in lithofacies; however, erosional surfaces displaying relief of up to 5 cm are recognizable in polished hand specimens and in thin-section (Figure 2.7I). Surfaces are also recognized based on the relief displayed by the undulating surface between carbonate to mudstone transitions. Other exposure features include microkarst and brecciation related to meteoric dissolution.

In the field, root traces and/or burrows are typically vertical to subhorizontal, infilled or lined with green mudstone (Figure 2.7), and range from 0.5 to 6 cm diameter. Root traces are recognizable petrographically as large irregular cavities partially occluded with angular to rounded micritic intraclasts, vadose silt, and/or calcite cement. These cavities are occasionally lined with laminar calcrete horizons and zones that are commonly brecciated or spalled away from the walls of voids (Figure 2.7). These horizons are characterized by cylindrical cavities (~1-3 mm diameter) lined with a concentrically laminated yellow to beige carbonate. The cavities are subsequently filled with calcite cement and clotted peloids (alveolar fabric, in the sense of Esteban and Klappa, 1983). A secondary type of root trace occurs as thin, wispy tubular structures (20-100 μm wide; up to 1.5 mm long), filled with calcite spar, and primarily vertical to subvertical.

Facies B_2 (ooid packstone/grainstone)

This facies was observed only in the Purgatoire area where well-bedded units 10-45 cm thick are particularly well-developed at the Purgatoire Trackway section. The ooid packstone/grainstones are composed of normal, superficial, and compound ooids ranging from 0.3 to 1.7 mm in diameter (Figure 2.5). Normal ooid cortices are well-developed, whereas the compound and superficial ooids typically have poor cortical development. The ooids generally have a tangential cortex with a distinct pseudo-uniaxial cross (when viewed under crossed polarizers) as well as a secondary, diagenetic radial-fibrous cortex. Bioclasts (gyrogonites, ostracodes, bone fragments), micritic peloids and intraclasts, smaller ooids, and detrital quartz grains comprise the majority of ooid nuclei. Broken ooids and micritization were also observed.

Vertebrate trackways, including theropod and sauropod, are also common in the Purgatoire Trackway section (Figure 2.2). The sauropod tracks locally thicken packstone-grainstone units by a factor of 2. In addition, ooid ripples with wavelengths of about 10 cm and amplitudes of 2-4 cm are present along the top of the main dinosaur trackway bed. Other depositional components included peloids, intraclasts, and lithoclasts (green mudstone, chert, siltstone); major skeletal components include unionid bivalves (articulated and disarticulated), gastropods (prosobranchs), ostracodes, and minor oncoids (2-4 mm); bone debris (fish, reptiles) is also locally common.

Facies B_3 (green mudstone)

This facies is characterized by a greenish-gray to olive, calcareous mudstone. The green mudstone lacks apparent bedding and is generally structureless to massive (Figure

2.4). Units are centimeters to meters thick and are generally laterally continuous across exposures. Laterally, this facies grades and pinches out into paleosol and marginal lacustrine units (Figure 2.4). Minor detrital quartz silt and sand are common, with rare lithic fragments including granules of igneous and sedimentary rocks. Carbonate nodules (mm- to cm-scale) are also present. The nodules are characterized by septarian and circumgranular cracks as well as 1-2 mm layers of micrite around the nodule. Skeletal components observed in the field and in hand specimens include gyrogonites and gastropods; rare unionid bivalve, bone, gyrogonite, and ostracode fragments were observed in the carbonate nodules. Red to purple mottles are common.

Facies B_4 (siltstone)

Light brownish yellow to greenish gray siltstones are calcareous and contain minor amounts of detrital quartz sand. This facies is commonly laminated and contains carbonaceous fragments (mostly plant debris), conchostracans, ostracodes, and bone fragments (Figure 2.4). The conchostracans are typically articulated, whereas the plant debris consists of cm-sized particles. Siltstone units up to 90 cm thick (thin to medium beds) exhibit a sheet to discontinuous lens-like geometry, and grade laterally into green mudstone, palustrine carbonate, and sandstone deposits.

Facies B_5 (sandstone)

This sandstone facies consists of fine- to medium-grained, quartzarenites to sublitharenites, and is commonly calcareous. Units are centimeters to decimeters thick with a lens-like geometry and are laterally discontinuous over 10-100 m. Fossil remains

include plant fragments and bone fragments (crocodile jaw). Bioturbation results in an homogenization of the sedimentary fabric with few distinct identifiable traces; however, the traces are commonly infilled with green mudstone (Figure 2.4). Other features include thin gypsum interbeds (<4 cm thick) and teepee structures (Figure 2.4) as well as rare symmetrical ripple marks.

Interpretations-Numerous post-Silurian shallow-water, marginal lacustrine deposits have been described (Table 2.1), and many of the palustrine carbonate deposits documented in these lacustrine successions are similar to Morrison marginal lacustrine carbonates. The Morrison Formation exhibits palustrine features similar to those described from the Lower Cretaceous Rupelo Formation of Spain (Platt, 1989), the Upper Cretaceous-Lower Tertiary of southern France (Freytet, 1973; Freytet and Plaziat, 1982) and Bolivia (Camoin *et al.*, 1997), the Paleocene Fort Union Formation (Yuretich *et al.*, 1984), and the Middle Eocene of Spain (Alonso Zarza *et al.*, 1992).

The mudstone to grainstone textures associated with the marginal lacustrine facies indicate that the margins of Morrison lakes were characterized by a varied energy regime. The presence of cross-laminations and ooid grainstone microfacies implies that lacustrine margins were periodically characterized by high-energy regimes. The presence of composite ooids indicates periods when the marginal experienced periods of relative quiescence. Modern lacustrine ooid sand shoals have been reported from Lake Tanganyika (Cohen and Thouin, 1987) and the Great Salt Lake. The lack of large-scale ooid dunes suggests a closer affinity to the ooid sand depositional environment in Lake Tanganyika, where shoals occur on flat, shallow-water, wave-influenced platforms or

benches parallel to the shore (Cohen and Thouin, 1987). The presence of relatively clean ooid grainstone deposits suggests that most of the carbonate mud has been reworked and transported into lower energy marginal and open lacustrine areas (Lockley *et al.*, 1986).

The predominance of mudstone and wackestone textures over grainstone and cross-stratified lithofacies, however, suggests that low-energy regimes were dominant. The presence of vertebrate footprints, subaerial exposure features, abundant pseudomicrokarst and microkarst, root traces and mottling, and rare biogenic laminar calcrete indicates that the marginal lacustrine environments were also characterized by shallow water depths and were subjected to frequent emergence and pedogenic modification. Wells (1983) noted that frequent exposure and re-inundation need not be caused by relative changes in the lake level, for winds can readily move water off or onto marginal lacustrine mudflats.

The green mudstone facies was deposited in a shallow-water, marginal lacustrine setting based on 1) the massive structureless nature, and 2) the presence of extensive pseudomicrokarst and pedogenic cracks in the carbonate nodules associated with the mudstones. Green mudstone deposits from the Morrison Formation are similar to those described from the Fort Union Formation (Paleocene) in Wyoming. The Fort Union mudstones are structureless, calcareous, olive-gray to yellowish gray and lack distinct laminae, suggesting a well-burrowed or disturbed bottom environment, which has been interpreted as representing low-energy muddy shorelines (Yuretich *et al.*, 1984). The relative paucity of carbonate skeletal grains in this marginal facies may reflect intense bioturbation, meteoric dissolution, and pedogenic leaching.

Colonization by shallow-water marsh and land plants around the lake margin formed a fringing vegetated zone, which acted as a clastic filter. Green mudstone, siltstone, and sandstone deposition dominated this fringe area. The generally low clastic component of carbonate facies and the presence of filter and suspension-feeding invertebrates associated with open and marginal lacustrine carbonates indicates that most clastic sedimentation occurred in an upper sublittoral to eulittoral setting on the lake margin. Adjacent to this fringe zone, local reducing and anoxic conditions allowed for the accumulation of plant debris (carbonaceous micrite). The presence of framboidal pyrite suggests that a prolific bacterial population also was present in the carbonate sediments. Laterally extensive siltstone and sandstone facies represent periodic influxes of clastic material through the fringing vegetation due to a flood event or progradation of clastic facies across the lake basin as accommodation space decreased. The presence of conchostracans and numerous burrows suggest ephemeral inundation in smaller secondary ponds around the margins of Morrison lakes.

The processes of carbonate sedimentation in the marginal lacustrine environment are similar to those described in the open lacustrine setting. Degradation of skeletal fragments, particularly calcified charophyte stems, with biogenically-induced inorganic calcite precipitation served as the major source for carbonate mud.

DISCUSSION

Lacustrine Deposition

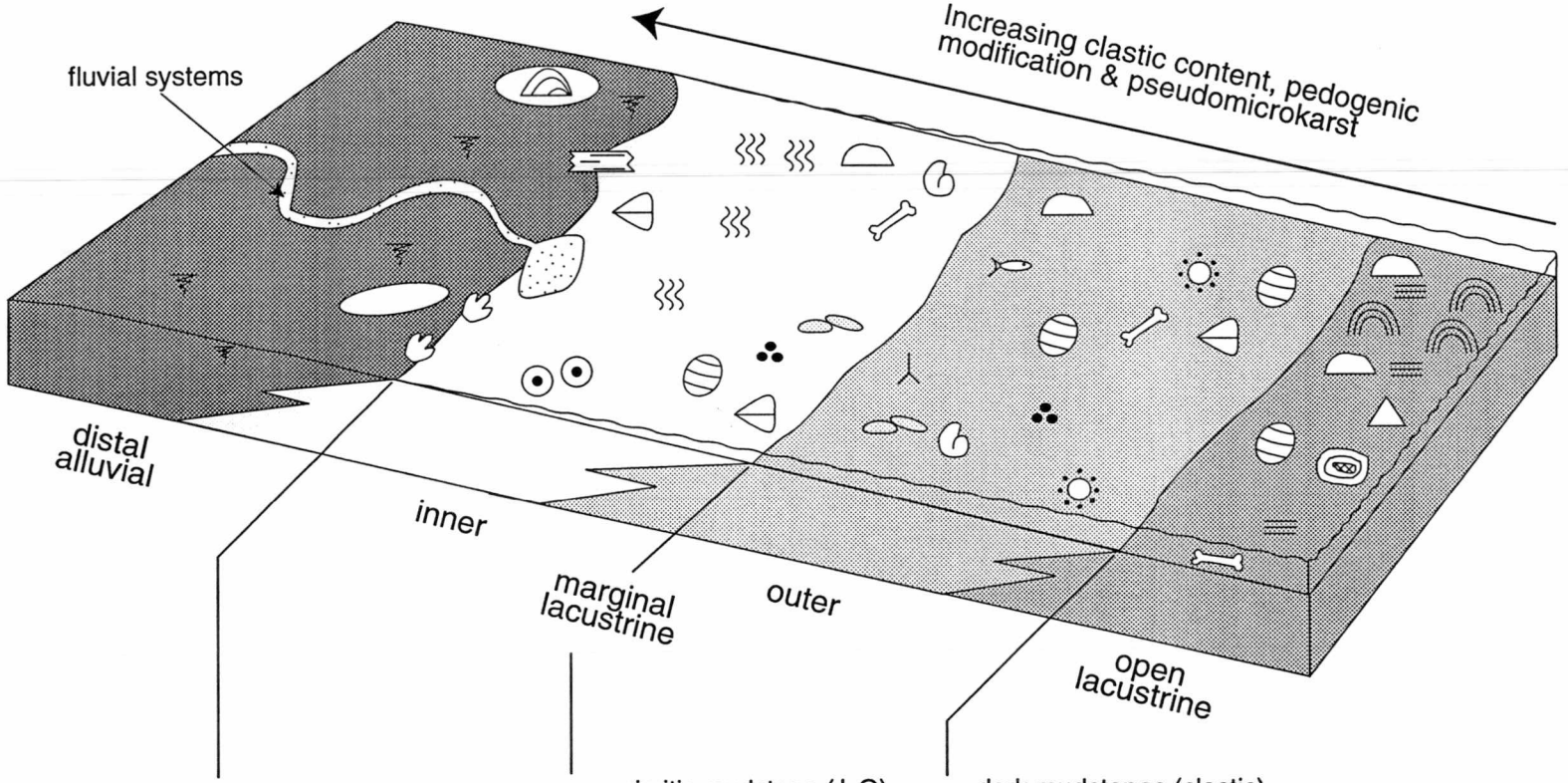
The lacustrine succession of the Morrison Formation represents a complex vertical sequence of complete and incomplete cycles of multiple lake formation and

filling, with the marginal-lacustrine deposits reflecting the dynamic interplay between open-lacustrine and adjacent alluvial sedimentation. An idealized Morrison lake would have been characterized by a relatively "deeper" open-lacustrine setting surrounded by a wide, low-relief marginal-lacustrine zone that laterally passed into adjacent alluvial depositional environments (Figure 2.8). The marginal-lacustrine settings of Morrison lakes were characterized by a low-gradient 'ramp' where frequent oscillations in lake level resulted in the exposure of large areas.

The marginal-lake areas may be subdivided into an inner and outer zone. The inner marginal area was characterized by higher clastic contents due to its proximity to the distal-alluvial plain. The energy regime in the inner marginal area ranged from primarily low-energy to local areas of higher-energy, which is reflected in the presence of mudstone to grainstone carbonate microfacies. Pedogenic activity, vegetative reworking, and meteoric diagenesis modified lacustrine fabrics through processes such as rooting, mottling, pseudomicrokarst, desiccation and pedogenic crack formation, and microkarst on carbonate substrates in both the inner and outer marginal-lacustrine zones. Modification was more intense in the inner zone. The outer marginal-lake setting had lower clastic input and low-energy regimes with associated carbonate microfacies. Open-lacustrine environments were characterized by mudstone to wackestone carbonate microfacies, (i.e., primarily low-energy), reduced clastic input, and minor exposure indicators. The paucity of laminated deposits suggests well-oxygenated conditions, which was probably a result of wind-generated currents.

The presence of unionid bivalves, prosobranch gastropods, and fish remains suggest that Morrison lakes experienced at least temporary periods of hydrologically-

Figure 2.8. Schematic block diagram of the lacustrine facies relationships for the Morrison Formation. Hypothesized vertical relationships for the open lacustrine, marginal lacustrine, and distal alluvial facies are shown. Symbols from Figure 2.1. Not to scale.


Increasing clastic content, pedogenic modification & pseudomicrokarst
fluvial systems
distal alluvial
inner
marginal lacustrine
outer
open lacustrine
- variegated mudstones
- paleosols
- fluvial sandstones & siltstones
- green mudstones
- lacustrine siltstones & sandstones
- ooid pack/grainstones
- carbonaceous packstones
- micritic mudstone (↑ Q)
- intraclast pack/grainstones
- peloid - skeletal pack/grainstones
- micritic mudstone (↓ Q)
- peloid - skeletal mud/wackestones
- dark mudstones (clastic)
- microbialites
- skeletal mud/wackestone

open conditions. However, as lake systems develop, changes in extrinsic and intrinsic factors such as climate, morphology, tectonics, and drainage systems may result in an evolution of their hydrologic balance.

Idealized Facies Models

Lakes are dynamic systems susceptible to rapid facies changes brought about by competing extrinsic and intrinsic controls. An understanding of the types, distribution, and relationships between marginal and open lacustrine facies helps constrain lake depth, morphology, and energy-regime. In the Morrison Formation, the abundance of shallow-water carbonate deposits characterized by a low detrital content and extensive lake margin facies is best explained by lakes dominated by low-energy, low-gradient 'ramp'-type margin settings (*sensu*, Platt and Wright, 1992). Ooid grainstone and cross-stratified peloid-skeletal packstone to grainstone facies indicate wave-influenced marginal settings (Figure 2.8).

In the idealized facies model, open-lake facies shallow upward into carbonate deposits associated with the outer-marginal facies, followed by the clastic and carbonate facies of the inner-marginal area, and eventually into distal alluvial deposits. Open-lacustrine facies record initial lake formation and the deposition of skeletal mudstones, microbialites, and dark laminated clastic mudstones in a relatively shallow, low-energy environment. Open-lake settings were characterized primarily by aggradation, and as accommodation space decreased marginal-lake facies prograded out into the lake basin. During lake lowstands, marginal-lacustrine settings, and to a lesser extent, former open-lacustrine areas, were subaerially exposed; reworking of marginal- and open-lacustrine

deposits produced intraclast packstone deposits and transported green mudstone rip-up clasts from along the lake margin. Clastic marginal lacustrine and distal alluvial deposits prograded into the lake basin, and ephemeral carbonate and clastic ponds were common.

The well-developed, carbonate deposits associated with the Morrison lacustrine succession are unique when compared to modern shallow-water and carbonate lakes. The low-energy, low-gradient margins that characterize Lake Chad provide an excellent modern analog for many shallow-water ('ramp'-type) lacustrine systems, where fluctuations up to ± 0.5 m occur on a seasonal basis, and long-term climatic variations produce even greater fluctuations (Carmouze *et al.*, 1983). However, the abundance of clastic deposition and the numerous relict eolian features associated with Lake Chad (Carmouze and Lemoalle, 1983) as well as the tectonic setting (i.e., intracratonic sag) precludes it as an analog for the well-developed Morrison carbonate lake deposits, which accumulated as part of a foreland basin fill. Direct analogs with modern carbonate lakes are complicated because most of these lakes are characterized as relatively "deep" with well-developed profundal deposits or with bench-type margins (i.e., Murphy and Wilkinson, 1980; Treese and Wilkinson, 1982). Carbonate deposits are common in these lakes, but the facies relationships and depositional conditions are unlike those interpreted for Morrison lakes.

The Florida Everglades, a coastal freshwater marsh, are commonly cited as an excellent modern analog for ancient shallow-water carbonate lakes, characterized by abundant palustrine deposits (Platt and Wright, 1992), which display numerous pseudomicrokarstic and other exposure features also observed in the marginal-lacustrine deposits of the Morrison Formation. However, differences in the depositional and

tectonic setting between the Everglades and the Morrison lake deposits preclude additional comparisons. The Pantanal wetlands of western Brazil occupy the modern back-bulge region of the Subandean foreland basin (Horton and DeCelles, 1997), and while the tectonic setting of the Pantanal wetlands are similar to tectonic conditions during Morrison sedimentation, little is unknown of the depositional environments and facies relationships. Consequently, numerous ancient, shallow-water, lacustrine carbonate successions, such as those of the Morrison Formation, lack reliable modern analogs and must rely on comparisons to a variety of lacustrine systems.

Paleohydrology

The three potential water sources for Morrison lakes and ponds were meteoric water, spring discharge, and groundwater. Direct precipitation onto lake surfaces and runoff from streams comprised the majority of the meteoric input into Morrison lakes. The paucity of lacustrine deltaic deposits suggests that these streams were probably ephemeral due to dry climatic conditions. Climate models also suggest dry conditions with yearly precipitation rates of <500 mm (Moore *et al.*, 1992; Valdes and Sellwood, 1992) because of the probable rainshadow effect of the Mesocordilleran high and the breakdown of the Pangean monsoon (Parrish, 1993a, b). Moore *et al.* (1992) stated that net precipitation minus evaporation (P-E) for the Western Interior during the Late Jurassic was near zero. Based on the presence of unionid bivalves and scarce vertebrate debris, some of which is tentatively interpreted as fish remains, most Morrison lakes apparently experienced hydrologically-open conditions, at least periodically. Meandering channel sandstone deposits within the lacustrine succession suggest that fluvial input

and/or flooding events could have periodically fed Morrison lakes. However, these deposits are not common and their contribution of water to Morrison lakes was probably limited. Hence, direct precipitation onto lake surfaces and fluvial runoff would have contributed only a relatively modest amount to the water budget of Morrison lakes and not enough to maintain perennial lacustrine conditions.

Spring water discharge into lakes is typically associated with travertine or tufa deposits or coated grains (Tucker and Wright, 1990). Coated grains and travertine deposits were observed in the Morrison Formation near Belt, Montana (Dunagan, field observation); hence, in the northern portion of the Morrison depositional system such spring discharges may have influenced lacustrine hydrology and carbonate sedimentation. However, tufas and other spring-related deposits were not observed in the primary study area and spring discharge is not considered as a factor in the hydrological budget of Morrison lakes.

Groundwater seepage from paleoaquifers (*i.e.*, the Navajo Sandstone, Entrada Formation, or the Salt Wash Member of the Morrison Formation) and/or from a high groundwater table into topographic lows, represents an important potential water source. In the westernmost Colorado Plateau, recharging paleoaquifers would have had a greater hydraulic head due to tectonic uplift and these paleoaquifers would have transported groundwater 100's of kilometers, potentially elevating the water table east of the Ancestral Rockies and seeping into paleotopographic lows. Evidence for a high groundwater table is present in the abundance of gleyed open- and marginal- lacustrine deposits; burrow depths for some types of trace fossils are generally shallower in east-central Colorado as opposed to the Colorado Plateau, also suggesting a higher water table

in the study area (Hasiotis and Demko, 1996). The presence of fossil wood from siliciclastic and carbonate deposits also indicates a water table high enough to permit tree growth despite prevailing aridity (Parrish, 1993b). Based on prevailing climatic conditions and the lack of evidence for springs, Morrison lakes appear to have been primarily groundwater-fed with minor meteoric contributions.

CONCLUSIONS

1. The well-developed lacustrine succession that comprises the Morrison Formation in east-central Colorado indicates that numerous low-gradient, and primarily low-energy, shallow-water, perennial to ephemeral carbonate lacustrine depositional systems were common within the Morrison paleoecosystem.
2. Based upon facies associations and stratigraphic relationships, Morrison paleolakes were characterized by a central open-lacustrine facies that graded laterally and vertically into marginal-lacustrine deposits and eventually into adjacent distal-alluvial deposits. The open- and marginal-lacustrine facies associations display abundant evidence for frequent subaerial exposure and modification resulting from pedogenic activity, meteoric diagenesis, and pseudomicrokarst. The abundance of these features indicates that hydrologic conditions and lake levels were subject to fluctuations.
3. The water column of Morrison paleolakes was well-oxygenated reflecting holomictic to polymictic conditions, as implied by the paucity of well-laminated mudstones and organic-rich deposits. The local presence of pseudomorphs after gypsum, halite, and trona, minor gypsum nodules, and Magadi-type cherts indicate periods of increased salinity and alkalinity. High groundwater tables, that possibly discharged into

paleotopographic lows, in addition to meteoric contributions, provided perennial Morrison lakes with periodically hydrologically-open conditions, which would have been required by unionid bivalves and prosobranch gastropods. However, the abundance and type of pseudomicrokarst indicate hydrologic conditions and lake levels were subject to fluctuations.

4. The major extrinsic and intrinsic controls that acted on Morrison lacustrine carbonate sedimentation was the low clastic input, due to the distal alluvial setting and the presence of a clastic-filtering fringe of macrophytes along lake margins, and the abundance of a prolific carbonate-producing biota (i.e., charophytes), respectively.

CHAPTER 3 -

PALEOSYNECOLOGY AND PALEOLIMNOLOGY OF LATE JURASSIC PERENNIAL TO EPHEMERAL CARBONATE LAKES AND PONDS (MORRISON FORMATION, COLORADO)

INTRODUCTION

The Morrison Formation is dominated by a broad spectrum of terrestrial environments superimposed on a vast alluvial plain, which covered over 1 million km^2 of the western United States during the Late Jurassic (Figure 1.1). Within this terrestrial setting, a diverse biota from floodplain, lacustrine, and eolian deposits has been documented. This biota includes dinosaurian and non-dinosaurian reptiles (Mook, 1918; Simpson, 1926; see references in Carpenter *et al.*, in press), amphibians (Chure, 1992), bony fish (Chure, 1992), mammals (Engelmann and Callison, in press), insects (Hasiotis and Demko, 1996; Hasiotis, in press), aquatic algae and invertebrates (Stanton, 1915; Branson, 1935; Peck, 1937, 1957; Holt, 1942; Yen, 1952; Ross, 1960; Schudack, 1993, 1995, 1996; Dunagan, 1997, in review; Schudack *et al.*, in press; Evanoff *et al.*, in press), and plants (Berry, 1915; Delevoryas, 1960; Brown, 1975; Tidwell, 1990b; Tidwell and Medlyn, 1992; Tidwell and Ash, 1994).

Paleoecological investigations of continental paleoecosystems provide useful constraints in detailed paleoenvironmental reconstructions. Dobson *et al.* (1980) utilized dinosaur taphonomy and paleoecology to suggest a strongly seasonal wet and dry climate for the Morrison Formation. Lockley *et al.* (1986) suggested gregarious behavior among

sauropods along large shallow lakes in southeast Colorado during Morrison deposition based upon dinosaur trackways, vertebrate taphonomic processes, and sedimentologic relationships. Unfortunately, mobile terrestrial vertebrates, such as dinosaurs, traversed multiple habitats limiting their paleoenvironmental and paleoecological specificity (Hasiotis and Demko, 1996) making their skeletal remains and traces of limited environmental and synecological value (Hasiotis, in press).

On the other hand, invertebrates and their trace fossils in aquatic communities were physiologically restricted to a limited number of depositional environments based on specific moisture, substrate, salinity, and temperature requirements (Hasiotis, in press), providing greater insights into lacustrine paleosynecology and paleolimnology as opposed to terrestrial vertebrates. Recent studies of Morrison freshwater molluscs (Evanoff *et al.*, in press), sponges (Dunagan, 1997), ostracodes and charophytes (Schudack, 1993, 1995; Schudack *et al.*, in press), and aquatic trace fossils (Hasiotis and Demko, 1996) have demonstrated this point. Interestingly, despite the abundance of aquatic invertebrates and traces associated with the lacustrine carbonate deposits of the Morrison Formation, this biota is only beginning to be systematically examined, described, and utilized to constrain paleoenvironmental interpretations of Morrison carbonate lakes and ponds.

This chapter documents the first detailed paleosynecological and paleolimnological investigation of the Morrison lacustrine carbonate succession. The results of this study include: (1) a description of the preserved biota and trace fossils within the open and marginal lacustrine facies, with an emphasis on the invertebrate biota and carbonate deposits; (2) a discussion of the paleolimnologic implications associated

with each fossil group; and (3) a paleoenvironmental synthesis using the paleosynecological and paleolimnological data. The results of this investigation are significant because these fossil assemblages are common in the Morrison Formation throughout much of the Western Interior basin; an understanding of this biota provides important insights into aquatic paleosynecology, paleolimnology (energy regime, hydrogeochemistries, taphonomy, trophic levels, water turbidity), paleobiogeography, and paleoenvironmental reconstructions.

METHODS

Field examinations generally do not reveal the type or diversity of skeletal fragments in the lacustrine carbonate deposits due to the small size (typically < 2 mm) and the low contrast of skeletal fragments within the micritic matrix. Observations in thin section and polished slabs of hand specimens were required to accurately determine the presence or absence and identity of fossil material. In addition to standard petrographic microscopy, scanning electron microscopy (SEM) was used to analyze sponge spicule types, morphology, ornamentation, and size. The SEM material was derived from a paired thin-section and billet chip (about 2.5 mm thick), which was etched with approximately 10% HCl for 10-15 seconds. A HITACHI S-3200N scanning electron microscope was used to examine sponge spicules imbedded in the carbonate matrix using an accelerating voltage of 20-25 kV.

STRATIGRAPHIC AND SEDIMENTOLOGIC OVERVIEW

The focus of this investigation is on the biota found in association with the open and marginal lacustrine deposits of the Morrison Formation (Figure 1.2). Sedimentologic and stratigraphic relationships indicate that open lacustrine deposits were dominantly carbonate in composition, with marginal lacustrine deposits becoming increasingly siliciclastic dominated toward the edges of the lakes and ponds. Typical stratigraphic relationships are displayed in Figures 2.1 and 2.2; fossil occurrences from the stratigraphic sections are shown in Table 3.1.

LACUSTRINE PALEONTOLOGY

Charophytes

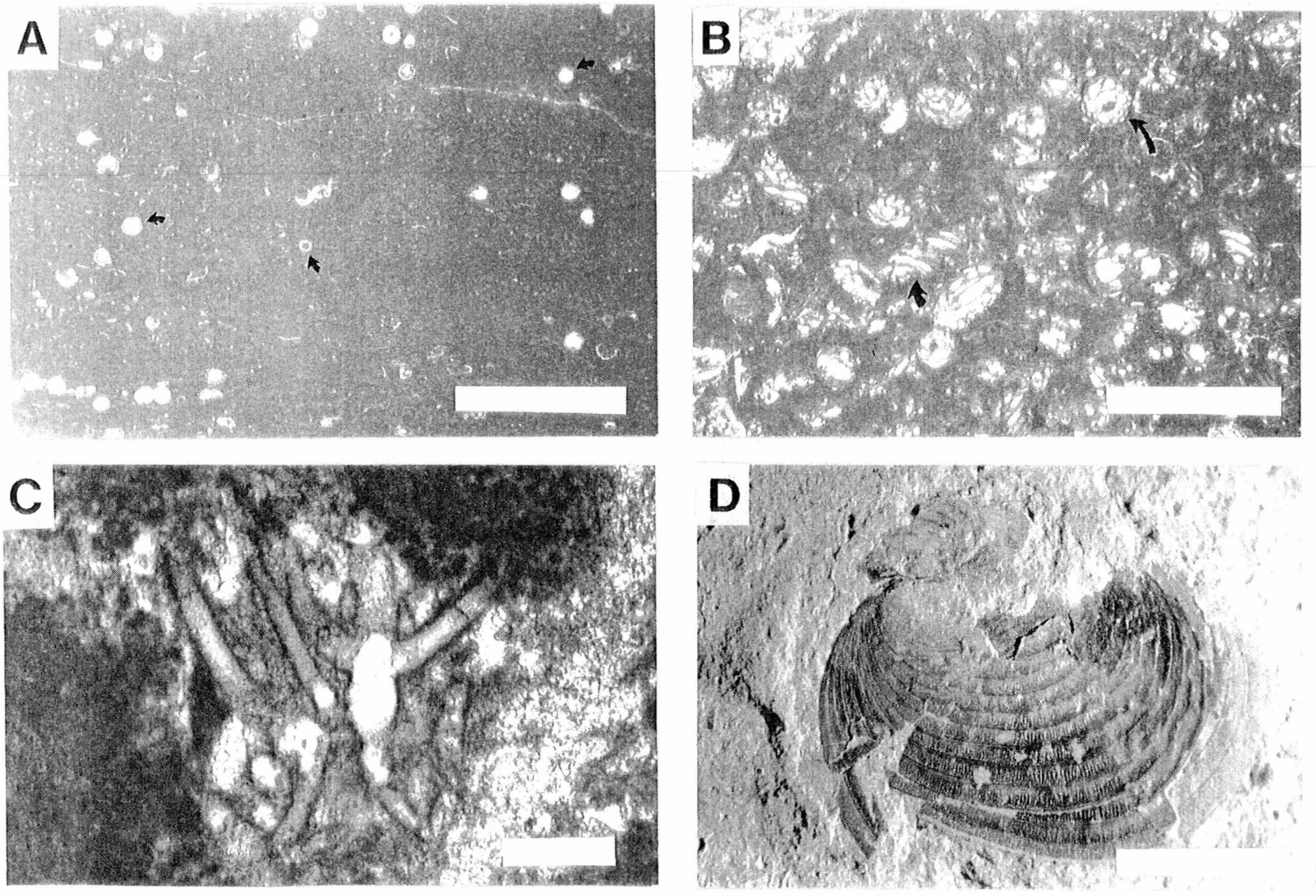
Occurrence-Calcified charophyte stems and gyrogonites represent one of the most common skeletal allochems associated with Morrison lacustrine deposits (Figures 2.5F and 3.1A-C). Charophyte stems and gyrogonites were observed at each stratigraphic section, however, the two charophyte elements were not typically observed together. Charophyte stems occur primarily within marginal lacustrine carbonates, whereas gyrogonites are more common in open lacustrine and low-energy marginal lacustrine deposits.

Fragments of calcite encrusted charophytes stems up to 4 mm in length and up to1 mm in diameter are present. The charophyte stems show spiral ribbing and are typically infilled with microspar and equant calcite cement. Locally, charophyte stems are

Table 3.1. Aquatic biota observed from the lacustrine carbonate deposits of the Morrison Formation. Stratigraphic section abbreviations include Park Creek Reservoir/Spillway (PCR), Highway 287 (H287), Horsetooth Reservoir (HR), I-70 (I70), West Alameda Parkway (WAP), Purgatoire (P), Marsh-Felch quarry (MFQ), Cope's Nipple (CN), and Skyline Drive (SD). See Appendix A for precise locality information.

	PCR	H287	HR	I70	WAP	P	MFQ	CN	SD
Conchostracans					✓	✓			✓
Gastropod: prosobranch	?	✓	✓	✓	✓	✓	✓	✓	✓
Gastropod: pulmonate	?	✓					✓	✓	✓
Ostracodes	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sponges		✓			?				
Unionid bivalves	✓	✓	✓	✓	✓	✓	✓	✓	
Microcodium	✓			✓	✓				
Microbialites	✓		✓			✓			
Oncoids			?			✓			
Charophyte gyrogonites	✓	✓	✓	✓	✓	✓	✓	✓	✓
Charophyte stems	✓	✓	✓	✓	✓	✓	✓	✓	✓
Plant fragments	✓	✓			✓		✓		✓
Fish	✓					✓	✓		✓
Bone fragments	✓	✓		✓	✓	✓	✓	✓	✓
Burrows (meniscate)					✓		✓		

Figure 3.1. Common aquatic components of the biota associated with the lacustrine carbonate deposits in the Morrison Formation. A, B, C, plane-polarized light photomicrographs; D, hand specimen photograph. A, Charophyte gyrogonites (arrows) within a skeletal mudstone. The lack of charophyte stems suggests this fossil assemblage was transported. Scale bar = 4 mm. B, Calcified charophyte stems (arrows) with minor spiral ribbing. Scale bar = 4 mm. C, Calcified charophyte filaments. Scale bar = ~ 200 μm. D, Conchostracan with at least 18 growth bands. Scale bar = 4 mm. A, Horsetooth Reservoir; B, C, Park Creek Reservoir; and D, Skyline Drive.


A
B
C
D

partially silicified and associated with Magadi-type cherts and calcite pseudomorphs after gypsum.

Gyrogonites are calcified oogonia (the female reproductive structure); these structures are broadly ellipsoidal with multiple spiral ridges along the outer part of the structure and measure 0.3 to 0.6 mm in diameter. Gyrogonites are whole to crushed and partially disintegrated (Figures 2.5F and 3.1A). The central intragranular porosity of the gyrogonites is filled with equant calcite cement

Taxa-According to Schudack (1996, Figure 6) and Schudack *et al.* (in press), nineteen species of charophytes have been described from the Morrison Formation from the following six genera: *Aclistochara*, *Echinochara*, *Latochara*, *Mesochara*, *Peckisphaera*, and *Porochara*.

Implications-Charophyte remains are ubiquitous in ancient carbonate lake deposits as calcified gyrogonites and calcite encrusted stems (Freytet and Plaziat, 1982; Tucker and Wright, 1990). In modern Lake Tanganyika, Cohen and Thouin (1987) described extensive charophyte meadows on muddy substrates; charophytes on wave-agitated, coarser-grained substrates are less common (Tucker and Wright, 1990). Modern lacustrine charophytes occupy relatively shallow waters (< 10 m) within the littoral zone (Cohen and Thouin, 1987).

In many respects charophyte meadows around the margins of Morrison lakes would function like sea-grasses (Tucker and Wright, 1990) in that the charophytes would baffle and trap fine clastic sediments entering the lake in addition to producing considerable quantities of carbonate mud. Carbonate sediment production by charophytes

is enhanced because they are capable of using HCO_3^- as well as CO_2 for photosynthesis (Raven *et al.*, 1986; Tucker and Wright, 1990); the greater efficiency of charophytes using HCO_3^- as a source of CO_2 as opposed to other macrophytes results in greater calcite encrustation on charophytes (Wetzel, 1975). Cucci (1974) reported sediment production rates by *Chara* in five New York lakes of 300 to 7,000 $g/m^2/yr$, which led Dean (1981) to report that charophytes could easily contribute several hundred grams of fine-grained carbonate per square meter per year. These high sedimentation rates are equivalent to gross productivity rates in some marine environments (0.5-1.5 m 1000 yr^{-1}; Tucker and Wright, 1990). The abundance of charophyte stems and gyrogonites in the lacustrine carbonate deposits suggests that Morrison charophytes represented a major biogenic source of carbonate sediments.

Lastly, salinity tolerance data from Schudack *et al.* (in press) indicate that Morrison charophytes primarily occupied freshwater lakes and ponds. However, it is important to note that several of the charophyte taxa could tolerate brackish water of up to 9-16 ‰ salinity (Schudack *et al.*, in press).

Ostracodes

Occurrence-Ostracodes are ubiquitous within Morrison lacustrine carbonate deposits occurring as 1) thin skeletal packstone laminae associated with microbial bioherms (Figure 2.3G), and within 2) skeletal mudstone to grainstone deposits (Figures 2.3B and 2.5G). Complete to disarticulated ostracodes are typically less than 0.5-1.3 mm in length. Locally, disarticulated ostracodes in hydrodynamically stable positions were

observed in open-water lacustrine and higher-energy, marginal lacustrine deposits. Articulated and disarticulated ostracodes were also observed in pseudomicrokarstic and microkarstic voids, as well as in gastropods.

Taxa-According to Schudack (1996, Figure 2), eighteen species of nonmarine ostracodes have been described from the Morrison Formation from the three major ostracode superfamilies - Cypridacea, Cytheracea, and Darwinulacea. Genera include *Cetacella*, *Cypridea*, *Candona*, *Rhinocypris*, *Trapezoidella*, *Bisulcocypris*, *Helmdachia*, *Theriosynoecum*, *Timiriasevia*, and *Darwinula*.

Implications-Salinity tolerance data from ostracodes indicate that Morrison lakes were predominantly freshwater (Schudack *et al.*, in press). In the study area, several of the ostracode taxa were interpreted to have been able to tolerate brackish-water conditions up to 9 ‰ (Schudack *et al.*, in press). Ostracode fragments also served as an important biogenic source carbonate.

Conchostracans

Occurrence-Conchostracans occur as weakly calcified, bivalved carapaces up to 11 mm (longest dimension) (Figure 3.1D). Three large and well-preserved carapaces displayed 10-15 growth bands. Conchostracans are found in association with fragmentary plant remains and ostracodes and were observed from the Skyline Drive, Purgatoire Trackway, and West Alameda Parkway sections along the bedding planes of marginal lacustrine calcareous siltstone and mudstone deposits.

Taxa-To date, no taxonomic work has been done on Morrison conchostracans.

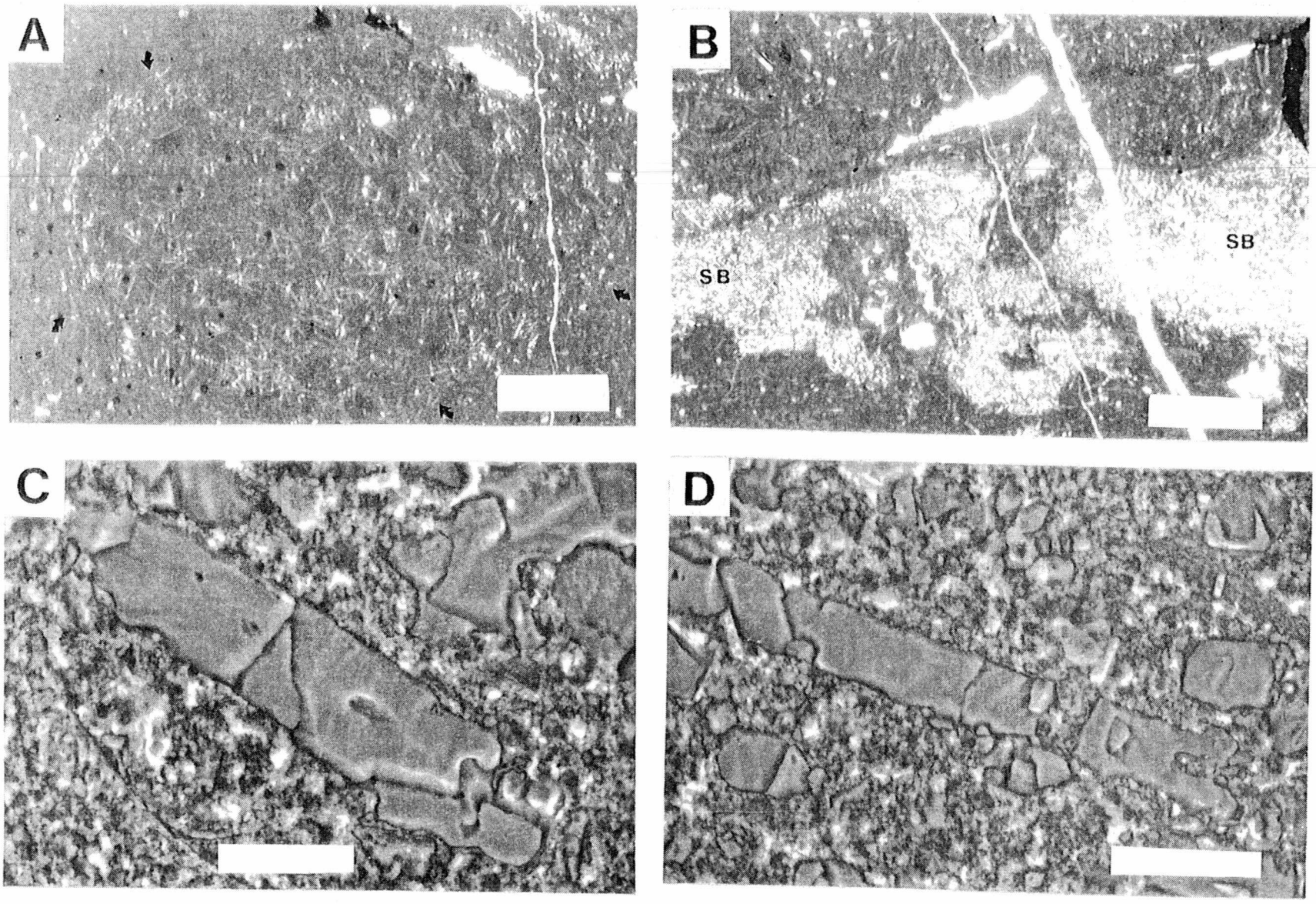
Implications-Conchostracans are indicators of endorheic environments and living species are largely confined to temporary, and often small bodies of freshwater that may have a relatively high pH and salt content, and that lack a resident fish population (Frank, 1988). Conchostracans are also most common in subarid warm regions (Frank, 1988).

Tasch (1973) noted that the number of growth bands on a given conchostracan valve represents the total lifespan of that individual; hence, the lifespan of the oldest individual represented on a bedding plane will approximate the actual duration of the given water body. The number of growth bands from three conchostracan specimens indicates a lifespan of at least 10-15 years for the ephemeral ponds at the Skyline Drive and Purgatoire sections. The paucity of conchostracans reflects 1) poor preservation of the weakly calcified shells, and 2) their association with ephemeral clastic lake and pond environments.

Spongillids

Occurrence-Low domical to cylindrical sponges 10-15 mm in diameter have been identified (Dunagan, 1997) based on a well-preserved outline of a regular meshwork of spicules tangential to the perimeter of the sponge (Figure 3.2A). Spicules also are present along the perimeter as bundles about 2.5-3.0 mm in length. Spicule bundles are common and are typically composed of greater than 50 spicules in a variety of orientations (Figure 3.2B). The sponge spicules are characterized by two types of megascleres - oxeas and

Figure 3.2. Spongillid remains from the Morrison Formation. A, B, plane-polarized light photomicrographs; C, D, SEM micrographs. A, Circular mass of spongillid (outlined by black arrows) with numerous megascleres. Scale bar = 1 mm. B, Spicule bundles (SB). Scale bar = 0.5 mm. C, D, Longitudinal and transverse sections of megascleres. Note that the spicules are recrystallized. Scale bars = 40 μm and 50 μm, respectively. A-D, Highway 287.


A
B
SB
SB
C
D

strongyles (*sensu* Rigby, 1995). Megascleres, in general, range from 180-300 μm in length and from 20-35 μm in diameter. Oxeas are straight, but the strongyles display a slight curvature. Both types of megascleres lack apparent ornamentation, such as spines, but this lack of ornamentation may be an artifact of diagenetic replacement. Microscleres are not present; gemmules and gemmoscleres were not observed.

In the case of Morrison spongillids the original siliceous spicules have been dissolved and replaced with non-ferroan calcite, and rarely with ferroan calcite, identified using petrographic staining techniques (Dickson, 1966). SEM analysis shows that the original spicule microstructures also were destroyed (Figure 3.2C-D). This is in contrast to the excellent preservation of low-Mg and high-Mg calcite allochems and microstructures associated with charophytes (stems and gyrogonites), bivalves, and stromatolites, which have not experienced the same degree of dissolution and replacement exhibited by the sponge spicules. The poor preservation of the original spicule mineralogy supports the interpretation that the spicules were originally siliceous, and not calcitic. The loss of freshwater sponge spicules due to diagenetic alteration may partially account for the poor fossil record of Mesozoic spongillids.

Taxa-This freshwater spongillid, *Eospongilla morrisonensis* (new genus and species) has been taxonomically described in Dunagan (in review).

Implications-The lacustrine carbonates of the Morrison Formation contain the oldest reported occurrence of freshwater sponges to date (Dunagan, 1997), which extends the family Spongillidae (Class Demospongia) more than 50 Ma to the Kimmeridgian and

possibly into the Oxfordian. The only other previously reported Mesozoic freshwater sponge was *Palaeospongilla chubutensis* (Ott and Volkheimer, 1972; Racek and Harrison, 1975), which is Cretaceous in age.

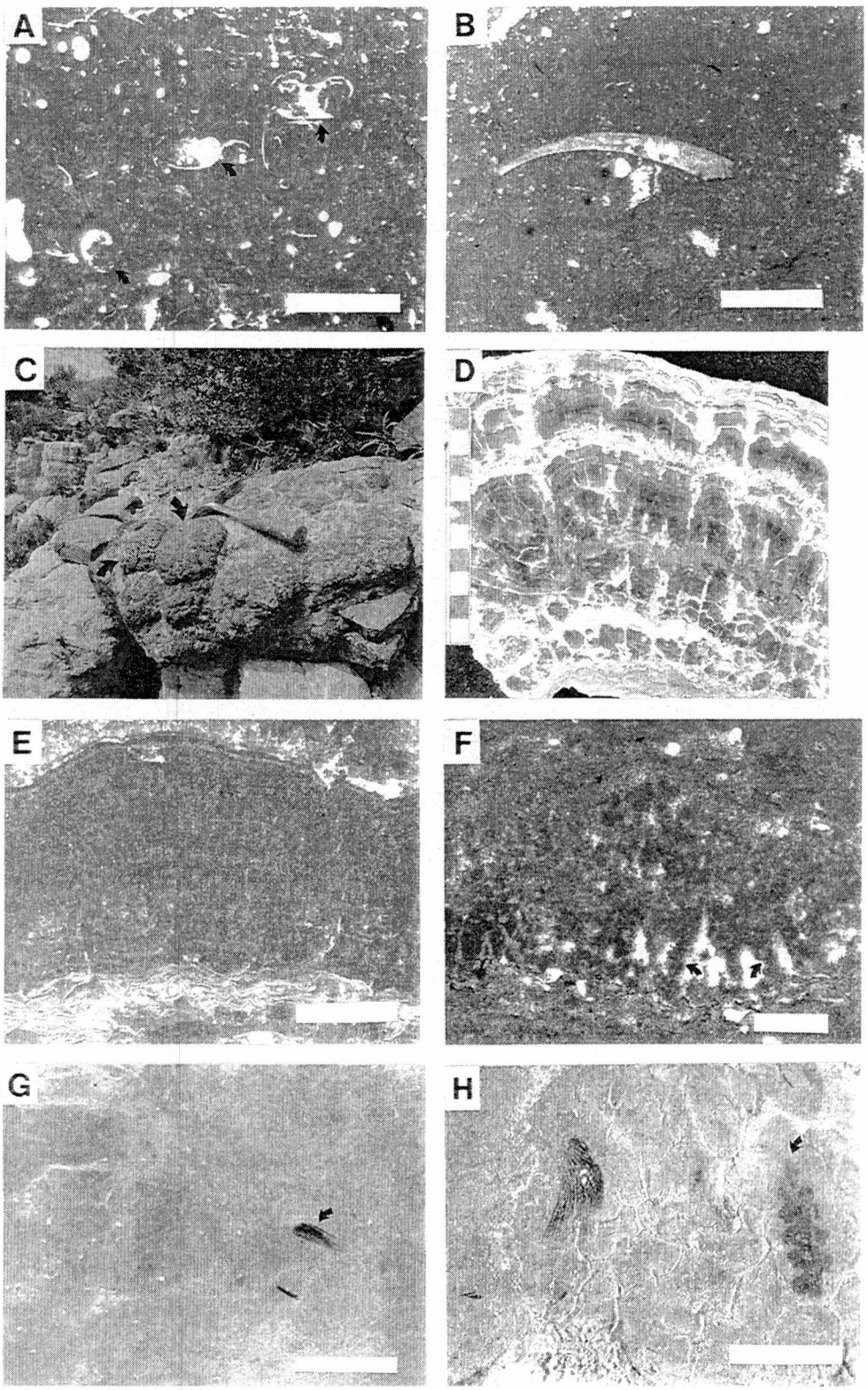
The association of pseudomicrokarst and microkarst with the freshwater sponges suggests that the sponges occupied a relatively shallow-water lacustrine setting (Dunagan, 1997). The presence of freshwater sponges and unionid bivalves within certain lacustrine units implies that 1) the nutrient content of the water column was significant enough to support filter- and suspension-feeders, and 2) the presence of at least mild currents, which would have assisted in the removal of accumulated silt, delivered food and oxygen, and removed waste.

Gastropods

Occurrence-Pulmonate (lung-breathing) and prosobranch (gill-breathing) gastropods were observed within open and marginal lacustrine carbonates, and within marginal lacustrine green mudstones. Gastropods were common at the Skyline Drive, Cope's Nipple, and Marsh-Felch Quarry sections, with lesser amounts from the Horsetooth Reservoir, Park Creek Reservoir, West Alameda Parkway, Purgatoire, and Highway 287 sections.

Gastropods occur primarily as: 1) moldic porosity with a recognizable outline (Figure 3.3), 2) calcite replacement of the original shell material (Figure 2.5A), where the original microstructure has been destroyed, and 3) silicified shell outlines. The shells are smooth and measure approximately 10-15 mm (longest dimension). Reworked

Figure 3.3. Gastropods, unionid bivalves, microbialites, and plant remains from the Morrison Formation. A-B, E-G, plane-polarized light photomicrographs; C, field photo; D, polished hand specimen; and H, hand specimen. A, Gastropods (arrows) in a faintly bioturbated, skeletal mudstone (open lacustrine). Scale bar = 4 mm. B, Disarticulated unionid bivalve fragment. Scale bar = 1 mm. C, Microbial bioherm composed of distinctive pustular to mammilary composite growth forms (arrows) across its surface. Hammer for scale. D, Two-dimensional view of microbial bioherm showing club-like columnar to digitate stromatolites. Note laterally linking across numerous intervals. Specimen is largely silicified (Magadi-type chert) except for the upper and lower 1-2 cm. Scale bar is in centimeters. E, Internal structure of the microbialites. Note that the base of the microbialite is on a thin ostracode packstone-grainstone lamina. Scale bar = 1 mm. F, Clotted thrombolitic to peloidal fabric (arrows) of club-like microbial buildups. Scale bar = 200 μm. G, Typical preservation state of unidentified plant remains (arrow) in a palustrine mudstone. Note the pseudomicrokarst in the upper left corner. Scale bar = 1 mm. H, Fern frond (arrow) from calcareous siltstone (marginal lacustrine). The plant remains come from the same interval as the conchostracans. Scale bar = 4 mm. A, Cope's Nipple; B, West Alameda Parkway; C-G, Park Creek Reservoir; and H, Skyline Drive.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ostracodes (articulated and disarticulated) and gyrogonites were observed as fillings in shells. Geopetal indicators, with a basal fill of vadose silt and angular micritic intraclasts followed by calcite cement, were also common in the gastropod shells. The lacustrine deposits contain pulmonate-dominated, prosobranch-dominated, and mixed gastropod assemblages.

Taxa-Yen (1952) documented *Amplovalvata*, *Liratina*, *Mesauriculstra*, *Lymnaea*, and *Gyraulus* from Morrison exposures near Cañon City, Morrison, and Boulder, Colorado. Lockley *et al.* (1986) also reported pulmonates, *Lymnaea* and *Gyraulus*, and the prosobranch, *Amplovalvata*, from the Purgatoire trackway site in southeastern Colorado.

Implications-Gastropods are useful indicators of hydrologic conditions. Pulmonates can live in both perennial waters as well as oxygen-poor or low-energy, ephemeral ponds or sloughs; in contrast, well-oxygenated, low-energy perennial lacustrine and fluvial environments are typically dominated by prosobranch gastropods (Evanoff *et al.*, in press). Evanoff (in press) has suggested that although prosobranch and pulmonate gastropods occur together, the dominance of the two groups changes stratigraphically in the Morrison Formation, with the lower Morrison dominated by pulmonates and the upper Morrison (above the clay change) dominated by prosobranch gastropods. This stratigraphic trend was not observed in the study area.

Unionid Bivalves

Occurrence-Unionid bivalve fragments were observed throughout the lacustrine succession and were present in lacustrine carbonate deposits at each locality. The fragmentary remains are easy to identify petrographically based on their distinct golden-yellow color and well-preserved microstructure (Figure 3.3). Bivalve fragments were observed from many of the open and marginal lacustrine carbonates microfacies (Tables 2.3 and 2.4), and in one instance a fragment was present in a pedogenic carbonate nodule. The unionids occur as disarticulated and fragmented shells up to ~ 6 mm in length with the majority of the shell fragments <2-3 mm; however, abraded shells were not observed.

Taxa-Yen (1952) noted the presence of two species of *Unio* in the study area.

Implications-Unionid bivalves thrive in well-oxygenated, perennial fluvial and lacustrine environments (Evanoff *et al.*, in press), where fish are present. The presence of fish is necessary because unionid bivalves utilize obligate parasitic larvae (glochidia) that attach to the gills and fins of freshwater fish, then detach and develop into a free-living adult stage as a dispersal method in aquatic environments (Kat, 1984). The presence of unionid bivalves suggests that Morrison aquatic habitats had currents, probably wind-driven, and a population of fish. The currents are necessary because unionids are suspension feeders and the fish are a reproductive prerequisite.

Fluvial sandstone deposits on the Colorado Plateau contain disarticulated and articulated unionid bivalve fragments that are commonly abraded as well as unionid bivalves and unionid trace fossils preserved in-living-position in fluvial sandstone deposits (Yen, 1952; Evanoff *et al.*, in press). The fragmentary nature of the unionid

shells associated with Morrison lacustrine deposits suggests that the shells may be, in fact, para-autochthonous or allochthonous. Seasonal or periodic flooding associated with fluvial systems may have transported unionid fragments into carbonate-dominated marginal lacustrine facies. Conversely, the fragmented but unabraded unionid fragments may represent para-autochthonous accumulations.

Microbialites

Occurrence-Morrison microbialites are well developed at the Park Creek Reservoir and Spillway sections, where a biostromal to biohermal bed (Figures 2.3E-F and 3.3C) up to 30 cm thick is exposed over an area of at least three square kilometers, possibly larger. Minor microbialites, oncoids, and/or cyanobacterial filaments were also observed at the Purgatoire and Purgatoire Trackway sections.

In the Park Creek Spillway area, microbialites with diameters from 9 to 60 cm occur as "domal" lithoherms displaying up to 20 cm of relief above surrounding "interdomal" areas within a larger biostromal unit. Internally, the microbialites exhibit a vertical zonation characterized successively by: 1) wavy to wrinkled microbial laminates and oncoids, 2) laterally-linked/wavy stromatolites, and 3) columnar and digitate stromatolites, up to 13 cm in height and 1-2 cm in diameter (Figures 2.3F and 3.3D-E). The columnar and digitate stromatolites are commonly linked laterally and coalesce to form large cauliflower to mammillary stromatolites. Thrombolitic fabrics were also observed, and were associated with cyanobacterial filament molds and stacked to clotted peloidal fabrics (Figure 3.3F).

In the Park Creek Reservoir area, the microbialites have similar dimensions and display a vertical succession of stromatolite layers similar to those described above. However, these microbialites exhibit more of a biohermal geometry, which is characterized by secondary pustular to mammillary aspects weathering in positive relief on the outer surface of the bioherm (Figure 3.3C). The bioherms are onlapped by desiccation cracked microbial laminates that contain reworked and overturned smaller microbial growths (mm-cm scale), Magadi-type cherts, charophyte filaments and gyrogonites, and possible fish remains.

The laminae are commonly organized as a doublet of light microsparitic and peloid laminae and a dark micritic laminae. Interdomal areas are composed of microbial laminates, oncoids, overturned microbialites (up to 6.5 cm long and 1.5 cm high), reworked clasts of Magadi-type chert, micritic intraclasts, ostracodes, and gyrogonites. Gastropods were not observed in these deposits.

The microbialites form prominent ridges above the sandstones of the Windy Hill Member of the Morrison Formation because they are partially silicified (up to 50%). The silicification is most common within columnar to digitate forms occupying the middle portion of the microbialites and less common within the microbial laminates. The intricate microstructure of the microbialites is typically preserved and is not obliterated across the silicification boundary; reworked partially silicified oncoids and overturned microbialites suggest that silicification occurred penecontemporaneously with microbialite growth.

Taxa-Rivularia was tentatively reported by Neuhauser *et al.* (1987) from Morrison stromatolites in New Mexico.

Implications-The presence of stromatolites has previously been noted from the Morrison Formation in northeastern New Mexico (Neuhauser *et al.*, 1987), north-central Colorado (Jackson, 1979; Johnson, 1991; Dunagan *et al.*, 1996), southeastern Colorado (Lockley *et al.*, 1986), and western Oklahoma (West, 1978). Only Neuhauser *et al.* (1987) provided a description of the internal microstructure of the stromatolites. The internal structure of the New Mexico stromatolites, which ranged in diameter from 7-43 cm, was characterized by Neuhauser *et al.* (1987) as non-columnar to pseudocolumnar, with distinct laterally-linked laminations and roll-over growth along the margins. Neuhauser *et al.* (1987) suggested that the stromatolites in this area occupied a lake that was moderately to highly saline.

The presence of microbial biostromes in the Morrison Formation is not solely indicative of a saline lake, as was assumed by Neuhauser *et al.* (1987). In the Park Creek Reservoir/Spillway area, the association of Magadi-type cherts with the microbial deposits indicates that the lake experienced periods of increased alkalinity; however, no evaporites or pseudomorphs after evaporites were observed. The occurrence of abundant ostracodes along laminae, in addition to gyrogonites and possible fish remains, also indicate freshwater lacustrine conditions.

Sedimentologic and stratigraphic relationships (discussed in Chapter 2) indicate an open-water lacustrine depositional environment. This is contrary to interpretations by Jackson (1979) and Johnson (1991), who interpreted the Morrison stromatolites as

shoreline deposits. The association of thin ostracode packstone laminae and Magadi-type cherts (Dunagan *et al.*, 1996) with the microbialites strongly suggests a depositional environment within the open portions of Morrison lakes, and not along the shoreline. The microbial laminates that onlap the microbial bioherms also contain diffuse bioturbated laminations and contain minor desiccation cracks on the upper bedding plane. These relationships suggest a general shallowing trend from the bioherms to the microbial laminates.

The general lack of trapped detrital quartz along stromatolitic laminae indicates that stromatolitic growth was primarily due to microbial-induced precipitation of calcite (Camoin *et al.*, 1997) and that the growth was in the open-water portions of the lake. Morrison microbialites are similar in morphology to those described from the paleo-Andean Basin (Maastrichtian-Danian) of Bolivia by Camoin *et al.* (1997).

Vascular Plants

Occurrence-Fragmentary remains of vascular plants were sporadically distributed in the marginal lacustrine and distal alluvial deposits of the Morrison Formation, including megafossil (SD, WAP, MFQ) and microfossil plant fragments (PCR, MFQ). Megafossil remains were characterized by carbonized impressions and pyritized and coalified fragments within marginal lacustrine deposits (green mudstone, siltstone, and palustrine carbonates; Figure 3.3G), tuffaceous mudstone, and paleosol deposits. Conifer needles and rare fern remains (Figure 3.3H) represented the only identifiable material. The vast majority of plant remains are finely comminuted to macerated and are typically

< 1-5 mm in length. Preservation quality of this material is typically poor, however, xylem and cortical tissue are preserved in pyritized plant remains from MFQ (Figure 2.5A).

Taxa-Unfortunately, the lack of preserved venation or fertile structures precludes taxonomic assignment of these plant remains, with the exception of the fern. Ash (1998, written communication) tentatively identified the fern as *Cladophlebis* sp.

Implications-The vast majority of reported occurrences of Morrison plant fossils have been restricted to the Colorado Plateau and to Montana (Miller, 1987; Tidwell, 1990b; see references therein). These plants included bryophytes, pteridophytes, sphenophytes, cycadophytes, ginkgophytes, fungi and conifers.

The present study represents one of the first reports of Late Jurassic plant remains east of the Colorado Front Range. The presence of plants ties a critical feature of the Morrison paleoecosystem to the carbonate lakes and ponds present on this vast alluvial plain. These lakes were not solitary features on an empty alluvial plain, but plants were present in abundance. Although direct evidence of their presence (fossilized remains) is rare, trace fossil evidence, preserved as pseudomicrokarst and other root traces in paleosols, is common.

The wide distribution, coupled with the poor preservation of these plant remains, suggest rapid oxidization in the well-mixed waters of Morrison lakes and ponds and on the adjacent alluvial plains; increased preservation potential was favored only in areas characterized by reducing or temporarily restricted dysaerobic waters.

Vertebrate Remains

Occurrence-Bone fragments are locally common in the open and marginal lacustrine carbonate and sandstone deposits. These remains typically occur as angular to well-rounded clasts < 4-6 mm (Figure 2.3B); however, rare fragments up to 10 cm in length were observed (PCR and MFQ). Most of the bone fragments have Haversian canals; few fragments have a cancellous or spongy structure. A single crocodile jaw was discovered on the upper bedding plane of a marginal lacustrine sandstone at PCR (identification by G. Engelmann, 1996).

Taxa-Taxonomic assignment of these fragmentary remains was not attempted.

Implications-Vertebrate quarries in marginal lacustrine and floodplain mudstones are common in Colorado (Kirkland and Armstrong, 1992), Utah (Bilbey, 1993), and Wyoming (Bakker, personal communication, 1996). However, only limited vertebrate remains have been reported specifically from Morrison lacustrine carbonate deposits (*e.g.*, fish remains from the Purgatoire Trackway, Lockley *et al.*, 1986). Dobson *et al.* (1980) suggested that the paucity of vertebrate remains was a result of inhospitable lake conditions, possibly due to periodically elevated alkalinity and salinity, or to high temperatures. In contrast, the Upper Cretaceous Lance Formation of Wyoming contain remains of small aquatic vertebrates (Estes and Berberian, 1970).

It is important to note that although the vertebrate material is generally assigned to crocodiles, dinosaurs or bony fish, a variety of mammals, sharks, salamanders, frogs, turtles, lizards, and sphenodontids have also been reported from the Morrison Formation; due to the small size of the bone fragments, precise taxonomic assignment of the remains

is uncertain. Despite the fragmentary nature, based on the size, microstructure, and previous reported occurrences, most of the bone remains were assumed to be derived from reptiles (dinosaurian and non-dinosaurian) and fish.

The paucity of vertebrate remains is a taphonomic function of paleolimnological conditions such as energy regime, current activity, scavenging, water temperature, and water depth. Freytet and Plaziat (1982) noted that the absence of fish remains in ancient lake successions appears to be a good indicator of holomictic conditions based on modern lake analogues due to oxidation of the organic remains. Experimental data have demonstrated that the fate of fish carcasses is partly a function of water temperature: above 16°C bacterial decay will cause whole fish to float and disperse, but below this temperature they tend to remain on the bottom (Elder and Smith, 1988). Facies relationships suggest that Morrison lakes were relatively shallow and well-oxygenated, and these conditions would have severely limited the preservation potential of Morrison fish, especially when lake water temperatures are considered. In addition, based on bone size and sorting, most of the vertebrate remains appear to have been transported into the lacustrine environment.

Lacustrine Ichnology

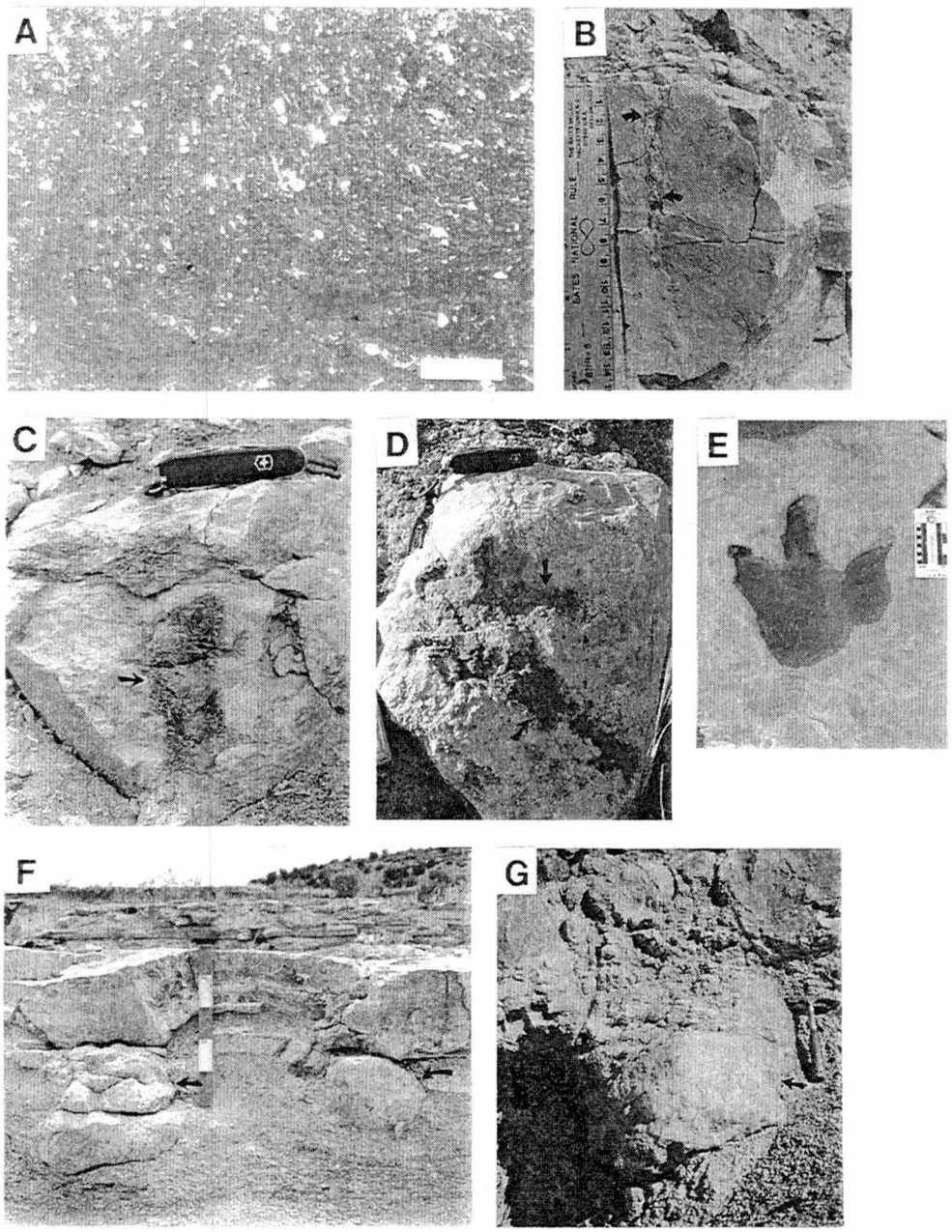
Occurrence-Several types of invertebrate and vertebrate trace fossils were observed in association with the open- and marginal-lacustrine deposits. Meniscate burrows were noted from micritic mudstones of the marginal lacustrine facies. These burrows were observed in thin-section, and ranged in length from 7-15 mm. The burrows

were characterized by a slightly darker wall structure as compared to the surrounding micrite, and a meniscate backfill, with 5-10 meniscate laminae per mm, that was composed of rounded to elliptical peloids (Figure 3.4A). The backfill component was clotted, but retained ~15-25 % porosity that is filled with calcite cement. The lined and meniscate features of this burrow are similar to *Scoyenia* sp. from the Jurassic East Berlin Formation (Gierlowski-Kordesch, 1991) and Late Triassic Lockatong Formation (Metz, 1995), both of which are within the Newark Supergroup of the eastern United States.

Six carbonate mudstone burrows were observed extending from the base of marginal lacustrine carbonates up to 20 cm into the underlying green mudstone and siltstone; the burrow diameter was approximately 5 cm. These burrows were observed only at the Highway 287 roadcut and were subsequently lost to weathering processes. Hasiotis and Demko (1996) described crayfish burrows from the Salt Wash Member of the Morrison Formation that are similar to these burrows.

Trace fossils infilled with green mudstone are common in the marginal lacustrine deposits, particularly in the upper Morrison Formation. These burrows are typically vertical to subvertical and subhorizontal. Several of the burrows have simple vertical shafts (< 10 cm in length and 1-6 cm diameter; Figures 2.4E and 3.4B-C), whereas others display secondary downward-branching structures (Figures 2.7E, H). These traces are similar to insect burrows and plant rhizoliths, respectively, described by Hasiotis and Demko (1996) from the Morrison Formation on the Colorado Plateau.

Figure 3.4. Trace fossils associated with the lacustrine carbonate deposits of the Morrison Formation. A, plane- polarized light photomicrograph; B-G, field photographs. A, Burrow with meniscate backfill. Note the abundant peloids in the backfill. Scale bar = 1 mm. B, Sharp-walled vertical burrow (arrows) within a palustrine carbonate infilled with green mudstone infill. C-D, Large green mudstone filled, vertical to sub-horizontal ?crayfish burrows (arrows). Note brecciated upper surface in D. Knife for scale is ~7 cm in length. E, Theropod track in ooid packstone. F-G, Dinoturbation structures (= dinosaur trackways; arrows) in ooid grainstone and skeletal wackestone, respectively. A, West Alameda Parkway; B, Park Creek Reservoir; C, D, Horsetooth Reservoir; E, F, Purgatoire Trackway section; and G, Highway 287.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Dinosaur trackways and associated dinoturbation are common features in the marginal lacustrine carbonates (Figure 3.4E-F), which have been previously described by Lockley *et al.* (1986) for the Purgatoire Trackway section. Dinoturbation was observed from marginal lacustrine deposits at H287 and HR, penetrating into carbonate beds to depths of up ~ 50 cm.

Implications-The meniscate, micritic, and green-mudstone-filled burrows provide insights into the trace-making invertebrate community, which was common within Morrison lakes and ponds. Preliminary trace fossil documentation indicates that insects, crayfish, and plants were present within and along the margins of Morrison lakes and ponds. Hasiotis (in press) noted that the presence of plants and aquatic invertebrates, such as crayfish, beetles, and caddisflies, from the Morrison Formation has commonly been documented solely on the basis of their trace fossil record. This is an artifact of the low preservation potential of many of these organisms.

Dinosaur trackways (Lockley *et al.*, 1986), as well as terrestrial and aquatic invertebrate traces (Hasiotis and Demko, 1996), are common from the Morrison Formation. Crocodilian tracks and tail drags have also been reported by Hatcher (1903) from the Garden Park Paleontological area near Cañon City, Colorado, and more recently by Foster and Lockley (1997) from the La Sal area in Utah. Based on bone fragments and trace fossils, dinosaurs and crocodiles were likely common along the margins of Morrison lakes and ponds; however, the preservation potential of these trace fossils is low unless rapidly buried.

DISCUSSION

A diverse biota is found in association with the open- and marginal-lacustrine facies of the Morrison Formation representing several trophic levels, including primary producers (charophytes and cyanobacteria), primary consumers ("annelids," ostracodes, conchostracans, sponges, unionid bivalves, and gastropods), and secondary consumers (crayfish, fish, and crocodiles). The crayfish and insects probably included omnivores and scavengers within Morrison lentic settings, as well as primary and secondary consumers (Hasiotis, in press). Fragmentary bone remains and trackways indicate that dinosaurs traversed areas between the marginal lacustrine and floodplain environments. Wells (1983) described a similarly diverse shallow lacustrine biota for Lake Flagstaff (Paleocene-Eocene, Utah), and suggested that the lake was probably always biologically productive due to the expansive littoral zone created by its shallowness.

Sedimentologic and stratigraphic relationships discussed in Chapter 2 indicate that Morrison lakes and ponds were predominantly shallow and characterized by low-energy, low-gradient 'ramp'-type margins (*sensu* Platt and Wright, 1992). Even though Morrison lakes and ponds were primarily low-energy settings, the fossil assemblages have experienced various degrees of reworking by a number of taphonomic processes, including wind-driven currents, periodic flood and storm events, oxidation of organic matter, and scavenging. These fossil assemblages are dominated by 'disturbed neighborhood,' 'transported,' and 'mixed' fossil assemblages with minor 'in-place' fossil assemblages (*sensu* Hanley, 1977). The biotic composition of in-place, disturbed neighborhood, and transported assemblages are ecologically homogeneous, whereas the

mixed assemblages are characterized by biotic elements that are ecologically heterogeneous (Hanley, 1977). The abundance of disturbed, transported, and mixed fossil assemblages suggests that taphonomic agents were active in Morrison lakes and ponds.

Disturbed and transported assemblages dominate the lacustrine deposits. These assemblages were observed from open lacustrine carbonate deposits (skeletal mudstone/wackestone, and more rarely, microbialites) and marginal lacustrine deposits (peloidal-skeletal mudstone/wackestone, intraclast wackestone/grainstone, and green mudstone). The disturbed assemblages are characterized by reworked and disarticulated charophyte stems, gyrogonites, prosobranch gastropods, ostracodes, and unionid bivalves with rare articulated ostracodes, sponges, and conchostracans (Figures 2.3B, 2.5G, and 3.2). Skeletal fragments are present in a variety of orientations, ranging from convex up to down. The transported assemblages typically consist of charophyte gyrogonites, prosobranch and pulmonate gastropods, ostracodes, and reptile bone (Figures 2.3G and 3.1A). Skeletal fragments are disarticulated and fragmented. Ostracodes in this assemblage are commonly in a convex down, hydrodynamically stable position.

Mixed and in-place assemblages rank third and fourth in abundance, respectively. Mixed assemblages are commonly associated with marginal lacustrine deposits (micritic mudstone, peloidal/skeletal packstone/grainstone, ooid packstone/grainstone, siltstone, and sandstone). The mixed fossil assemblages are characterized by charophyte stems, ostracodes, sponges, pulmonate gastropods, vascular plant fragments, and minor amounts of crocodile and dinosaur bone (Figures 2.5A, F; and 3.2). This assemblage typically

displays the same characteristics as the disturbed neighborhood assemblages, with the external pulmonate gastropod and reptile bone elements.

In-place assemblages are generally limited to open-lacustrine deposits containing microbialites and marginal lacustrine deposits (peloidal/skeletal packstone, carbonaceous packstone). Although microbialites are predominantly in place (Figure 3.3C-F), evidence for minor reworking and overturning is present. In-place assemblage deposited in marginal lacustrine settings are composed primarily of concentrations of delicate charophyte stems (Figure 3.1B) and replaced and pyritized plants fragments (Figure 2.5A).

PALEOLIMNOLOGICAL SYNTHESIS

Paleontologic and sedimentologic evidence indicates that during the Late Jurassic the paleogeography of east-central Colorado consisted of numerous perennial to ephemeral lakes and ponds that were predominantly freshwater. Perennial lacustrine conditions are suggested by the presence of prosobranch gastropods, unionid bivalves, and rare fish remains; ephemeral conditions are indicated by restricted faunas, such as conchostracans and pulmonate gastropods.

The freshwater nature of Morrison lakes and ponds is demonstrated by the abundance of freshwater ostracodes and charophytes. Based on data from Schudack *et al.* (in press), salinity ranges were typically < 9 ‰. The presence of Magadi-type cherts indicated that the lakes experienced temporary periods characterized by high alkalinity (high pH > 9.0-9.5; Eugster and Jones, 1968; Hay, 1968; Eugster, 1969; Sheppard and

Gude, 1986), probably due to high productivity associated with charophyte photosynthesis. These cherts, however, are restricted to the lower Morrison Formation and their association with microbialites and freshwater ostracodes and charophytes indicates highly alkaline, and not necessarily highly-saline conditions.

Unionid bivalve paleobiogeography indicates that a paleo-drainage system from Utah to Colorado was present (Evanoff *et al.*, in press). This paleo-drainage system extended past the Ancestral Rockies and into east-central Colorado (Evanoff *et al.*, in press) and would have fed Morrison lakes and allowed for the migration of biotic elements, such as unionid bivalve and fish, from the Colorado Plateau. The presence of unionid bivalves and spongillids also implies Morrison lakes were characterized by at least mild currents, probably driven by winds over the shallow lakes.

CONCLUSIONS

1. A diverse biota was present in the carbonate lakes and ponds of the Morrison paleoecosystem. Body fossils include charophytes, ostracodes, sponges, unionid bivalves, prosobranch and pulmonate gastropods, microbialites, and conchostracans; bone fragments suggest that fish, crocodiles, and dinosaurs also were present. Trace fossil evidence also suggests that insects, crayfish, plants, and dinosaurs were present.
2. The low-gradient, ramp-type margins that characterized Morrison lakes were subjected to periodic reworking by wind-driven currents, and by storms and flood events. Wind-driven currents, scavenging/oxidation of organic material, and periodic high-energy events, such as storms and floods, served as the primary taphonomic and

biostratinomic processes acting on the fossil assemblages. The lacustrine carbonate deposits are dominated by disturbed and transported fossil assemblages, with minor mixed and in-place fossil assemblages.

3. Paleontological data provide an independent source of hydrogeochemical and hydrologic information for Morrison lakes and ponds. The lacustrine biota indicates that Morrison lakes were primarily freshwater in nature and were characterized by perennial to ephemeral and hydrologically open to closed conditions.

CHAPTER 4 -

INSIGHTS INTO LATE JURASSIC PALEOLIMNOLOGY AND HYDROGEOCHEMISTRY FROM MAGADI-TYPE CHERTS IN THE MORRISON FORMATION (COLORADO)

INTRODUCTION

Magadi-type cherts represent important indicators of continental hydrogeochemistry in lacustrine successions. Studies of Magadi-type chert from lacustrine deposits in eastern Africa have demonstrated that such cherts form in association with sodium silicate minerals (magadiite, $NaSi_7O_{13}(OH)_3 \cdot 3H_2O$) and typically sodium carbonate-bicarbonate minerals (trona, primarily). Chert formation commonly involves a process of evaporite precipitation and subsequent alteration, Na-silicate precipitation, and subsequent alteration to a silica gel, which dehydrates to chert. Although the dynamics of this chert forming process are not completely understood, the restriction of modern Magadi-type chert to semi-arid environments and limnological settings characterized by high alkalinity (pH > 9.0-9.5; Eugster and Jones, 1968; Hay, 1968; Eugster, 1969; Sheppard and Gude, 1986) make the identification of Magadi-type chert useful in interpreting paleoclimate and paleohydrogeochemical conditions within ancient lacustrine deposits.

In east-central Colorado, the Morrison Formation is characterized by a well-developed lacustrine carbonate succession containing authigenic chert deposits. The

focus of this chapter is the authigenic chert that is texturally and petrographically similar to Magadi-type cherts. The objectives of this chapter are: 1) to present textural and petrographic descriptions of the authigenic chert deposits and evidence for a magadiite precursor; 2) to postulate the necessary conditions for Magadi-type chert precipitation in Morrison paleolakes; 3) to present a scenario for chert precipitation in Morrison paleolakes; and 4) to discuss the paleolimnologic implications of Magadi-type cherts. This investigation is significant in that it represents the first detailed textural and petrographic study of Magadi-type chert from the Morrison Formation.

METHODS

The description of the characteristics and distribution of Magadi-type chert in the Morrison Formation is based upon field observations, examination of polished slabs and thin-section billets, and standard petrographic microscopy techniques. Preliminary X-ray diffraction analyses were run using a Scintag XDF 2000 with a Co tube (45 kV, 40 mA) to determine the mineralogical composition of the chert, the 101/100 peak ratios, and the extent of diagenetic alteration. Chert samples were crushed and powdered using a corundum mortar and pestle and then elutriated onto glass slides for analysis.

PREVIOUS INVESTIGATIONS

The formation of penecontempareous chert within sedimentary depositional environments represents a long standing geological conundrum (see review in McBride,

1979). Most penecontempareous cherts typically have been regarded as products of early diagenetic processes that mobilized metastable biogenic silica with subsequent carbonate replacement.

The description of chert from alkaline carbonate lakes associated with the Coorong Lagoon in Australia provided the first insights into the physical and chemical dynamics of inorganic chert precipitation (Peterson and von der Borch, 1965). Chert deposits associated with other ancient and recent alkaline-carbonate lakes in the east African Rift system are also common, and an inorganic origin has been suggested based on textural characteristics and field relationships (Hay, 1968; Eugster, 1969).

The ancient and modern chert deposits associated with Lake Magadi, a carbonate-rich lake in the east African Rift system, have served as a useful natural laboratory in understanding of the processes of synsedimentary inorganic chert formation. Studies of hydrous sodium silicates and silica in alkaline brines from Lake Magadi point toward the formation of the precursors of bedded chert deposits through inorganic precipitation (Eugster, 1967; Jones *et al.*, 1967). Numerous mineralogical, sedimentological, and geochemical studies of Lake Magadi have characterized the geographic distribution and textural features of the chert deposits as well as discussing various mechanisms of silica gel formation and conversion to chert (Hay, 1968; Eugster, 1969). Interestingly, despite these numerous studies of Magadi-type chert, no comprehensive or detailed petrographic studies of Magadi-type cherts have been performed to date with the exception of Schubel

and Simonson's (1990) survey of chert specimens from Lake Magadi deposits and interpreted Magadi-type chert specimens.

Chert has been recognized from the Morrison Formation for over a century. Early stratigraphic and sedimentologic studies documented the presence of chert pebble horizons and partially to completely silicified limestones. Surdam *et al.* (1972) first reported the presence of Magadi-type chert from several stratigraphic units in Wyoming, including the Morrison Formation; however, Surdam *et al.* (1972) provided only a generalized textural description of Morrison Magadi-type cherts. The present investigation represents the first detailed textural and petrographic study of Magadi-type chert from the Morrison Formation.

MORRISON MAGADI-TYPE CHERT

Distribution

Authigenic chert is present at several Morrison outcrops examined as part of this study and appears to be restricted to the lowermost portions of the lacustrine carbonate succession. However, not all of the observed authigenic chert was interpreted as Magadi-type chert. Authigenic chert displaying typical textural and petrographic features (described below) associated with Magadi-type cherts were observed at five localities (PCR, H, HR, SD, and P; Figure 4.1). The Morrison Magadi- type cherts appear to be restricted to lacustrine carbonate deposits and were not observed in other lacustrine facies.

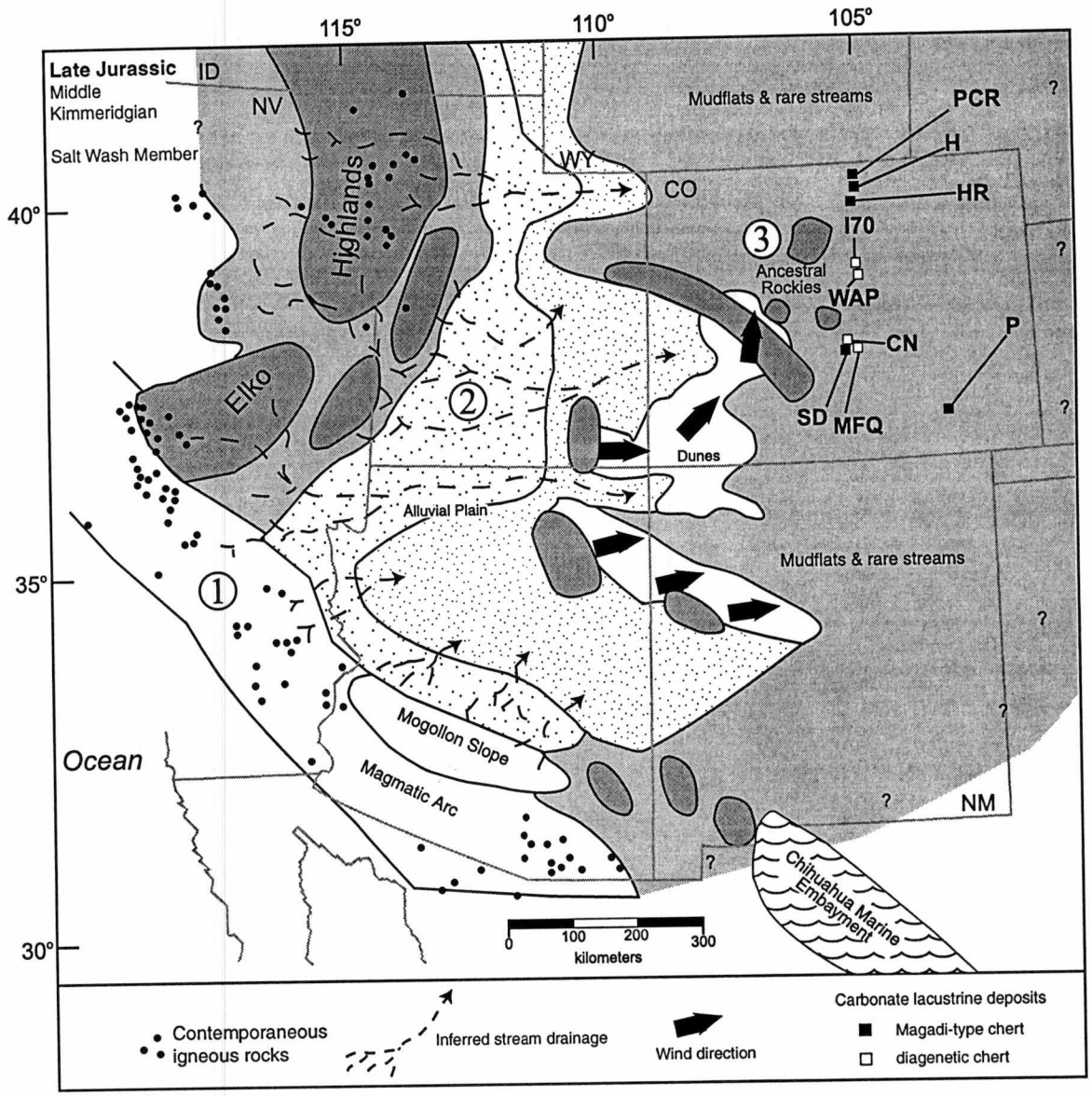


Figure 4.1. Magadi-type chert localities (black squares) in the Morrison Formation superimposed on the paleogeographic reconstruction of the Morrison paleoecosystem during deposition of the Salt Wash Member (modified from Peterson, 1994, Fig. 20). Three major sources for dissolved silica are indicated (circled numbers). 1, magmatic arc source for volcanic glass shards from airfall of volcanic ash; 2, detrital quartz silt and sand derived from the Elko Highlands and magmatic arc; 3, detrital quartz sand and silt, and silicate rock clasts derived from the Ancestral Rockies. Refer to Figure 1.1 for locality abbreviations.

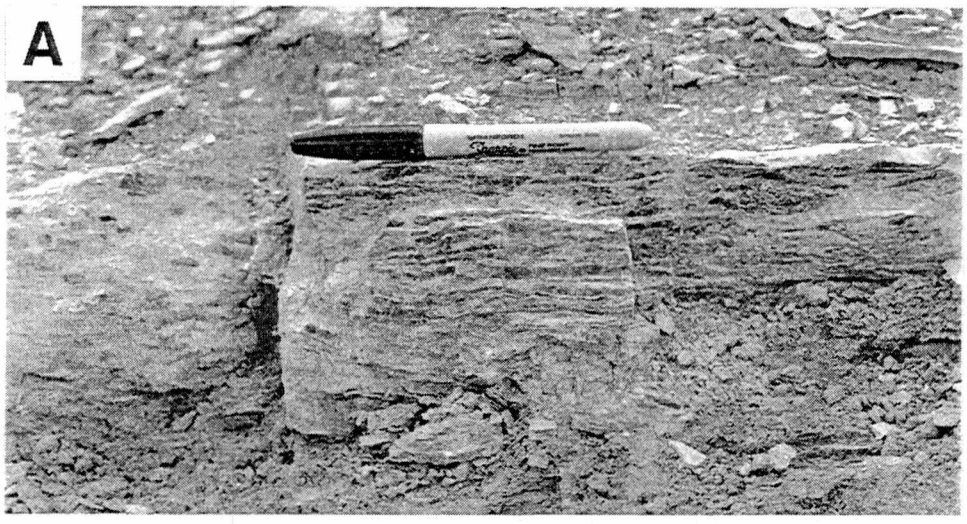
Textural Features

Morrison chert deposits exhibit a variety of colors from reddish brown to dark gray (Figure 4.2), commonly weathering with a positive relief. In the field, the cherts are characterized by thin beds (<1-4 cm thick) that 1) are laterally discontinuous on a centimeter to decimeter-scale, and 2) display a platy to nodular appearance. Locally, the chert layers exhibit evidence for soft-sediment deformation (Figure 4.2). Surface reticulation was not observed in the Morrison chert specimens examined in this study.

Petrographic Characteristics

The Morrison chert samples consist primarily of aggregates of interlocking fine chalcedony and microcrystalline quartz (2-250 μm, most <70 μm). The chalcedony is commonly length-slow with irregular wavy extinction. The aggregates are characterized by botryoidal to concentrically-ringed bodies (80-500 μm, longest dimension) of chalcedony (Figure 4.3). The ringed chalcedony bodies are typically composed of a fine grained core (<5 μm) and a coarser, fibrous rim. The ring structures are defined by the relative presence or absence of Fe-staining. Numerous inclusions are also associated with these ring structures, but their distribution is not directly related to the Fe-staining. Discontinuous chert layers are separated vertically by micrite, coarse microspar, or blocky equant calcite. Spherulites and crystal molds were also observed. The spherulites (<200 μm) are rare and are composed of length-slow chalcedony (Figure 4.3). Chert pseudomorphs after gypsum and/or (?)nahcolite were also observed (Figure 4.4).

Figure 4.2. Typical field occurrences of Magadi-type chert from the Morrison Formation. A, B, C, and D, field photographs of chert nodules and thin, discontinuous to platy beds. A, Platy red chert deposits from the lowermost portion of the lacustrine succession at Horsetooth Reservoir (HR). B, Discontinuous chert beds to chert nodules from HR. C, Thin, discontinuous chert beds (arrows). Note paucity of chert in the overlying limestone (HR). D, Discontinuous and black chert displaying signs of synsedimentary deformation (arrows) from Skyline Drive.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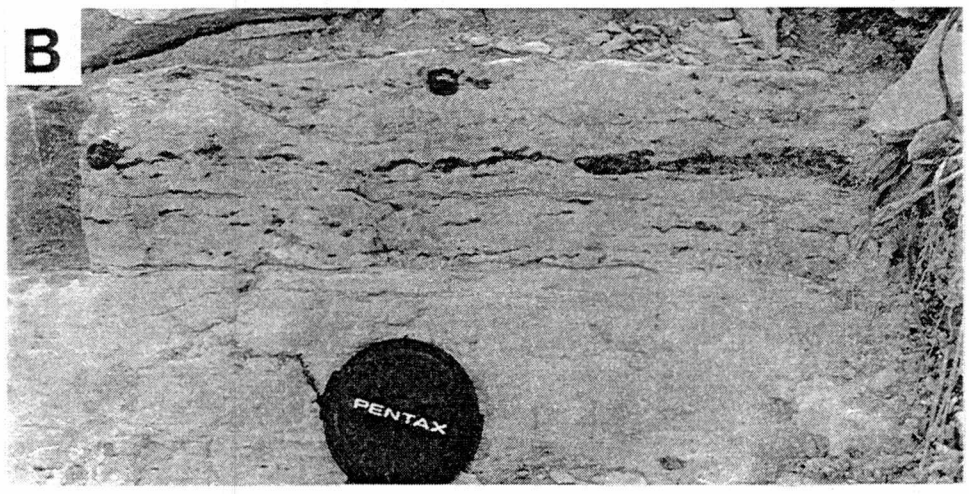
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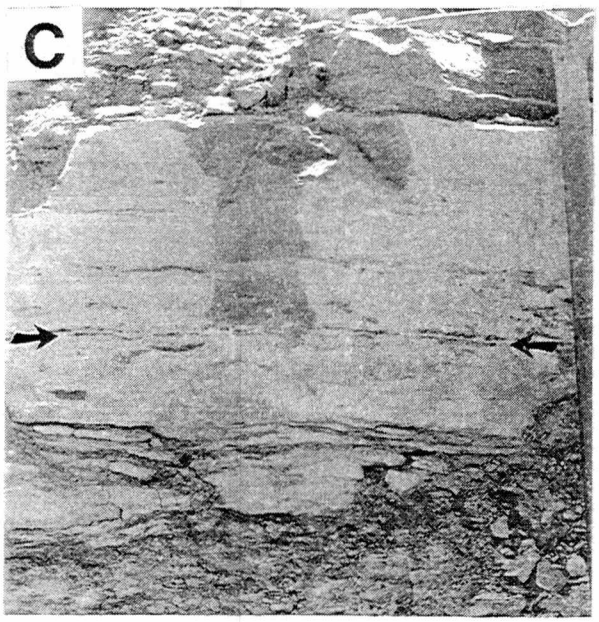
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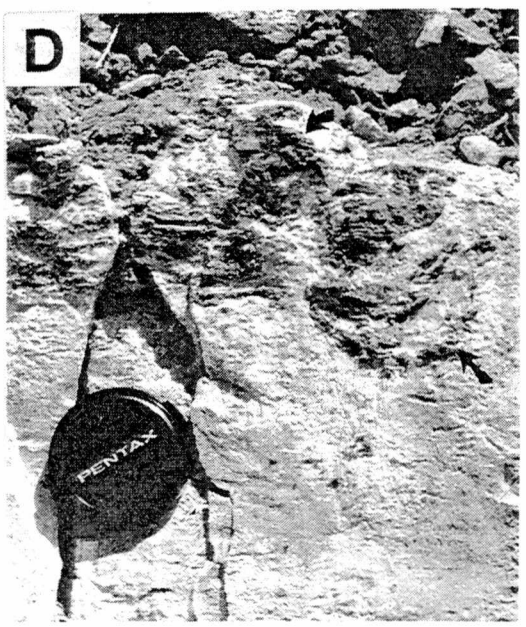
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Figure 4.3. Petrographic features associated with the Magadi-type cherts from the Morrison Formation. A-C, plane-polarized light photomicrographs; D, cross-polarized light photomicrograph. A, Chalcedony botryoids and ringed bodies passing upward into chalcedony pseudomorphs after nahcolite or gypsum (black arrows) Scale bar = 500 μm. B, Chalcedony botryoid enclosed by blocky calcite. Note the "quasi"-concentric nature of the fibrous chalcedony bands within the botryoid. Scale bar = 200 μm. C, Plane- and D, Cross-polarized light photomicrographs of chert groundmass with abundant chalcedony exhibiting undulatory extinction. Length-slow spherulitic aggregate is present in the center. Scale bar = 200 μm.

B
D
A
C

Figure 4.4. Pseudomorphs after evaporites associated with Morrison Magadi-type cherts. A, B, and C, plane-polarized light photomicrographs; D, cross-polarized light. A, Chalcedony pseudomorphs after ?nahcolite or gypsum above chalcedony botryoids (Horsetooth Reservoir). Note the abundance of oxidized Fe (black) associated with the chalcedony. B, Calcite pseudomorphs after gypsum in a skeletal wackestone (Highway 287). C-D, Plane-polarized (C) and cross-polarized (D) view of same field of view. Chalcedony pseudomorphs after ?nahcolite or gypsum (Horsetooth Reservoir). Note twinned crystals (arrow). Scale bars on all photomicrographs are ~ 500 μm.

A
B
C
D

The optic axes of chalcedony and microcrystalline quartz are primarily randomly oriented, but there are rare patches with optic axes that display a rectilinear or grid-work extinction pattern (Figure 4.5). These patterns are best observed with crossed polarizers and with the gypsum plate inserted.

X-Ray Diffraction Characteristics

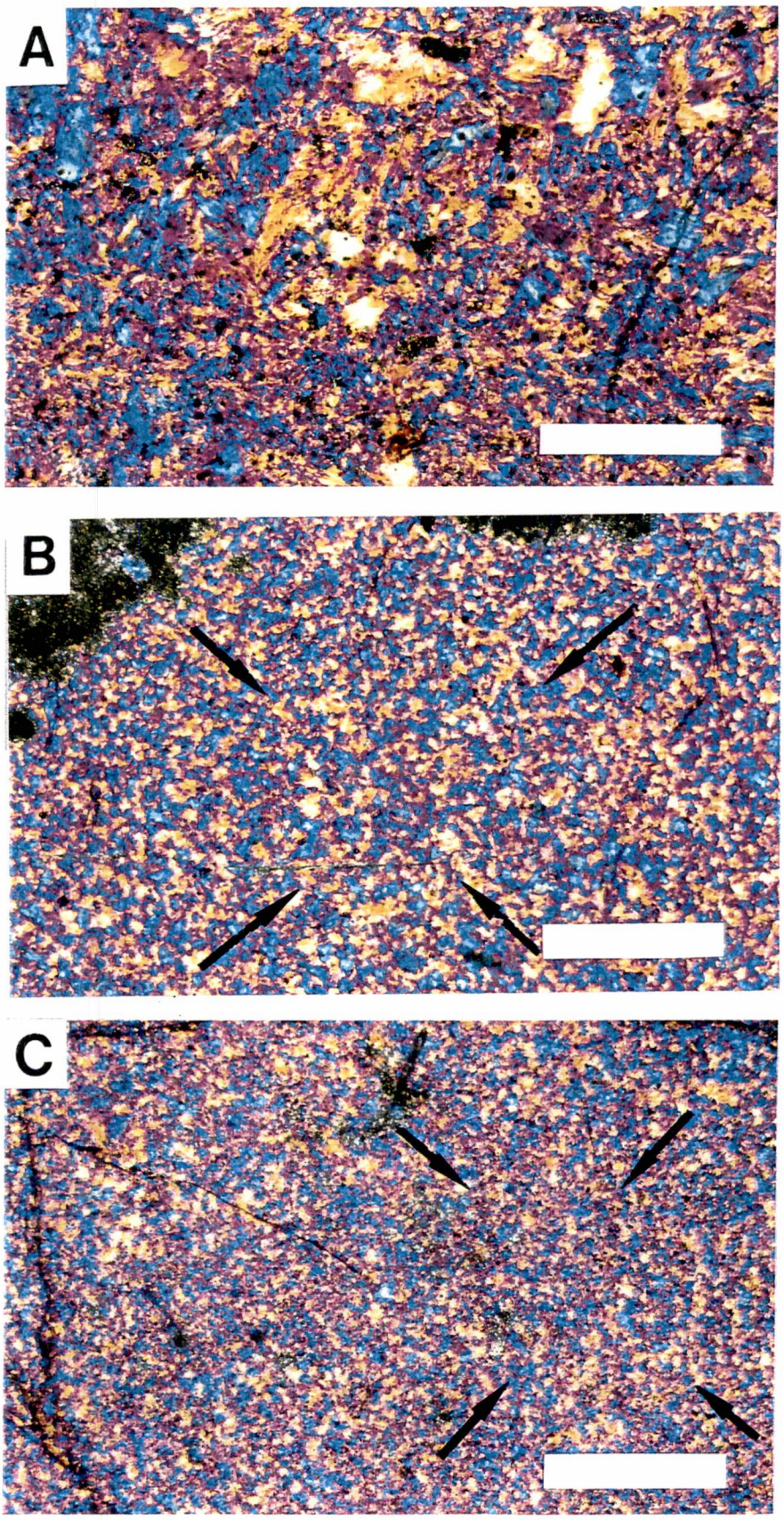
A preliminary set of three Morrison chert samples were examined using X-ray powder diffraction (XRD) methods (Figure 4.6). The XRD patterns confirm the presence of quartz and calcite with minor amounts of dolomite. All of the peaks were sharp, suggesting well-crystallized mineral phases. The ratio of intensities of the 101 peak to the 100 peak for the Morrison cherts were 6.4, 4.7, and 5.9 for HR-6.0A, HR-7.85, and HR-7.5-7.65, respectively (Figure 4.6). In comparison, the intensity ratio of the 101/100 peak with well-crystallized quartz is about 4, but this ratio for most of the Magadi-type cherts is 6-8 (Sheppard and Gude, 1986).

DISCUSSION

Evidence of a Magadiite Precursor for Morrison Cherts

Based on textural and petrographic characteristics, the authigenic chert deposits are interpreted as Magadi-type cherts. These textural and petrographic observations include the presence of a rectilinear extinction pattern, concentrically-ringed chalcedony bodies, length slow chalcedony, spherulites, and pseudomorphs after evaporites.

Figure 4.5. Randomly oriented to rectilinear or gridwork extinction patterns in the chalcedonic groundmass of Magadi-type cherts. A, B, C, Cross-polarized light photomicrographs with the gypsum plate inserted. A, Groundmass of chert with randomly oriented quartz crystals (Horsetooth Reservoir). B-C, Rectilinear or gridwork extinctions pattern in chert groundmass (Park Creek Reservoir). Note the alignment of blue stringers parallel to the diagonal arrows. Scale bars = 200 μm.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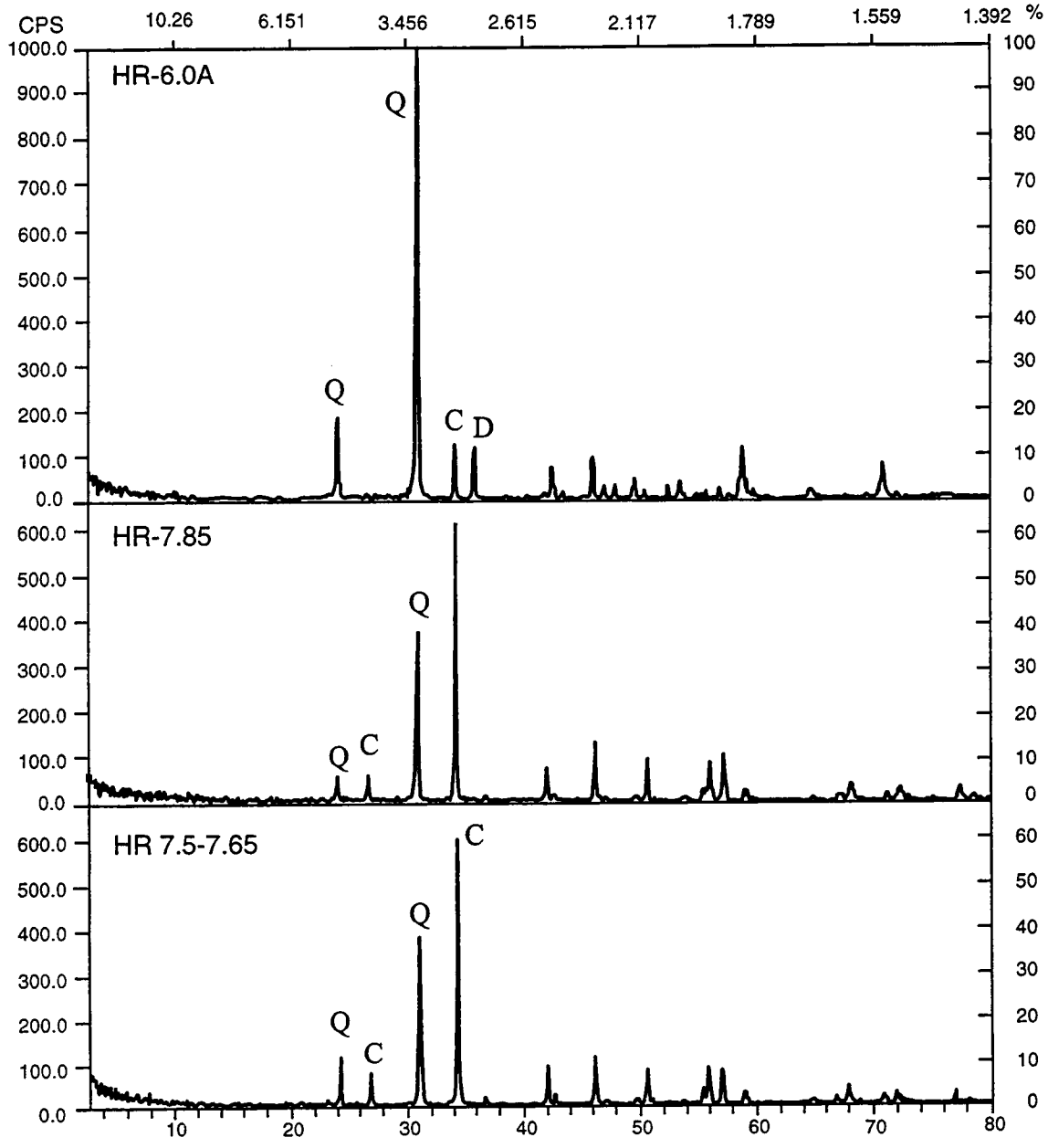

Figure 4.6. X-ray diffractometer patterns of three Morrison chert specimens from Horsetooth Reservoir (HR 6.0A, HR 7.85, HR 7.5-7.65). Major quartz (Q) calcite (C), and dolomite (D) peaks are labeled.

Whereas the Morrison Magadi-type cherts appear to lack surface reticulation, a characteristic commonly cited by Hay (1968) and Eugster (1969) as diagnostic for Magadi-type chert, Schubel and Simonson (1990) noted that no single characteristic is unique to Magadi-type chert, including the presence of surface reticulation, with the possible exception of a rectilinear or grid-work extinction pattern.

Of the Morrison chert deposits interpreted as having a magadiite origin, the rectilinear extinction pattern was observed in chert specimens from Park Creek Reservoir, Horsetooth Reservoir and the Purgatoire area. Based on petrographic and scanning electron microscopy, Schubel and Simonson (1990) concluded the rectilinear extinction pattern forms as a result of a volume-for-volume replacement of magadiite by quartz with retention of the original magadiite crystallographic orientation.

Direct replacement of magadiite is not demonstrable in chert where the chalcedony in the groundmass exhibits a "random orientation" (Schubel and Simonson, 1990). This "random orientation" is typical of many Morrison chert deposits and reflects (1) that diagenetic replacement did not retain the crystallographic orientation of the magadiite, (2) that the rectilinear extinction pattern is masked by the numerous inclusions in the chert, or (3) that magadiite was not the precursor for that specific chert specimen.

Sources of Silica

The silica (Si) concentrations of modern lacustrine brines where magadiite and chert have been identified range from 400-2700 ppm (Peterson and von der Borch, 1965; Jones *et al.*, 1967). Potential sources of dissolved silica in these brines include detrital

quartz, other silicate minerals, silica-rich springs, alteration of volcanic glass or igneous rocks in the surrounding basin, and biogenic silica.

The dissolved Si concentration of the natural waters of Morrison lakes is, of course, unknown. However, several silica sources were available that may have contributed dissolved Si to the lake waters (Figure 4.1). Detrital quartz silt and sand are common with minor amounts of embayed volcanic quartz grains and corroded volcanic fragments. Other silicate sources include detrital feldspar and igneous rock fragments, which are locally common, and were derived from weathering of the Ancestral Rockies. Volcanic glass shards are also present locally in carbonate and welded tuff deposits, particularly in the upper portions of the Morrison Formation.

Even if the amount of dissolved Si of the natural waters was relatively low in Morrison paleolakes, evaporative concentration is a mechanism by which the necessary levels of dissolved silica could have been attained. Evidence for evaporative processes in these lakes is common, including disseminated pseudomorphs after gypsum, ?halite, and other evaporite minerals as well as gypsum nodules (<1-4 mm). Such evaporitive processes were apparently present locally throughout the study area because pseudomorphs after evaporites have been identified at all localities and bedded gypsum is abundant in the Purgatoire area. Moreover, evaporative increases in dissolved Si would also have contributed to a rise in the Na concentration of the natural waters.

Formation of Magadiite

Hay (1968) described two different mechanisms for precipitating a sodium-silicate mineral in a sodium-carbonate lake given a high concentration of dissolved silica: (1) evaporative concentration to the point of precipitation, and (2) lowering of the silica solubility by decreasing the pH. Direct evaporative concentration seems unlikely due to the lack of massive sodium carbonate (i.e. trona) beds in the Morrison Formation, because an evaporated silica-brine should yield far more trona that magadiite or chert (Hay, 1968). Eugster (1967) and Hay (1968) suggested the lowering of pH by dilution, which would, in turn, lower silica solubility and result in precipitation of sodium silicate at the epilimnion-hypolimnion interface. Rapid, seasonal freshwater input into a Morrison lake basin would produce temporary stratification of the water column with magadiite saturation and precipitation occuring along the interface (Figure 4.7). Hay (1968) interpreted the roughly uniform layers of magadiite and chert at Lake Magadi, Kenya, as having been deposited in this fashion.

In the Morrison Formation, evaporitic concentration was probably necessary to reach high Si and Na concentrations, with magadiite formation triggered by a rapid influx of seasonal freshwater into the lakes (Figure 4.7).

Conversion of Magadiite to Chert

Chert can form from a sodium silicate precursor in a few hundred years (Eugster, 1969). Two primary mechanisms are cited in the rapid process of magadiite to chert conversion: 1) spontaneous transformation of magadiite to chert in the presence of

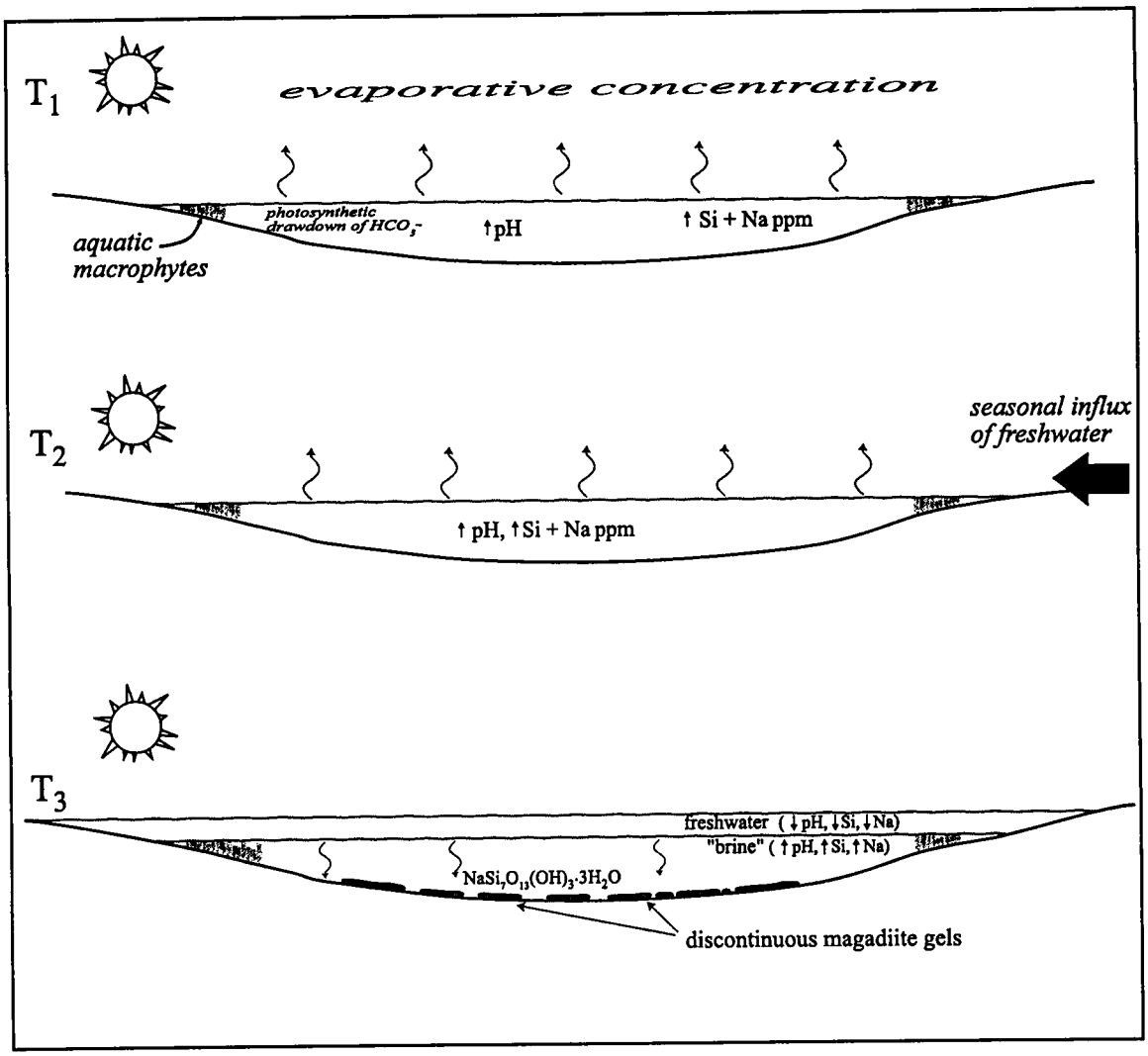

Figure 4.7. Schematic illustration showing the evolution of alkaline-saline lacustrine waters in some Morrison lakes. T_1, evaporative concentration increases the Si and Na content of the lacustrine waters; photosynthetic activity of aquatic macrophytes (i.e., charophytes) increases the pH of the waters via carbonate and then bicarbonate drawdown. T_2, a rapid influx of freshwater due to episodic or seasonal flooding or storms. T_3, the density (and temperature) contrast between the saline-alkaline waters and influx freshwater produces a temporary stratification across which magadiite precipitates and accumulates at the bottom of the lake.

alkaline brines (Hay, 1968); and 2) leaching of Na from magadiite gels by percolating ground waters (Eugster and Jones, 1968). Both of the mechanisms were reviewed at length by Schubel and Simonson (1990), and they concluded that although some aspects of leaching occur, the textural and petrographic evidence suggests the actual magadiite-to-chert conversion probably occurs in the presence of a saline brine. The mechanism of conversion is assumed to be associated with dewatering of the magadiite in the presence of the brine. Evidence for rapid conversion in the Morrison Formation includes rounded, synsedimentary Magadi-type chert clasts in intraclast grainstone and intraclasts containing angular fragments of Magadi-type chert.

PALEOLIMNOLOGIC IMPLICATIONS

The occurrence of Magadi-type chert in the Morrison Formation provides significant insights into the complexities of Upper Jurassic lacustrine sedimentation across the Western Interior, which are just beginning to be understood on a basinal scale (Turner and Fishman, 1991; Dunagan *et al.*, 1997). Previously reported paleontological and sedimentological data (Dunagan *et al.*, 1996; see discussions in Chapters 2 and 3), together with the evidence from the Magadi-type cherts, strongly suggest that carbonate sedimentation was common in both freshwater and alkaline lakes and ponds east of the Ancestral Rockies in Colorado. The wide range of hydrogeochemistries with the presence of a diverse aquatic biota significantly alters typical simplistic paradigms of Morrison lacustrine systems within this Late Jurassic paleoecosystem.

CONCLUSIONS

1. Magadi-type chert is present in carbonate lacustrine deposits of the Morrison Formation in Colorado, based upon textural and petrographic observations of authigenic chert deposits.
2. The Magadi-type chert of the Morrison Formation consists of length-slow, botryoidal to concentrically-ringed bodies of chalcedony with minor microcrystalline quartz. The Morrison chert is also characterized by rare spherulitic aggregates, a chert groundmass of randomly oriented chalcedony crystals with rare patches displaying a rectilinear or grid-work extinction pattern, and pseudomorphs after (?)nahcolite and gypsum.
3. Evaporative concentration and episodic input of freshwater into the alkaline-saline lakes combined to produce temporary stratification, with magadiite precipitation occurring across the interface of the water bodies.
4. This investigation to use Magadi-type chert to demonstrate that a range of hydrogeochemistries from freshwater to alkaline-saline settings were present within this lacustrine system.

CHAPTER 5 -

CONSTRAINING LATE JURASSIC PALEOCLIMATE WITHIN THE MORRISON PALEOECOSYSTEM: INSIGHTS FROM THE TERRESTRIAL CARBONATE RECORD (MORRISON FORMATION, COLORADO)

INTRODUCTION

A semi-arid to arid Late Jurassic climate with strong seasonal contrasts has been suggested for the western United States as a result of the breakdown of the Pangean megamonsoon (Parrish, 1992, 1993a, b) and based on the global sedimentary and fossil records (Hallam, 1992). Global climate models also have suggested a semi-arid to arid climate for most of the Western Interior during the Late Jurassic (Moore *et al.*, 1992; Valdes, 1992). On the Colorado Plateau, sedimentologic evidence from the Morrison Formation corresponds well with a Late Jurassic paleoecosystem dominated by semi-arid to arid conditions. This sedimentologic evidence is derived from two main sources: 1) the siliciclastic and volcaniclastic deposits associated with the Lake T'oo'dichi' complex, an extensive alkaline-saline lake in the Brushy Basin Member (Bell, 1983, 1986; Turner and Fishman, 1991); and 2) the eolian sand complexes associated with the Bluff Sandstone Member (Peterson and Turner-Peterson, 1987).

Controversy over Morrison climatic interpretations has arisen due to apparently conflicting paleontological interpretations from the plant and terrestrial vertebrate records. Paleofloral interpretations of pteridophytes, cycadophytes, and other plants have suggested a humid and subtropical climate for the Colorado Plateau during deposition of

the Brushy Basin Member (Jensen, 1966; Tidwell and Medlyn, 1992; S. Ash, written communication, 1998). Similarly, a consideration of the metabolic demands of large terrestrial vertebrates, such as dinosaurs, has resulted in the invoking of strong seasonal precipitation to correspond with high seasonal plant productivity to try to explain dinosaur biogeography and taphonomy (Dobson *et al.*, 1980).

One aspect of the sedimentary record that has yet to be utilized in the discussion of Late Jurassic paleoclimate is the terrestrial carbonate record; this is despite the fact that these deposits are valuable archives of continental paleoclimatology and paleohydrology on a fine temporal scale (Gierlowski-Kordesch and Kelts, 1994). The purpose of this chapter is: 1) to describe the major climatically- and hydrologically-sensitive sedimentologic indicators associated with the terrestrial carbonate record, 2) to present stable oxygen and carbon isotope data for paleohydrologic interpretations, and 3) to present a paleoclimatic synthesis for east-central Colorado during the Late Jurassic. Although terrestrial carbonates may not be volumetrically significant, these carbonates are present throughout the Morrison Formation and provide a high resolution record of subtle Late Jurassic climatic and hydrologic changes. This record is particularly well-developed in east-central Colorado, and a detailed examination should provide critical climatic insights and a framework for studies in other parts of the Western Interior, especially where terrestrial carbonates occur.

PALEOCLIMATIC AND PALEOHYDROLOGIC INDICATORS

The utilization of carbonate lacustrine deposits as sensitive paleoclimatic and paleohydrologic indicators is not a new approach (Allen and Collinson, 1986; Platt and Wright, 1991). The various extrinsic and intrinsic factors controlling carbonate sedimentation in lakes (see discussion in Chapter 2) makes aspects of this depositional system particularly useful in interpreting ancient climates and hydrologic conditions. Primary carbonates are common to many ancient and modern lacustrine deposits (Talbot, 1990), and the oxygen and carbon isotopic compositions of these deposits provide useful climatic and hydrologic information. Stuiver (1970) first proposed the use of stable oxygen and carbon isotopic analyses of lacustrine carbonates as paleoclimate indicators. Pearson and Coplen (1978) also noted the usefulness of oxygen and carbon isotopic compositions of lake carbonate in determining the hydrologic conditions of a lake or for a succession of lacustrine strata. The routine use of stable isotopic compositions is a well-established method of paleolimnological research, and the literature has been recently reviewed (see reviews in, Pearson and Coplen, 1978; Kelts and Talbot, 1989; Talbot, 1990; Talbot and Kelts, 1990). Interestingly, Anadón and Utrilla (1993) noted that the integration of sedimentologic investigations with stable isotopic geochemistry studies is still uncommon, despite obvious usefulness in the study of lacustrine paleoenvironments, paleohydrology, and paleoclimate.

Sedimentologic Indicators

In east-central Colorado, the lacustrine succession present within the Morrison Formation contains a well-developed terrestrial carbonate record, consisting of 1) a complex of open- and marginal-lacustrine carbonate deposits, and 2) pedogenic carbonate within paleosols. The open- and marginal-lacustrine carbonates were deposited in shallow, perennial to ephemeral lakes and ponds with low-gradient ('ramp'-type) margins surrounded by extensive marginal lacustrine mudstones and floodplain deposits.

Palustrine Limestones and Pseudomicrokarst

Marginal lacustrine carbonate facies containing abundant pseudomicrokarst, pedogenic, and subaerial exposure features are referred to as 'palustrine' ('hypercalcimorph soils'; *sensu* Freytet and Plaziat, 1982; Wright and Platt, 1995). The Morrison Formation displays classic 'palustrine' characteristics that are similar to other well-documented post-Silurian examples (Table 2.1) from Europe (Freytet, 1973; Freytet and Plaziat, 1982; Platt, 1989; Gierlowski-Kordesch *et al.*, 1991; Alonso Zarza *et al.*, 1992; Armenteros *et al.*, 1997) and North America (Stanley and Collinson, 1979; Wells, 1983; Yuretich *et al.*, 1984; Platt and Wright, 1992; Dunagan and Driese, in press; Dunagan and Caudill, unpublished data). These features suggest that Morrison lake margins were repeatedly subjected to subaerial exposure. Pseudomicrokarst is common and includes such features as: 1) complex voids filled with vadose silt and internal sediment, micritic clasts, and calcite cement; 2) root traces (mm to decimeter-scale), columnar and stacked rhizoconcretions, and *Microcodium*; 3) circumgranular,

desiccation, horizontal, and septarian cracks; and 4) brecciation and grainification (Figure 2.7). Microkarstic features also were observed, such as dissolution of metastable skeletal allochems and dissolution voids.

Platt and Wright (1992) noted that climatic control exerts a particularly strong effect on the evolution of palustrine facies. Their study of Carboniferous to Quaternary palustrine examples from Europe and the United States indicates that three characteristic types of palustrine sequences are recognizable, each deposited under different climatic regimes: semi-arid, intermediate, and sub-humid (Table 5.1; Platt and Wright, 1992). Based on the abundance of pseudomicrokarst features and the relative paucity of evaporites and calcrete horizons, Morrison lacustrine carbonates collectively imply deposition under Platt and Wright's (1992) 'intermediate'-type climatic conditions. The presence of bedded evaporites in the basal Morrison Formation in southeastern Colorado (discussed below) suggests playa-lake deposition under semi-arid climatic conditions.

The progressive effects of subaerial exposure on the lacustrine carbonate substrate produce characteristic sedimentary structures and diagenetic features that can be used to construct a conceptual freshwater carbonate exposure index (Platt and Wright, 1992). Using the exposure features associated with the lacustrine facies associations from the Morrison Formation, an inferred hydroperiod is estimated for the both the marginal- (i.e., palustrine) and open-lacustrine facies associations (Figure 5.1). The marginal-lacustrine deposits have an estimated hydroperiod of about 15-310 days as compared to approximately 180-325 days for the open-lacustrine facies. The duration and intensity

Table 5.1. Climatic regimes and associated palustrine features. Based on data from Platt and Wright (1992).

Climatic Regime	Palustrine Features
Semi-arid	calcrete development, evaporites, brecciation and nodularization, and laminar coatings
Intermediate	extensive pedogenic activity (rhizoliths), desiccation and pedogenic cracks, *Microcodium*, pseudo-microkarst and microkarst
Sub-humid	well-developed organic-rich horizons (coals, lignites), channel deposits, and blackened pebbles ± desiccation cracks and rhizoliths

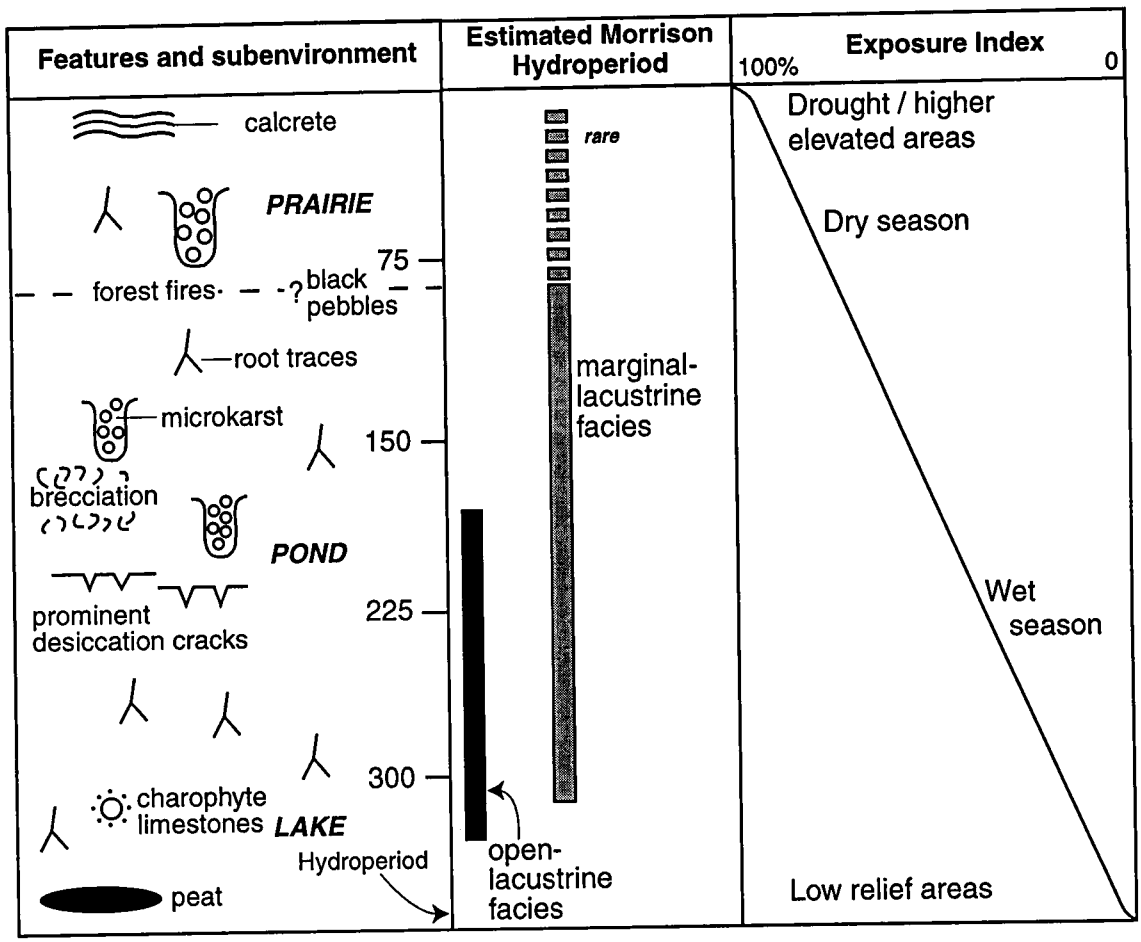

Figure 5.1. Estimated hydroperiod and exposure index for Morrison lacustrine environments, based upon features observed from the lacustrine facies associations. The hydroperiod represents the number of days the sediment surface is inundated over the course of the year. The exposure index is the percentage of time the sediment surface is exposed. The freshwater carbonate exposure index is based on Platt and Wright (1992, Figure 8, p. 1069).

of exposure experienced by the different lacustrine settings is reflected in the two distinct hydroperiods. This difference in hydroperiods also illustrates the effects of lake-level fluctuations on open- and marginal-lacustrine deposits in low-gradient ('ramp'-type) settings. The exposure index suggests that the Late Jurassic climate was characterized by a distinct wet and dry season during periods associated with lacustrine carbonate deposition.

Magadi-Type Cherts

Open lacustrine facies are typically restricted to the lower portions of the Morrison Formation. Within this lacustrine facies, Magadi-type cherts associated with microbialite- and charophyte-rich carbonates are present. The occurrence of Magadi-type cherts strongly suggest that carbonate sedimentation was common in both freshwater and alkaline lakes in east-central Colorado (Dunagan *et al.*, 1997). Previously, Magadi-type cherts only were known from Wyoming (Surdam *et al.*, 1972); however, the distribution of Magadi-type cherts now includes east-central Colorado (Dunagan *et al.*, 1997) and the Colorado Plateau (Dunagan, unpublished data).

Magadi-type cherts have been reported from a variety of ancient and modern lacustrine settings (Hay, 1968; Eugster, 1969; Surdam *et al.*, 1972; Sheppard and Gude, 1974, 1986; Parnell, 1986, 1988; Dunagan *et al.*, 1997), and more rarely from marginal marine settings (Houser, 1982). The alkaline-saline conditions required for modern Magadi-type cherts occurring in East African rift lakes, such as Lake Natron and Lake

Magadi (Hay, 1968), suggest formation in Morrison lakes during climatic periods characterized by semi-arid conditions.

Pedogenic Carbonates

Reddish-gray to drab olive gray paleosols interbedded with lacustrine and fluvial deposits are present in east-central Colorado. The paleosols are characterized by pedogenic slickensides, pedogenic carbonate (Figure 2.4B), and pseudoanticlines. Pedogenic carbonate occurs as sharp to diffuse nodules disseminated through the paleosol matrix, stacked nodules, and columns (Figures 2.4B). Petrographically, the pedogenic carbonate is composed of nodules and micro-nodules displaying circumgranular cracks, craze planes, and evidence for multiple cycles of nodule breaking, healing and re-cracking similar to features observed in marginal lacustrine carbonates (Figure 2.7A-D).

Evaporite Deposits

Calcite and chert pseudomorphs after evaporites, evaporite nodules, and evaporite pore-fillings are associated with the lacustrine carbonate deposits. Pseudomorphs after evaporites, such as gypsum (H, MFQ) and trona? (MFQ, P), are present within micritic mudstones and skeletal mudstone to packstones (Figure 2.6A-C). These pseudomorphs are typically displacive and disrupt the sedimentary fabric. Sweet (1984) noted calcite pseudomorphs after evaporites in the Cañon City area and interpreted them as pseudomorphs after trona, gypsum, shortite, and gaylussite. Other evaporites, such as anhydrite, and pseudomorphs after halite, are present only within pore-fillings. The

evaporite nodules are rare; they are ellipsoidal (up to 0.7 cm diameter) and are composed of calcite pseudomorphs after gypsum and possibly trona. Bedded evaporites are restricted to southeastern Colorado (Purgatoire area), where a prominent evaporite sequence approximately 25 m thick is present in the lower Morrison. This sequence is composed of 10-130 cm thick, nodularly bedded gypsum interbedded with red, gypsiferous mudstone units.

The presence of evaporites and evaporite nodules in lacustrine carbonates indicates hydrologic periods characterized by a high evaporation rate relative to groundwater, meteoric, and/or fluvial input into Morrison lakes. In addition, the presence of evaporites (as pseudomorphs) may signify a short-term climatic shifts to dominantly semi-arid to arid conditions. The bedded gypsum-mudstone deposits represent deposition within an evaporitic playa environment and were apparently restricted to the lowermost Morrison Formation in southeastern Colorado. The distribution of these deposits suggests deposition in a hydrologically closed basin under semi-arid to arid conditions. These conditions apparently moderately because a distinct lacustrine carbonate sequence is present above the evaporite deposits.

STABLE ISOTOPE GEOCHEMISTRY

Methods

Detailed petrographic analyses were performed on all thin sections prepared from the Morrison Formation, with sections stained following the procedures of Dickson (1965, 1966). The stained thin sections were used as a preliminary step to identify

predominantly monomineralic phases in the selection of carbonate samples for isotopic analysis. Selected thin sections also were examined using a Citl Cold Cathode Luminescence 8200 mk3 microscope under the following operating conditions: 10-12 kV and 150-180 μA. Cathodoluminescence microscopy assisted in determining the extent of diagenetic alteration of the individual depositional, pedogenic, and diagenetic phases.

The samples for stable oxygen and carbon isotope analysis were collected by drilling 0.3-8.0 mg of individual carbonate depositional and selected diagenetic components from polished thin-section billets using a microscope-mounted microdrill assembly. Organic matter was removed by roasting the powdered carbonate samples at 380°C for one hour. Samples were reacted using two methods: 1) off-line reaction with 100% H_3PO_4 at 25°C for 24 hours; and 2) in a Carbo-Flo helium-sparged common acid bath at 120°C in 100% H_3PO_4.

To evaluate the isotopic contribution of dolomite-derived CO_2 in micritic samples containing both calcite and up to 15% dolomite, a timed-extraction procedure was used (Epstein *et al.*, 1963; Walters *et al.*, 1972). The CO_2 produced after reacting for one hour was generated primarily from calcite dissolution. A mixture of calcite- and dolomite-derived CO_2 evolves over the next three hours, but the gas produced after four hours of reaction is considered representative of dolomite-derived CO_2. Samples identified using petrographic staining techniques as containing up to 15% dolomite in micrite yielded < 0.12 μmol of dolomite-derived CO_2/mg of sample. Given the low yields of dolomite-derived CO_2, the isotopic composition of the micritic samples was assumed to be primarily calcite.

The isotopic ratios were measured on a Finnigan MAT Delta plus mass spectrometer and the isotopic results are reported in standard delta-permil (‰) relative to PDB (Craig, 1957). Isotopic results and laboratory standards are listed in Appendix B; the five primary laboratory standards indicate an external precision ($\pm 1\sigma$) of ± 0.08 for $\delta^{13}C$ and ± 0.04 for $\delta^{18}O$. Isotopic results obtained from the common acid bath were corrected to 25°C.

Sample Description

The micritic matrix is predominantly non-ferroan calcite and displayed dull to moderate luminescence, with only minor (<5-10%) interspersed brightly luminescent patches associated with component and compositional boundaries (e.g., micritic matrix-allochem, micritic matrix-crystalline calcite in fracture or more rarely dissolutional voids). Non-ferroan microspar and micrite are associated with the microbialites and microbial laminates. Replacement dolomicrite and ferroan micrite were present in the non-ferroan micrite, however, these diagenetic phases represent <15% of the matrix. Sampling of micrite focused on areas of a billet where contamination by diagenetic phases would be minimized.

Dissolution, intragranular, fenestral, and fracture porosity were typically infilled with non-ferroan to ferroan, equant to blocky calcite cement (Figure 2.5A and F; Figure 2.6C; Figure 2.7A-D); Magadi-type cherts and other types of silicification were less common. The voids were commonly infilled with vadose and crystal silt and micritic clasts spalled from the side of cavities (Figure 2.7A-C). Diagenetic phases were generally

dully luminescent, with the exception of fracture-filling calcite cements that commonly displayed a bright to a zoned bright- to dull-luminescence. Only the stable isotope compositions of the common non-ferroan and ferroan calcite diagenetic phases were analyzed, where sufficient quantities of cement could be micro-sampled. Ferroan saddle dolomite also was observed but occurs only as a minor pore-filling cement, and was not sampled for isotopic analysis.

Valero Garcés and Gisbert Aguilar (1993) noted that lacustrine carbonate phases undergo diagenetic alteration very early where an abundance of vadose and subaerial exposure features, as well as non-luminescent cements, are present. Given the abundance of both dull and non-luminescent depositional components and cements, and the abundance of vadose and subaerial exposure features in both the open and marginal lacustrine facies, very early diagenetic stabilization is suggested for the lacustrine carbonates of the Morrison Formation. In addition, the preservation of cyanobacterial tubules, charophyte stems, and clotted "aggregates" of micrite within Morrison lacustrine carbonates are indicators of minimal post-depositional alteration (Wright *et al.*, in press). Hence, primary carbonates from the lacustrine facies of the Morrison Formation are considered to be non-ferroan calcitic micrite and microsparite that were homogeneous in luminescence intensity and color. Whereas a variety of primary and secondary carbonate mineral precipitates is known to occur in lakes (Müller *et al.*, 1972), low-magnesium calcite is the most common carbonate precipitate in freshwater lakes (Kelts and Hsü, 1978), and the abundance of this mineral in the micritic matrix of the Morrison lacustrine carbonates supports preservation of the original geochemical composition.

Heterogeneous and mottled micritic fabrics, clusters of dolomicrite crystals, micrite associated with root traces, and calcite and dolomite cement in voids were considered diagenetic phases.

Stable Isotope Results

Modern and ancient lacustrine carbonate deposits display a wide range of isotopic compositions (Hoefs, 1997); however, carbonates precipitated in lakes typically have ^{18}O- and ^{13}C-depleted isotopic ratios when compared to coeval marine carbonates (Keith and Weber, 1964). Isotopic compositions in Morrison Formation lacustrine deposits are no exception (Figure 5.2). The stable carbon and oxygen isotopic compositions of primary depositional and diagenetic phases from the Morrison Formation are summarized in Table 5.2; detailed descriptions of the different phases are presented in Appendix B.

Diagenetic Carbonates

The stable isotope compositions of the non-ferroan and ferroan calcite diagenetic phases are shown in Figure 5.3. The cement types include: non-ferroan equant to blocky calcite, ferroan equant to blocky calcite, and non-ferroan and ferroan calcite (Table 5.2). The diagenetic phases were generally depleted in ^{18}O and ^{13}C relative to the primary depositional phases, however, there was some overlap.

The non-ferroan, equant to blocky calcite cements ranged in $\delta^{13}C$ values from -3.07 to -10.65 ‰, and in $\delta^{18}O$ from -8.47 to -14.65 ‰. Ferroan, equant to blocky calcite displayed a great isotopic composition range, particularly in carbon, with $\delta^{13}C$ values

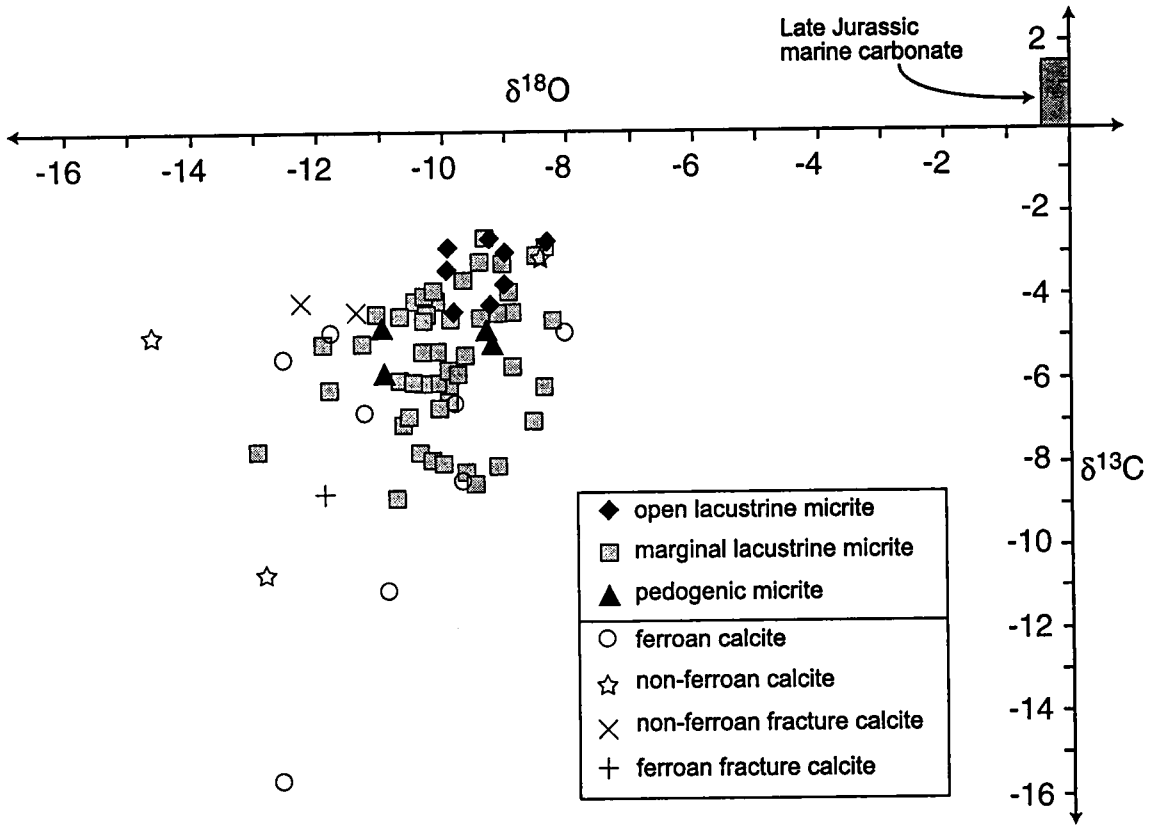

Figure 5.2. Stable isotopic compositions of the primary depositional and diagenetic phases from the Morrison Formation. The Late Jurassic marine carbonate field is based on data from Lindh (1984).

Table 5.2. Summary of stable oxygen and carbon isotope compositions for the depositional and diagenetic components from lacustrine carbonate deposits of the Morrison Formation.

	Component	$\delta^{18}O$ (‰, PDB)		$\delta^{13}C$ (‰, PDB)	
		range	Avg. (n)	range	Avg. (n)
Depositional	Micritic matrix: open lacustrine facies	-8.34 to -9.96	-9.33 (8)	-2.57 to -4.53	-3.30 (8)
	Micritic matrix: marginal lacustrine facies	-8.26 to -12.99	-9.97 (48)	-2.58 to -8.80	-5.46 (48)
	Micritic matrix: pedogenic nodules	-9.24 to -11.00	-10.24 (4)	-4.69 to -5.77	-5.07 (4)
Diagenetic	Non-ferroan drusy to blocky calcite	-8.47 to -14.65	-12.07 (4)	-3.07 to -10.65	-5.68 (4)
	Ferroan drusy to blocky calcite	-8.05 to -12.61	-10.71 (7)	-4.80 to -15.53	-8.30 (7)
	Non-ferroan blocky calcite in fractures	-	-11.41 (1)	-	-4.33 (1)
	Ferroan blocky calcite in fractures	-	-11.92 (1)	-	-8.68 (1)

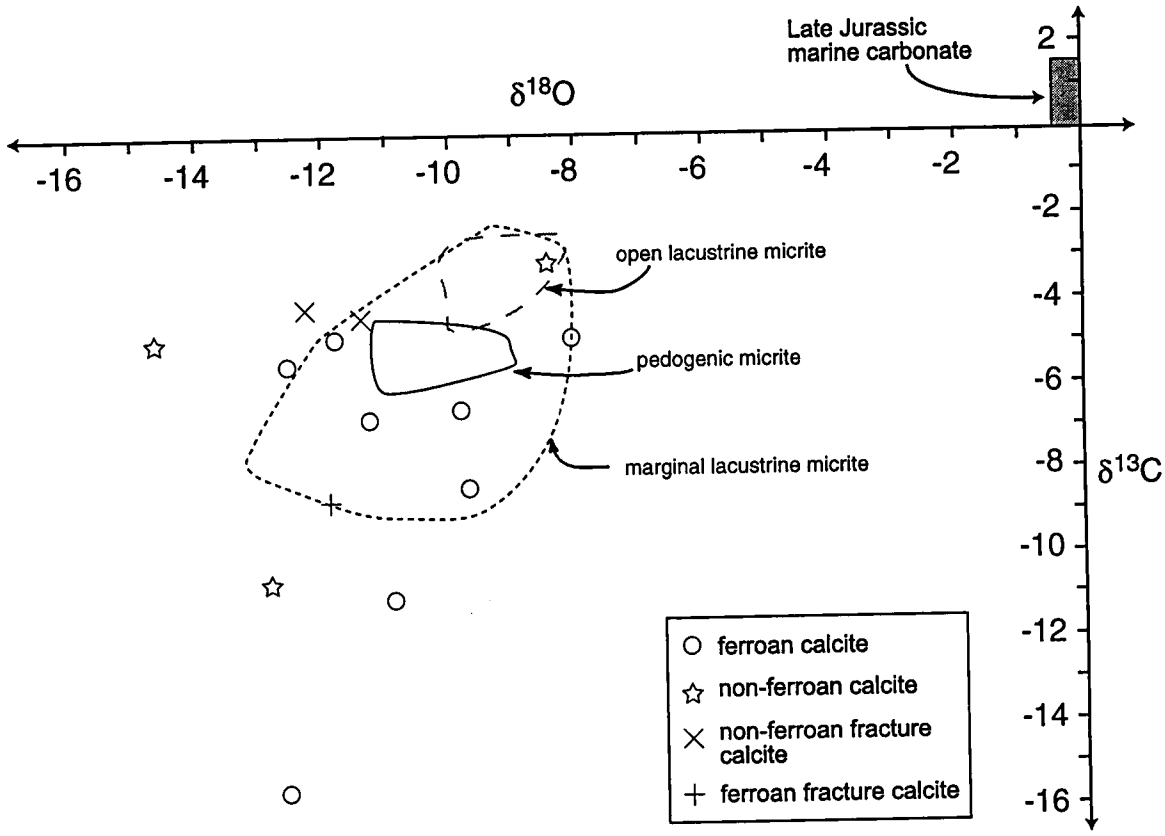

Figure 5.3. Stable isotopic compositions of the diagenetic phases from the Morrison Formation. The fields represent open lacustrine micrite (n=8; large dashes), marginal lacustrine micrite (n=48; small dashes), and pedogenic micrite (n=4; solid line). The Late Jurassic marine carbonate field is based on data from Lindh (1984).

ranging from -4.8 to -15.53 ‰, and in $\delta^{18}O$ from -8.05 to -12.61 ‰. The isotopic composition of non-ferroan and ferroan calcite from tectonic fractures had similar $\delta^{18}O$ values (-11.41 and -11.92 ‰, respectively), but markedly different $\delta^{13}C$ values (-4.33 and -8.68 ‰, respectively).

The non-ferroan equant to blocky calcite commonly filled cavities produced during pedogenic processes and subaerial exposure. These cements are interpreted as vadose cements, where the diagenetic pore fluids were not highly evolved and retained a similar isotopic composition to the lake waters. The ferroan drusy to blocky calcite cements are interpreted as burial in origin. Ferroan cements are commonly associated with pseudomorphs after evaporites and Magadi-type cherts. The $\delta^{18}O$ values, typically <-9 ‰, associated with diagenetic phases indicate precipitation from lacustrine pore fluids at slightly elevated temperatures (15-25°C). The wide range of $\delta^{13}C$ compositions displayed by the diagenetic phases, from -3.07 to -15.53 ‰, reflects diagenetic fluids that were enriched in isotopically-light, soil-derived CO_2 in a vadose diagenetic setting (Allan and Matthews, 1982; Cerling, 1984; Cerling and Quade, 1993). Diagenetic phases with the lightest $\delta^{13}C$ compositions are associated with palustrine carbonates displaying intense pseudomicrokarstic features.

Primary Carbonates

The oxygen and carbon isotopic compositions of primary depositional micrite are subdivided into open- and marginal-lacustrine facies. The open-lacustrine carbonates

have $\delta^{13}C$ values from -2.5 to -4.3 ‰, and in $\delta^{18}O$ from -8.3 to -9.9 ‰; marginal or palustrine carbonates show an increase in isotopic heterogeneity as compared to the open-lacustrine carbonate, with $\delta^{13}C$ values ranging from -2.5 to -8.8 ‰, and $\delta^{18}O$ from -8.2 to -12.9 ‰ (Figure 5.4). These isotopic compositions are generally enriched in ^{18}O and ^{13}C as compared to diagenetic carbonate phases (Figure 5.3). Linear regression analysis using the "least squares" method described by Koch and Link (1971) with the $\delta^{13}C$ and $\delta^{18}O$ values revealed a lack of strong covariant trends through selected stratigraphic intervals ($r = 0.1$ to 0.50) and through the lacustrine succession for all the isotope results ($r = 0.36$). Talbot (1990) stated that a high correlation between $\delta^{13}C$ and $\delta^{18}O$ required r values of greater than or equal to 0.7.

The open lacustrine facies are typically enriched in ^{18}O and ^{13}C as compared to marginal lacustrine facies. The greater range in $\delta^{18}O$ displayed by the marginal-lake carbonates is a result of interaction with isotopically-light meteoric waters, or possibly burial conditions at slightly elevated temperatures. The three samples with the most depleted $\delta^{18}O$ values (< -12‰) have either abundant pseudomicrokarst or microsparitic textures. Pedogenic modification of lacustrine carbonates typically results in lower $\delta^{18}O$ and $\delta^{13}C$ values due to calcite stabilization in the presence of isotopically-light meteoric fluids and fluids charged with soil-derived CO_2 (Allan and Matthews, 1982; Platt, 1992). Microbial respiration associated with bacterial sulfate reduction, as suggested by the presence of framboidal pyrite, also may have been contributed isotopically-light carbon.

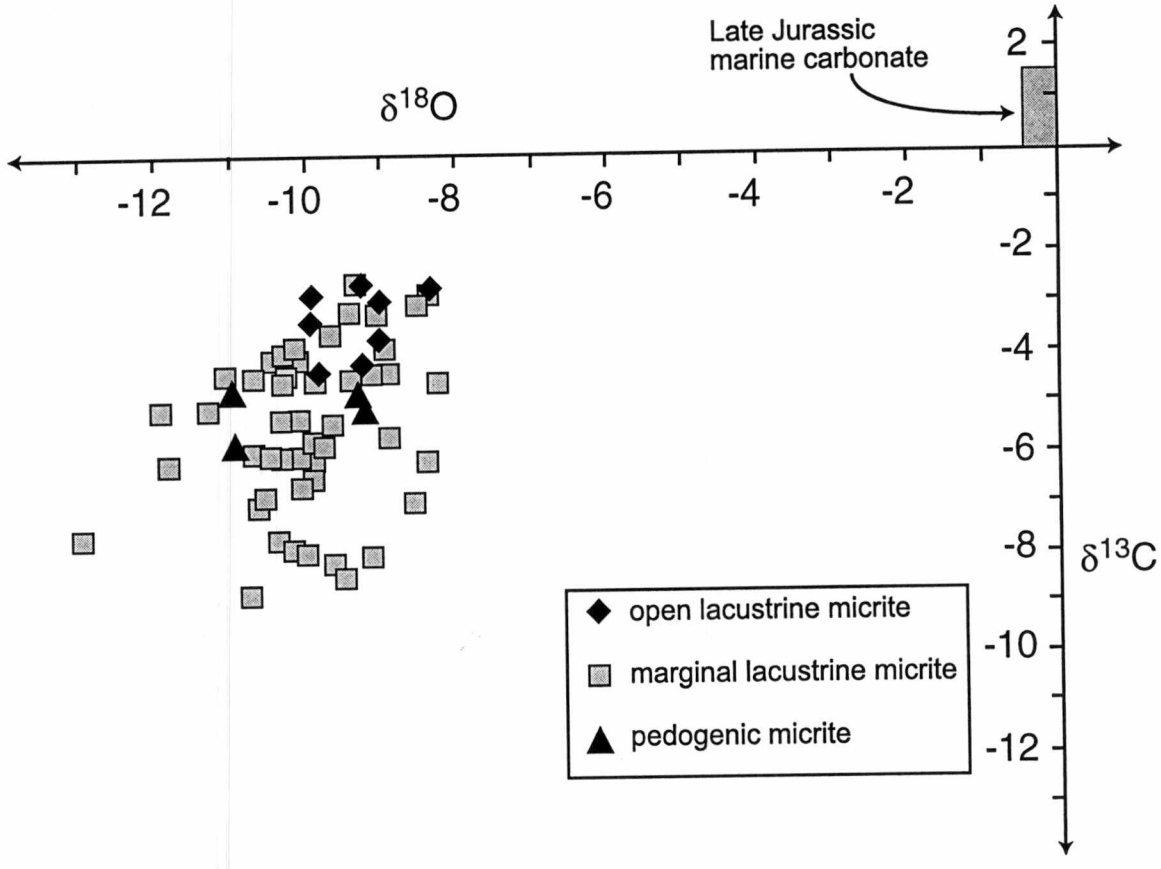

Figure 5.4. Stable isotopic compositions of the primary depositional components from the Morrison Formation. The Late Jurassic marine carbonate field is based on data from Lindh (1984).

Pedogenic Carbonates

Carbonate samples (n = 4) derived from pedogenic nodules have a relatively homogeneous isotopic composition, with $\delta^{13}C$ from -4.6 to -5.7 ‰ PDB and $\delta^{18}O$ from -9.2 to -11.0 ‰ PDB (Figures 5.3 and 5.4). These data from the Morrison Formation in east-central Colorado are similar to soil carbonate data (n = 13) from the Colorado Plateau, where $\delta^{18}O$ values ranged from approximately -6.5 to -12 ‰ PDB (Ekart and Cerling, unpublished data). Comparing these isotopic compositions to modern soils and climatic setting based on Cerling and Quade (1993), Ekart and Cerling suggested that meteoric precipitation in Morrison paleoecosystem ranged in $\delta^{18}O$ values from -9 to -16 ‰ SMOW.

INTERPRETATION AND DISCUSSION

The lack of covariant trends between $\delta^{18}O$ and $\delta^{13}C$ values and the relatively invariant oxygen isotopic compositions ($\delta^{18}O$ = -9.88‰; $\pm 1\sigma$ = 0.93) in the primary carbonates collectively suggest the presence of hydrologically open lakes in the Morrison paleoecosystem. In a hydrologically-open lake, water has a short residence time, and the oxygen isotopic composition of the carbonates is relatively invariant and should be closely related to the bulk isotopic compositions of inflow waters (Talbot and Kelts, 1990; Talbot, 1990). The indication of hydrologically-open lake conditions is consistent with sedimentological relationships (see discussion in Chapter 2). Hydrologically closed lakes display a characteristic, highly-correlated covariance ($r > 0.7$) (Talbot and Kelts,

1990; Talbot, 1990), which reflects evaporative concentration of heavier isotopes in the evolving isotopic composition of lake waters (Platt, 1992).

Ekart and Cerling (unpublished report) used the $\delta^{18}O$ values of pedogenic carbonate ($\delta^{18}O$ = -6 to -12 ‰, PDB; n = 13) to estimate the oxygen isotopic composition of paleoprecipitation in the Morrison paleoecosystem ($\delta^{18}O$ = -9 to -17 ‰, SMOW). Their estimates were based on the correlation between the isotopic composition of modern soil carbonate and associated meteoric waters from a variety of environments having a range in mean annual temperature of 30°C (Cerling and Quade, 1993). In east-central Colorado, pedogenic carbonate displays a narrower oxygen isotopic composition ($\delta^{18}O$ = -9.24 to -11.00 ‰, PDB; n = 4) (Figure 5.4). This isotopic composition would correspond to calculated $\delta^{18}O$ meteoric water values of -7.3 to -9.0 ‰ SMOW at 25°C using Friedman and O'Neil's (1977) calcite-water fractionation factor. The $\delta^{18}O$ isotopic composition of pedogenic carbonate tends to be 2-4 ‰ heavier than local meteoric waters due to evaporative enrichment of soil waters (Quade *et al.*, 1989). This suggests that the calculated "meteoric" isotopic composition from Morrison pedogenic carbonates actually reflects an evaporated soil-water compositions.

This isotopically-light meteoric water composition was probably a result of the effects of a Jurassic rainshadow created by the Elko highlands and the magmatic arc to the west continental interior. The effects of the rainshadow resulted in reduced precipitation across the Western Interior, and sedimentological evidence suggests this rainshadow and the persistent effects of the Pangean monsoon resulted in semi-arid

conditions throughout most of the Western Interior during the Jurassic (Parrish, 1992, 1993a, b). The depleted $\delta^{18}O$ calcite and meteoric values and the paucity of bedded evaporites indicate that Morrison lacustrine carbonates were not subjected to evaporative processes despite being under semi-arid conditions. The primary source of water for Morrison lakes was groundwater, which was recharged with depleted meteoric waters in the highland regions to the west.

In lacustrine settings, a number of mechanisms have been proposed to explain variations in $\delta^{13}C$ values, including: 1) variations in biological productivity (McKenzie, 1985; Talbot, 1990, 1994); 2) input of detrital marine carbonate (Oberhansli and Allen, 1987; Platt, 1992); 3) diagenetic production of isotopically-heavy ^{13}C due to bacterial methanogenesis in anoxic subenvironments (Irwin *et al.*, 1977; Talbot and Kelts, 1990) or isotopically-light ^{12}C from bacterial sulphate reduction (Irwin *et al.*, 1977); and 4) input from isotopically-light soil-derived CO_2 (Allan and Matthews, 1982; Cerling, 1984).

Sedimentologic features and paleoecologic relationships (see discussion in Chapter 2 and 3) indicate Morrison lakes were characterized by shallow-water, and primarily, holomictic conditions. Morrison lakes probably experienced variations in biologic productivity; however, ^{13}C-enrichment of the surface waters, which is common in many modern eutrophic lakes, such as Lake Greifen and Lake Zürich (McKenzie, 1985), did not occur due to the unstratified water column. The negative $\delta^{13}C$ values of Morrison lacustrine carbonates are also not typical of ^{13}C-enriched 'methanic' carbonates described by Talbot and Kelts (1990). In addition, no detrital marine carbonate clasts have been observed in the Morrison Formation in east-central Colorado.

The isotopic heterogeneity of the marginal lacustrine carbonates ($\delta^{13}C$ = -2.5 to -8.8 ‰) are best explained by contact with variable input of isotopically-light soil-derived CO_2. The abundance of pseudomicrokarstic features displayed by these deposits indicates that pedogenic processes played a critical role in altering the isotopic composition as well as the sedimentary fabric of the palustrine carbonates. The input of isotopically-light, soil-derived CO_2 varied as a function of the intensity and length of pedogenesis on Morrison palustrine carbonates and the amount of oxidized C_3 organic matter within the lake. Microbial respiration associated with bacterial sulfate reduction, as suggested by the presence of framboidal pyrite, probably contributed isotopically-light carbon.

IMPLICATIONS FOR LATE JURASSIC CLIMATE

The Morrison Formation occupies a unique paleogeographic position that is useful for interpreting the climatic evolution in North American during the Mesozoic. Strong monsoonal conditions have been documented for the Triassic and into the Early Jurassic (Dubiel *et al.*, 1991; Parrish, 1993a) followed by the breakdown of the Pangean monsoon during the remainder of the Jurassic (Parrish, 1993b). Eventually, the establishment of zonal circulation and relatively cooler climate occurred, which was characteristic of the Cretaceous (Parrish, 1993b; Schudack, in press). Interpretations of a semi-arid to arid Late Jurassic climate for the western United States are based on sedimentologic evidence of the waning Pangean monsoon (Parrish, 1992, 1993a, b). A semi-arid to arid climate for most of the Western Interior has also been interpreted for the Late Jurassic based on global climate models (Moore *et al.*, 1992; Valdes, 1992). Moore *et al.* (1992, Figure 6)

also suggested that a high-pressure system dominated southwestern North America during the Late Jurassic, which contributed to seasonality with surface temperatures during June/July/August of 30-40°C and 0-20°C during December/January/February. Schudack (in press) recently suggested that oxygen isotope compositions from ostracodes and charophytes point toward a generally arid climate that cooled throughout Morrison time.

Numerous sedimentologic indicators point toward a dry, semi-arid to arid climate, but much of the debate is currently centered around the presence or absence of seasonality in the Morrison paleoecosystem, because there is also evidence that is suggestive of wetter periods. These climate indicators for the Morrison Formation were summarized recently (Peterson, 1994) and are presented in Table 5.3. Sedimentologic evidence from Western Interior Jurassic deposits documents extensive evaporite precipitation and eolian dune fields, and the formation of a large saline-alkaline lake complex toward the latest Jurassic (Peterson, 1994), which appears to agree with the interpretations of Parrish (1993a, b) and the predictions of global climatic models. Peterson (1994) presented two main interpretations of Morrison climate: 1) an overall semi-arid climate that fluctuated between relatively wetter and drier conditions; or 2) an overall dry climate with abundant water resources brought into the region by fluvial systems originating from the western and southern highland regions.

The well-developed terrestrial carbonate record in east-central Colorado points toward a climatic regime for this region characterized by seasonality. In the study area, pedogenic carbonate displays evidence of repeated cracking, micro-nodule formation, healing and re-cracking, which suggests a wet and dry climate as well as a net water

Table 5.3. Summary of climate indicators from the Morrison Formation. Based on Peterson (1994).

Dry Indicators	Moderately "Wet" Indicators
1. Gypsum beds are present in the basal Tidwell Member and equivalent beds in south-central Utah, southwestern Colorado, and eastern Colorado (Peterson, 1980; O'Sullivan, 1992; Dunagan, field observation).	1. An abundance of dinosaur remains that must have had large vegetation requirements (Dobson *et al.*, 1980).
2. Large eolian dune fields in southwestern Colorado and northwestern New Mexico; small dune fields also present in southeastern Utah and central Wyoming (Peterson, 1980, 1988).	2. The necessary plant population would have required large quantities of water.
3. Large saline-alkaline lake complex occupied most of the east-central Colorado Plateau (Turner and Fishman, 1991).	3. The "freshwater" lake deposits are abundant and scattered throughout the depositional area (see references in, Turner-Peterson and Peterson, 1987; Peterson, 1994).

deficit in the ancient soils (Cerling, 1991). The type of pseudomicrokarst features associated with Morrison open and marginal lacustrine carbonates (see detailed descriptions above and in Chapter 2) are common from climatic regimes 'intermediate' (*sensu* Platt and Wright, 1992) between semi-arid and sub-humid.

Platt and Wright (1992) demonstrated the close association between the hydroperiod, seasonality, and exposure features in modern freshwater marshes, which serve as an analog for "palustrine" limestone forming environments. Platt and Wright (1992) noted that a freshwater exposure index, similar to the marine exposure index of Ginsburg *et al.* (1977), could be developed thereby linking the development of characteristic pseudomicrokarstic and exposure features found in marginal lake settings to hydroperiod and seasonality (Figure 5.1). Assuming that this model is applicable to the lacustrine carbonate record and that the spectrum of features observed from the marginal lacustrine carbonates of the Morrison Formation are representative of the average climatic and hydrologic conditions, Morrison lakes and ponds had sum hydroperiod of 15-325 days, corresponding to an exposure index between 15 and 98%. This broad hydroperiod and exposure range suggests that Morrison open- and marginal-lake settings were probably in a constant state of evolution as the lakes shallowed and each basin eventually filled. The relatively small range of $\delta^{18}O$ values (~ 4 ‰) and the absence of covariant trends with a high degree of correlation in the stable isotope data indicate that Morrison lakes remained hydrologically-open, at least during carbonate deposition.

CONCLUSIONS

1. The lacustrine carbonate succession in the Morrison Formation of east-central Colorado contains sensitive sedimentologic and stable oxygen and carbon isotopic indicators that record variations in paleoclimate and paleohydrology.
2. The abundance and type of pseudomicrokarst associated with the lacustrine carbonate succession indicates the Late Jurassic climate was characterized by a distinct wet and dry season that was intermediate between semi-arid and sub-humid conditions. Magadi-type cherts and minor evaporites indicate periods within the lacustrine succession when the climate temporarily deteriorated to more semi-arid conditions.
3. Exposure features associated with the lacustrine facie associates indicate that the shallow-water, lake settings within the Morrison paleoecosystem were characterized by a wide range of hydroperiods, approximately 180-325 days for open-lacustrine areas and about 15-310 days for marginal-lacustrine settings.
4. Stable isotopic results indicate: a) that the average primary micrite in open-lake settings had $\delta^{18}O$ values of -9.33 ‰ and $\delta^{13}C$ values of -3.30 ‰, whereas, average primary micrite from marginal-lacustrine facies had $\delta^{18}O$ values of -9.97 ‰ and $\delta^{13}C$ values of -5.46 ‰; b) average pedogenic micrite had $\delta^{18}O$ values of -10.24 ‰ and $\delta^{13}C$ values of -5.07 ‰; and c) the average diagenetic non-ferroan to ferroan calcite phases were depleted in ^{18}O and in ^{13}C relative to lacustrine micrite and pedogenic carbonate, with average $\delta^{18}O$ values of -11.28 ‰ and $\delta^{13}C$ values of -7.23 ‰.
5. The results of stable isotope geochemistry revealed a lack of strong covariant trends through selected stratigraphic intervals ($r = 0.1$ to 0.50) and through the lacustrine

succession for all the isotope results ($r = 0.36$), which indicates that Morrison lakes were primarily hydrologically-open during carbonate deposition.

6. The wide range of $\delta^{13}C$ compositions displayed by depositional and diagenetic phases reflects precipitation from fluids enriched in isotopically-light, soil-derived CO_2 and/or ^{13}C-depleted CO_2 derived from the oxidization of C_3 organic matter or microbial respiration.

CHAPTER 6 -

DEPOSITIONAL SYNTHESIS AND SUMMARY

In Colorado following the mid-Oxfordian erosional event that produced the J_5 unconformity, initial deposition of the Morrison Formation began with a short-lived marine transgression into north-central Colorado that is represented by the nearshore sandstone deposits of the Windy Hill Member (Peterson, 1994). Throughout the rest of east-central Colorado, Morrison deposition was characterized by the accumulation of distal alluvial, mudflat, and overbank deposits with minor fluvial sandstones; evaporative basins characterized by gypsiferous red mudstones and bedded gypsum were present southeast Colorado. Deposition of a lacustrine carbonate succession followed the accumulation of several meters of distal alluvial deposits in east-central Colorado, the marine deposits in north-central Colorado, and evaporite deposits in southeast Colorado (Figure 1.6).

The lacustrine carbonate succession consists of open- and marginal-lacustrine facies associations. The open-lacustrine facies association is composed of lacustrine carbonates (skeletal mudstone/wackestone and microbialites) and laminated mudstone. The marginal-lacustrine facies association includes: palustrine carbonates (carbonaceous packstone, intraclast wackestone-grainstone, peloid skeletal mudstone-wackestone, peloid skeletal packstone-grainstone, and micritic mudstone), green mudstone, ooid packstone-grainstone, siltstone, and sandstone. The paucity of well-laminated and organic-rich deposits indicates the water column of Morrison paleolakes was well-oxygenated, reflecting holomictic to polymictic conditions.

Facies and stratigraphic relationships suggest that Morrison paleolakes were characterized by central and shallow, open-lacustrine settings that graded laterally and vertically into marginal-lacustrine and eventually into adjacent distal-alluvial environments. The open- and marginal-lacustrine facies display evidence for frequent subaerial exposure and modification resulting from pedogenic activity, pseudomicrokarst, and meteoric diagenesis. The abundance of these features indicates that Morrison lakes are best characterized by a low-gradient ('ramp'-type) margin that was subjected to periodic reworking by wind-driven currents, by storms and flood events, and where oscillations in lake level resulted in the exposure of large areas. High groundwater tables discharging into paleotopographic lows, with minor meteoric contributions, served as the primary water source for Morrison lakes. The fine-grained mudstone deposits may have also facilitated the "ponding" of waters on relative impermeable muddy layers.

A diverse biota was present in the lakes of the Morrison paleoecosystem. Charophytes, ostracodes, prosobranch and pulmonate gastropods, and unionid bivalves were commonly observed, with lesser amounts of spongillids, microbialites, and conchostracans. Bone fragments indicate that fish, crocodiles, and dinosaurs also were present within and around the lakes and ponds. Trace fossils record the presence of insects, crayfish, plants, and dinosaurs within and along the margins of Morrison lakes and ponds. The biota associated with the lacustrine deposits occurs primarily as disturbed and transported fossil assemblages, with minor mixed and in-place fossil assemblages. Wind-driven currents and periodic high-energy events as well as scavenging/oxidation of organic matter were the primary taphonomic processes acting on the fossil assemblages. Paleontological data indicate that Morrison lakes and ponds were

primarily freshwater in nature and were characterized by perennial to ephemeral and hydrologically open to closed conditions.

Sedimentologic evidence indicates that Morrison lacustrine depositional environments were characterized by a wide range of hydroperiods (15-325 days) probably controlled by various extrinsic (climate, tectonics, morphology, and clastic input) and intrinsic (biological productivity) factors. The major factors controlling lacustrine carbonate sedimentation were the low clastic input, due to the distal-alluvial setting and the presence of a clastic-filtering fringe of macrophytes along lake margins, and the abundance of a prolific carbonate-producing biota (i.e., charophytes).

The results of stable isotope geochemistry revealed a lack of strong covariant trends between $\delta^{18}O$ and $\delta^{13}C$ values ($r = 0.1$ to 0.50), which indicates that Morrison lakes were primarily hydrologically open. Isotopically-depleted soil CO_2 due to pedogenic modification produced the heterogeneous $\delta^{13}C$ values associated with the marginal-lacustrine (i.e., palustrine) deposits. Late Jurassic climate was intermediate between semi-arid and sub-humid and characterized by a distinct wet and dry season, based on the abundance and type of pseudomicrokarst associated with the lacustrine carbonate deposits. Magadi-type chert and minor pseudomorphs after evaporites indicate intervals within the lacustrine succession when the climate temporarily deteriorated to more semi-arid conditions and the water column was more alkaline-saline. However, the lack of evaporite beds capping lacustrine sequences suggests the lakes maintained primarily freshwater, and probably hydrologically-open, conditions during carbonate precipitation. Stable isotope compositions also point toward non-evaporated lake waters, at least during carbonate precipitation, due to the lack of covariant trends. The evolution

of Morrison lakes apparently was driven by filling of the accommodation space as open-lacustrine facies aggraded and marginal-lake facies prograded into the central portions of the lake.

Lacustrine deposition was abundant in the lower Morrison Formation of east-central Colorado but deposition was not continuous in space and time (Figure 1.6). The distribution of the lakes probably represents variations in local and regional accommodation space. The lakes probably occupied paleotopographic lows which locally formed as a result of 1) differential compaction of Morrison and underlying clastic sediments and 2) regional subsidence associated with the Denver-Julesburg basin (Figure 1.3), which produced a slightly irregular depositional topography.

In east-central Colorado, the end of the lacustrine carbonate succession is associated with renewed uplift of clastic source regions to the west and south (Peterson, 1994) and an increase in Late Jurassic volcanic activity and ash deposition (Christiansen *et al.*, 1994). Fluvial channels and overbank deposits are more abundant in the upper Morrison Formation, with fluvial sandstone deposits observed from several stratigraphic sections (Figure 1.6); overbank deposits with minor amounts of altered tuffaceous deposits dominate the upper Morrison Formation at all localities. The minor carbonate deposits that are locally present in the uppermost Morrison represented ephemeral ponds.

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APPENDICES

APPENDIX A:

FIELD AND STRATIGRAPHIC DATA

Numerous stratigraphic sections were examined as part of this study and the field observations and relationships were critical to the interpretations presented in this dissertation. Eleven stratigraphic sections were measured and described in detail; fourteen additional exposures of the Morrison Formation were examined as reconnaissance sections. Additional exposures of the Morrison Formation included outcrops in Colorado (Fruita Paleontological Area and Colorado National Monument), Montana (Gibson Reservoir, Armington, Belt, and Mother's Day quarry), Utah (Hannah, Moore, San Raphael Swell, Green River, and Cleveland-Lloyd Dinosaur Quarry), and Wyoming (Greybull, Thermopolis, and Bighorn National Recreation Area). The primary objective of fieldwork in the summer of 1996 was the centimeter-scale measurement and description of the carbonate units present within the stratigraphic sections as well as sample collection. The siliciclastic units were also measured and described but on a decimeter-scale. The summer of 1997 was used to field check the previous summer's work and to examine additional reconnaissance sections.

Stratigraphic sections were described beginning at the base, where exposed, or at the lowest stratigraphic position attainable. The descriptions are based primarily on field observations. The rock names are from Dunham (1962). Rock color was determined using the 1995 GSA Rock-Color Chart. Terms used for bedding thickness are from McKee and Weir (1953). Latitude and longitude data were collected using a hand-held Garmin GPS 38. The symbols and scale used with the stratigraphic sections are the same as in Figure 2.1.

Unit descriptions have the following format:

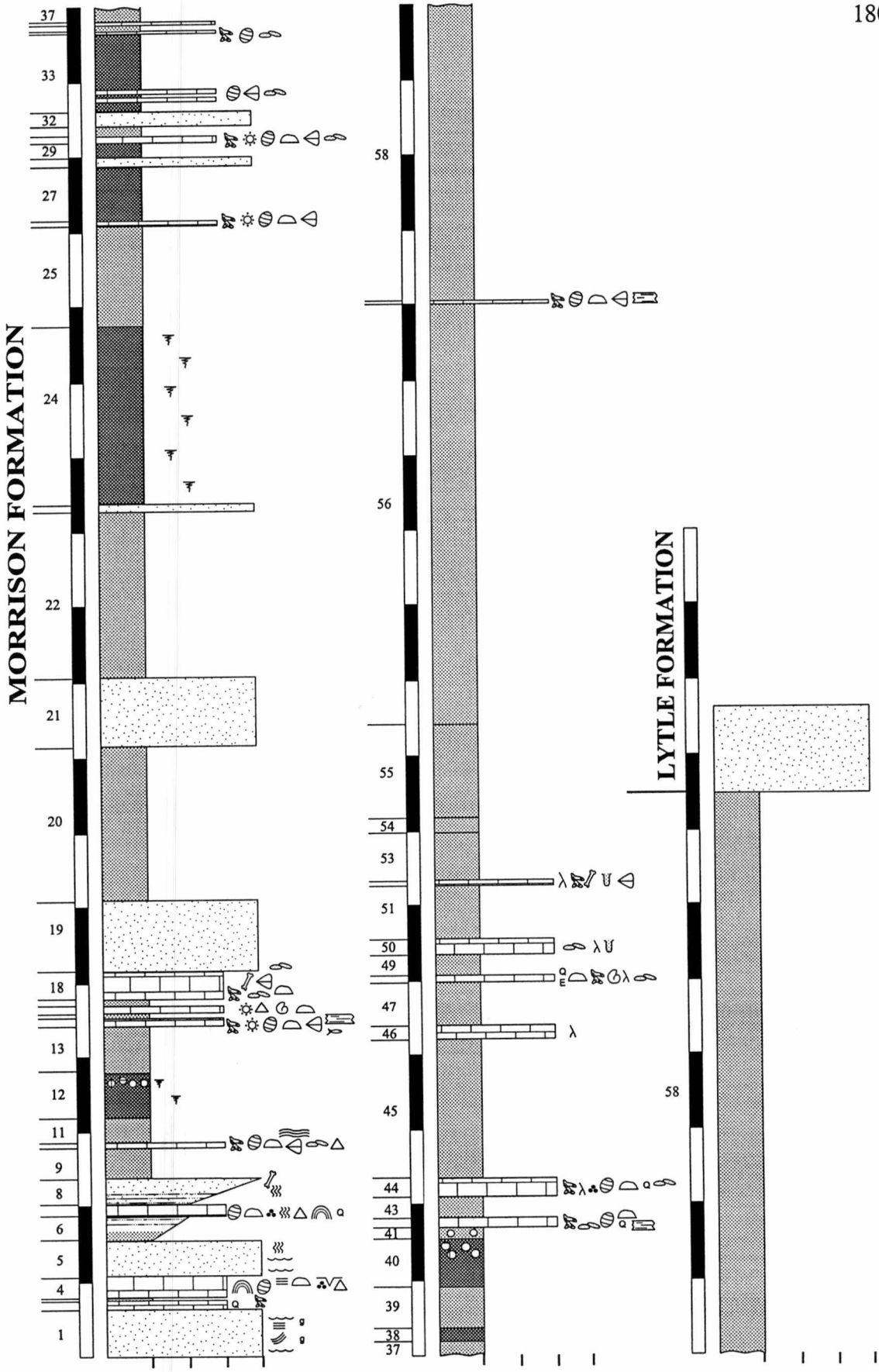
Unit: corresponds to the division designation of a stratigraphic section into units at each measured section.

T (m): thickness of the individual unit in meters.

CT (m): cumulative thickness in meters of measured stratigraphic section.

Description: lithology, color, lithologic classification, grain size/type, texture, skeletal allochems, sedimentary structures, diagenetic and weathering features, bed relationships.
Sample (hand specimen), ***Sample*** (thin-section).

Figure A.1. Stratigraphic section measured at the Park Creek Reservoir outcrop.


MORRISON FORMATION
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Park Creek Reservoir (PCR)

PCR is located approximately 7 km northeast of Livermore, Colorado. The section is approximately 0.5 km north of the Park Creek Spillway (PCS) section after crossing the earthen dam. PCR is located at a latitude of 40°50.693'N and a longitude of 105°09.020'W.

Unit	T (m)	CT (m)	Description
SUNDANCE FORMATION			
Pine Butte Member			
	15.00	15.00	Sandstone, yellowish gray (5Y 8/1) to medium light gray (N6), fine- to medium-grained, moderately-sorted sublitharenites; interbedded mudstone and siltstone are present, olive gray (5Y 4/1) to greenish gray (5GY 6/1); units are generally calcareous to strongly calcareous; mudstones are silty with minor (2-3 mm) gypsum stringers; the "welded chert" is present 2.5 m below the Windy Hill Member; the mudstones are massively bedded, whereas coarser units consist of thin to thick beds; the basal contact is not exposed; laterally continuous over the exposure.
			~~ J-5 unconformity ~~~~~
MORRISON FORMATION			
Windy Hill Member			
1	1.60	1.60	Sandstone, very pale orange (10YR 8/2) to grayish orange (10YR 7/4); fine- to medium-grained, moderately to well-sorted quartzarenite; strongly calcareous and gypsiferous; planar tabular and horizontal cross-stratification; thick to massive beds; prominent ledge-former; sharp basal contact and laterally continuous over the exposure.
undifferentiated			
2	0.30	1.90	Limestone, yellowish gray (5Y 7/2) to medium light gray (N6); strongly calcareous; marly, arenaceous micritic mudstone; no trace or body fossils; irregular upper surface; sharp basal contact; laterally continuous over the exposure.
3	0.10	2.00	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); strongly calcareous; deformed around the irregular surface of Unit 2; no trace or body fossils; appears fissile to very thinly bedded; very poorly exposed; sharp basal contact and laterally continuous over the exposure.
4	0.70	2.70	Limestone, medium gray (N5) to medium light gray (N4); very strongly calcareous; "domal" lithoherms with a diameter of 30-50 cm and a height of 10-30 cm; microbial laminates onlap the domal lithoherms; the upper ~ 10 cm of the unit is microbially laminated with Fe-stained desiccation cracks; partially silicified areas common in the domal lithoherms and more rare in the microbial laminates; fracture and fenestral porosity is present; irregular thin to medium beds; the unit has a sharp basal contact and is laterally continuous over 2 km^2. **PCR-2.2, PCR-2.65,** ***PCR-2.2, PCR-2.65, PCR-2.65-1, PCR-52797-C***
5	1.20	3.90	Sandstone, yellowish gray (5Y 8/1) to light olive gray (5Y 6/1), very fine- to fine-grained, moderately- to well-sorted, sublitharenite to quartzarenite; five sandstone beds are interbedded with mudstone; mudstone interbeds are light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); all beds are very strongly

			calcareous; ripple marks are common in the lower four sandstones, whereas the upper sandstone is bioturbated; beds are thin to thick; the mudstone lacks trace or body fossils and the bedding is massive; sharp basal contact and laterally continuous over the exposure.
6	0.85	4.75	Mudstone to siltstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); strongly calcareous; no trace or body fossils; massive bedding; poorly exposed on a slope; sharp basal contact; laterally continuous over the exposure.
7	0.35	5.10	Limestone, medium light gray (N6) to medium dark gray (N4); very strongly calcareous; charophytes in the lower 3 cm and the fabric is laminated to crinkled in the lower (non-sandy) portion; intraclasts present on the upper bedding plane; limestone becomes increasingly arenaceous upward; sharp basal contact; poor lateral control due to restricted to exposure in the draw. **PCR-4.8, PCR-5.0,** ***PCR-4.8, PCR-5.0***
8	0.90	6.00	Siltstone, light olive gray (5Y 6/1), grading upward to sandstone, yellowish gray (5Y 8/1); non-calcareous to strongly calcareous; the sandstone is fine-grained, moderately-sorted sublitharenite to quartzarenite; upper 10-15 cm is bioturbated; crocodilian jawbone on upper surface; gradational basal contact; thins laterally to the south.
9	1.00	7.00	Mudstone, light greenish gray (5GY 8/1) to dark greenish gray (5GY 4/1); very strongly calcareous and silty; no trace or body fossils; massive to structureless; sharp basal contact and laterally continuous over the exposure.
10	0.20	7.20	Limestone, light gray (N7) to medium light gray (N6); very strongly calcareous; skeletal wackestone; ostracodes, charophytes, and intraclasts (upper surface) are present; massive bedding; sharp basal contact and laterally continuous over the exposure. **PCR-7.2,** ***PCR-7.2***
11	0.80	8.00	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); silty; no trace or body fossils; gradational basal contact with limestone; laterally continuous over the exposure.
12	1.45	9.45	Mudstone, dusky brown (5YR 2/2); strongly calcareous; weakly developed peds and light greenish gray (5GY 8/1) mottles (distinct, abundant, coarse) are present; minor carbonate nodules present in the upper 45 cm; massive structureless bedding; very poorly exposed; gradational basal contact; laterally continuous over the exposure.
13	1.60	11.05	Mudstone, light greenish gray (5GY 8/1) to dark greenish gray (5GY 4/1); very strongly calcareous and silty; no trace or body fossils; massive structureless bedding; very "hard" with a brecciated weathering appearance; slope-former; gradational basal contact and laterally continuous over the exposure.
14	0.30	11.35	Limestone, medium gray (N5) to medium light gray (N5); very strongly calcareous; marly mudstone to wackestone; charophytes and possible fish bones; nodular to massively bedded; gradational basal contact and laterally continuous over the exposure. **PCR-11.2,** ***PCR-11.2***

15	0.10	11.45	Mudstone, light greenish gray (5GY 8/1) to dark greenish gray (5GY 4/1); calcareous; no trace or body fossils; massive structureless bedding; sharp basal contact and laterally continuous over the exposure.
16	0.30	11.75	Limestone, medium gray (N6) to medium light gray (N5); very strongly calcareous; skeletal wackestone to packstone; charophytes, gastropods, ostracodes, and ?fish bone; minor silicification; sharp basal contact and laterally continuous over the exposure. **PCR-11.7,** ***PCR-11.7***
17	0.25	12.00	Mudstone, dark greenish gray (5GY 4/1); strongly calcareous; no trace or body fossils; massive structureless bedding; sharp basal contact and laterally continuous over the exposure.
18	0.90	12.90	Limestone, medium gray (N6) to medium light gray (N5); strongly calcareous; skeletal wackestone to microbial deposit becomes increasingly marly in upper 30 cm; intraclasts are abundant and fish bone; stromatolites to clotted microbial balls at 12.85 m; minor detrital quartz; nodular to medium beds; gradational basal contact and laterally continuous over the exposure. **PCR-12, PCR-12B, PCR-12.2, PCR-12.85,** ***PCR-12.0b, PCR-12.2, PCR-12.25***
19	2.40	15.30	Sandstone with siltstone interbeds, yellowish gray (5Y 8/1) to grayish black (N2); very fine-grained, moderately- to well-sorted sublitharenite; seven alternating sandstone and siltstone interbeds are present; the sandstone is weakly calcareous and is characterized by medium beds; siltstone beds are generally < 10 cm thick; the siltstone is calcareous, lacks trace or body fossils, and is thinly bedded; intraclasts are present in the lowermost sandstone; generally very poorly exposed on the hillslope with best expose in the wash; sharp basal contact and laterally continuous over the exposure.
20	5.10	20.40	Mudstone, light greenish gray (5GY 8/1) to dark greenish gray (5GY 4/1); calcareous; carbonate nodules are present at ~ 18.2 m; massive structureless bedding; very poorly exposed; ?sharp basal contact (poorly exposed); laterally continuous over the exposure.
21	2.30	22.70	Sandstone, pale olive (10Y 6/2) to dusky yellow (5Y 6/4); fine- to coarse-grained, moderately-sorted sublitharenite; strongly calcareous; rip-up clasts are common, particularly in the upper 70 cm; abundant trough cross-beds, ripple marks and planar laminations; bedding is thin to thick; sharp to erosional basal contact; unit pinches out laterally to the south.
22	5.50	28.20	Mudstone, greenish gray (5GY 6/1) to dark greenish gray (5GY 4/1); strongly calcareous and silty; no trace or body fossils; massive structureless bedding; very poorly exposed; sharp basal contact and laterally continuous over the exposure.
23	0.25	28.45	Sandstone, pale olive (10Y 6/2) to dusky yellow (5Y 6/4); fine- to medium-grained, moderately-sorted, sublitharenite; strongly calcareous; rip-up clasts along the base; ripple cross-stratification; very poorly exposed; sharp basal contact and laterally discontinuous.

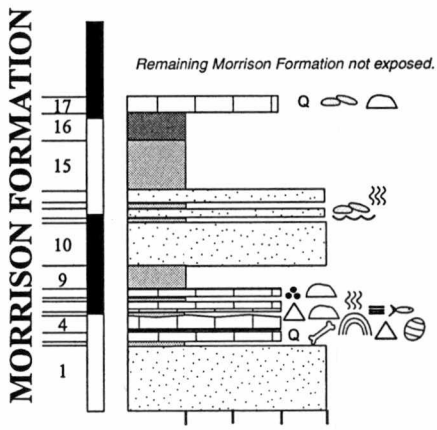
24	5.95	34.40	Mudstone, moderate reddish brown (10R 4/6); high variegated; calcareous to strongly calcareous; no trace or body fossils; mottles are present throughout; reddened intervals have peds and minor carbonate stringers; bedding is massive to structureless; sharp basal contact and laterally continuous over the exposure.
25	3.30	37.70	Mudstone, greenish gray (5GY 6/1); calcareous to strongly calcareous; no trace or body fossils; bedding is massive to structureless; sharp basal contact and laterally continuous over the exposure.
26	0.20	37.90	Limestone, light greenish gray (5GY 8/1); marly micritic mudstone; silty?; irregular to nodular bedding; very poorly exposed; gradational basal contact; laterally discontinuous. **PCR-37.8**
27	1.80	39.70	Mudstone, moderate reddish brown (10R 4/6) in the lower half to greenish gray (5GY 6/1) in the upper part; non-calcareous; no trace or body fossils; possible slickensides; massive structureless bedding; gradational basal contact and laterally continuous over the exposure.
28	0.30	40.00	Sandstone, light olive gray (5Y 6/1); fine- to medium-grained, moderately sorted, sublitharenite; no trace or body fossils; massive bedding; sharp basal contact; laterally continuous for at least 30 m.
29	0.50	40.50	Mudstone, moderate reddish brown (10R 4/6) to greenish gray (5GY 6/1) in the uppermost 10 cm; non-calcareous; no trace or body fossils; massive to structureless bedding; sharp basal contact and laterally continuous over the exposure.
30	0.20	40.70	Limestone, greenish gray (5GY 6/1); marly micritic mudstone; minor porosity with cement; nodular bedding; very poorly exposed; gradational basal contact and laterally discontinuous. **PCR-40.6, *PCR-40.6***
31	0.30	41.00	Mudstone, greenish gray (5GY 6/1); calcareous; no trace or body fossils; massive structureless bedding; sharp basal contact and laterally continuous over the exposure.
32	0.50	41.50	Sandstone, light olive gray (5Y 6/1); fine- to medium-grained, poorly- to moderately-sorted, sublitharenite; ?bioturbated; large therapod bone fragments present (15 cm diameter) and mudstone rip-up clasts; massive to medium beds; gradational basal contact; laterally continuous over less than 40 m.
33	2.60	44.10	Mudstone, dusky red (5R 3/4) to greenish gray (5GY 6/1) in the upper part, with limestone, moderate red (5R 5/4), interbeds; the mudstone is smectitic and non-calcareous; no trace or body fossils; massively bedded; the limestones are marly micritic mudstones (<10 cm thick), nodularly bedded, very poorly exposed, and laterally discontinuous over the exposure; the lower limestone has sharp contacts with the mudstone, whereas the upper limestone has a gradational contact; the unit as a whole has a sharp basal contact and is laterally continuous. **PCR-42.3, PCR-43.1, *PCR-43.1***

34	0.10	44.20	Limestone, medium light gray (N6); wackestone; grainy texture; massively bedded; sharp basal contact and the unit thins laterally. **PCR-44.2, *PCR-44.2***
35	0.20	44.40	Mudstone, greenish gray (5GY 6/1); silty and calcareous; no trace or body fossils; massively bedded; sharp basal contact and laterally continuous over the exposure.
36	0.10	44.50	Limestone, medium light gray (N6); wackestone; intraclasts and skeletal allochems; massively bedded; sharp basal contact and laterally continuous over the exposure. **PCR-44.4**
37	1.00	45.50	Mudstone, dark greenish gray (5GY 4/1); strongly calcareous and silty; no trace or body fossils; pedogenic slickensides; massive bedding; sharp basal contact and laterally continuous over the exposure.
38	0.40	45.90	Mudstone, moderate red (5R 5/4) to greenish gray (5GY 6/1); non-calcareous; no trace or body fossils; mottles are common, distinct, and coarse; massive bedding; gradational basal contact and laterally continuous over the exposure.
39	1.40	47.30	Mudstone, light greenish gray (5GY 6/1); strongly calcareous; no trace or body fossils; minor carbonate nodules (small); massive bedding; gradational basal contact and laterally continuous over the exposure. *Note: a 30 cm error is present from my field notes which will affect all proceeding sample numbers.*
40	1.60	48.90	Mudstone, moderate reddish brown (10R 4/6); non-calcareous; no trace or body fossils; carbonate nodules are present; pedogenic slickensides (?prismatic peds); gypsum stringers are present; massive bedding; sharp basal contact and laterally continuous over the exposure.
41	0.40	49.30	Mudstone, greenish gray (5GY 4/1); strongly calcareous; no trace or body fossils; carbonate nodules are present (2-3 cm diameter) massive bedding; gradational basal contact and laterally continuous over the exposure.
42	0.30	49.60	Limestone, medium light gray (N6) to greenish gray (5GY 4/1); marly wackestone; intraclasts are present; nodular bedding; small, thin greenish-gray mudstone lenses (<10 cm long and <5 cm thick) present; gradational basal contact and laterally continuous over the exposure. **PCR-49.0, *PCR-49.2***
43	0.70	50.30	Mudstone, dark greenish gray (5GY 4/1); weakly calcareous; carbonate nodules are present and appear stacked to prismatic (?rhizoconcretions); mottles are greenish-gray (5GY6/1), common to abundant, distinct and coarse; pedogenic slickensides; Fe-stains common; very poorly exposed; massive to structureless bedding; sharp basal contact and laterally continuous over the exposure.
44	0.60	50.90	Limestone, medium gray (N5) to medium light gray (N6); strongly calcareous; wackestone; silty; intraclasts are common, especially on the upper surface; unit

			geometry is similar to a recumbent "V" with a mudstone interbed in the middle of the "V"; the mudstone interval is greenish gray (5GY 6/1), contains carbonate nodules (~1 cm diameter), and pinches out laterally; unit as a whole has a gradational basal contact and is laterally continuous over 40 m. **PCR-50.4,** ***PCR-50.4***
45	4.60	55.50	Mudstone; three basic subdivisions (A, B, C) from bottom to top; "A" (basal part) is 3.5 m thick, light greenish gray (5 GY 8/1), non-calcareous, smectitic mudstone with no trace or body fossils; "B" is 0.40 m thick, moderate reddish brown (10R 4/6), non-calcareous smectitic mudstone with no trace or body fossils; "C" is light to dark greenish gray (5 GY 8/1-4/1), calcareous mudstone; internal sub-unit contacts are generally gradational; the unit as a whole displays massive to structureless bedding and has a sharp basal contact; the unit is laterally continuous over the exposure.
46	0.45	55.95	Limestone, medium light gray (N6) and light olive gray (5Y 6/1); strongly calcareous; micritic mudstone with greenish gray (5GY 6/1) and blackened (N1) intervals; severely pedogenically altered; root traces; nodularly bedded; very poorly exposed; gradational basal contact; laterally continuous over 30 m. **PCR-55.3**
47	1.50	57.45	Mudstone, light to dark greenish gray (5GY 8/1-4/1); strongly calcareous; silty and "hard"; no trace fossils but possible ?organic fragments (black, <1 mm); massive to structureless bedding; gradational basal contact and laterally continuous over the exposure.
48	0.25	57.70	Limestone, medium light gray (N6) and light olive gray (5Y 6/1); very strongly calcareous; not marly; wackestone; intraclasts and fossil allochems (ostracodes, gastropods); moldic, fracture, and fenestral spar-filled porosity; fenestral porosity may be pseudomicrokarstic; ?evaporite molds (>5 cm); massively bedded; sharp basal contact and laterally continuous over the exposure. **PCR-57.2**
49	0.70	58.40	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); strongly calcareous; silty and "hard"; no trace or body fossils; massive to structureless bedding; sharp basal contact and laterally continuous over the exposure.
50	0.50	58.90	Limestone, medium light gray (N6) and light olive gray (5Y 6/1); strongly calcareous; wackestone; intraclasts are common; rhizoconcretions may also be present; burrows filled with green gray (5GY 6/1) mudstone is common; the vertical burrow taper downward ~9 cm and have a maximum diameter of ~1 cm; burrows are more common in the upper limestone bed; thin to medium beds (35, 15 cm); gradational basal contact and laterally continuous over 30 m. **PCR-58.3, PCR-58.4**
51	1.80	60.70	Mudstone, light to dark greenish gray (5GY 8/1-4/1); weakly calcareous; no trace or body fossils; massive to structureless bedding; sharp basal contact and laterally continuous over the exposure.
52	0.15	60.85	Limestone, medium light gray (N6) and light olive gray (5Y 6/1); very strongly calcareous; intraclast wackestone to packstone; abundant intraclasts; a large, downward-tapering root trace (~4-5 cm diameter; ?tap root) is filled with green

			gray mudstone; massive bedding; gradational basal contact and laterally continuous over 20 m. **PCR-60.3,** ***PCR-60.3, PCR-60.3a, PCR-60.3b***
53	1.60	62.45	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); non-calcareous and smectitic; no trace or body fossils; massive to structureless bedding; very poorly exposed; sharp basal contact and laterally continuous over the exposure.
54	0.50	62.95	Mudstone, dark greenish gray (5GY 4/1); non-calcareous and tuffaceous; no trace or body fossils; massive bedding; very poorly exposed; gradational basal contact and laterally continuous over the exposure.
55	3.10	66.05	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); non-calcareous and smectitic; no trace or body fossils; massive bedding; very poorly exposed; gradational basal contact and laterally continuous over the exposure.
56	14.00	80.05	Mudstone, greenish gray (5GY 6/1); this unit is largely covered and very poorly exposed; cover material is mostly sandstone from the Lytle Formation; gradational basal contact.
57	0.10	80.15	Limestone, medium light gray (N6) and light olive gray (5Y 6/1); strongly calcareous; marly micritic mudstone; ostracodes, rip-up clasts, and gyrogonites; plant fragments; 3-4 cm burrows/root tubes filled with greenish gray mudstone; pyrite nodules (2-4 cm) weathered to limonite; extremely poorly exposed; nodularly bedded; basal contact appears sharp; thickens laterally to 40 cm; lateral continuous for at least 5 m. **PCR-79.7,** ***PCR-79.7***
58	28.60	108.75	Mudstone, greenish gray (5GY 6/1); extremely poorly exposed and largely covered by Lytle sandstone float.
			~~ K-1 unconformity ~~~~~
LYTLE FORMATION			
	2.00	2.00	Sandstone, yellowish gray (5Y 8/1) to moderate yellow (5Y 7/6); fine- to medium-grained, moderately to well-sorted quartzarenite; conglomeratic in places; non-calcareous; commonly cross-bedded; Fe-concretions; massive and medium to thick beds; prominent ridge former; sharp basal contact and laterally continuous.

Figure A.2. Stratigraphic section measured at the Park Creek Spillway outcrop.


MORRISON FORMATION
Remaining Morrison Formation not exposed.
17
16
15
10
9
4
1

Park Creek Spillway (PCS)

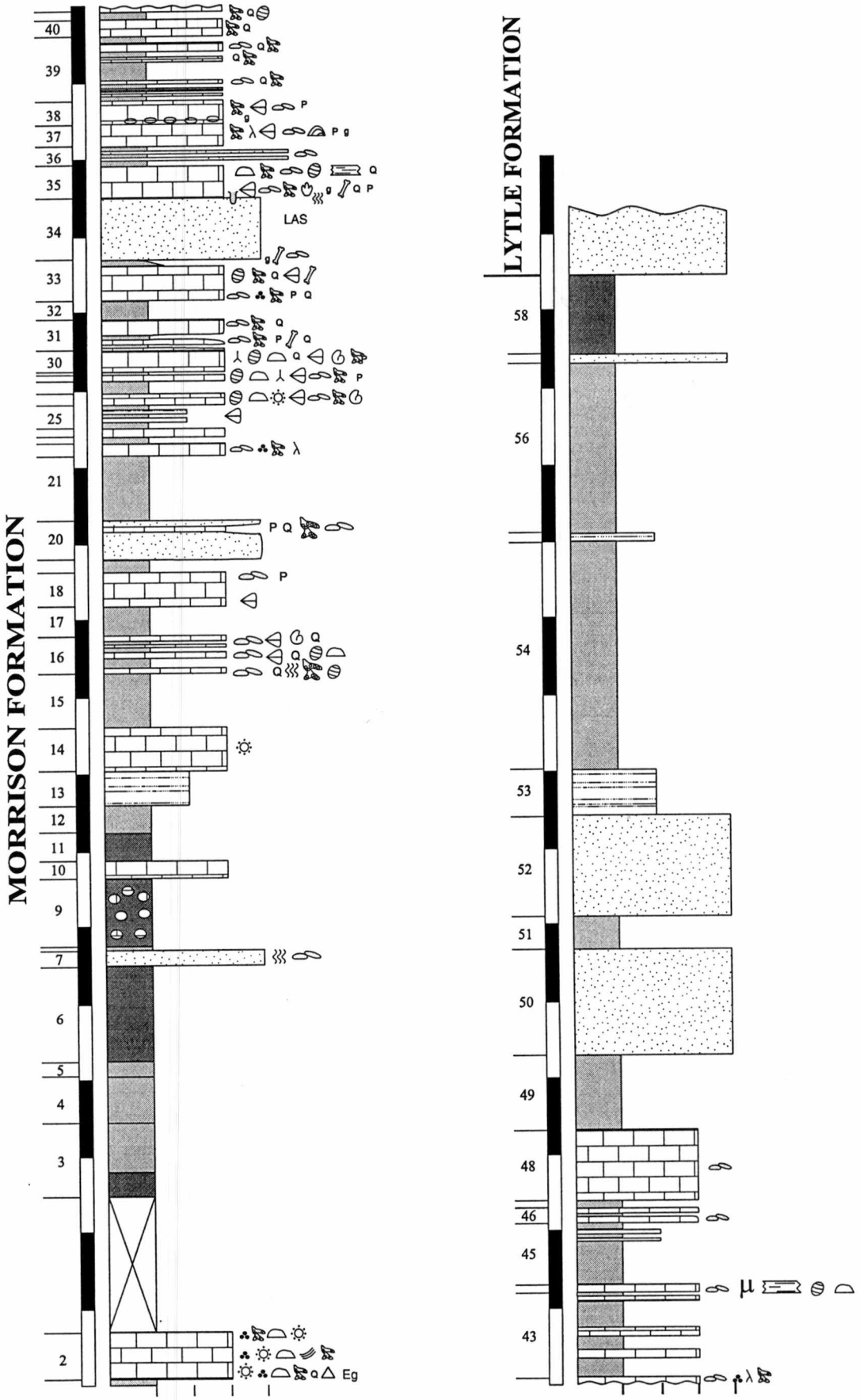
PCS is located approximately 6.5 km northeast of Livermore, Colorado, just north of State Road 80 at a latitude of 40°50.176'N and a longitude of 105°09.345'W. The section is on the property of the North Poudre Irrigation Company (Ft. Collins, Colorado) and permission must be granted because of restricted access. Note that sample numbers reflect total measure section, which included Middle Jurassic strata, in addition to the Morrison Formation. Cumulative thickness numbers reflect just total Morrison numbers.

Unit	T (m)	CT (m)	Description
SUNDANCE FORMATION			
Pine Butte Member			
	2.00	2.00	Sandstone, yellowish gray (5Y 8/1) to medium light gray (N6), with interbedded mudstone and siltstone, olive gray (5Y 4/1) to greenish gray (5GY 6/1); fine- to medium-grained, moderately-sorted sublitharenites; units are generally calcareous to strongly calcareous; mudstones are silty with minor (2-3 mm) gypsum stringers; a sandstone containing the "welded chert" is present 2.5 m below the Windy Hill Member; the mudstones are massively bedded, whereas the coarser units consist of thin to thick beds; the basal contact is not exposed; laterally continuous over the exposure.
			~~ J-5 unconformity ~~~~~
MORRISON FORMATION			
Windy Hill Member			
1	1.65	1.65	Sandstone, grayish orange (10 R 7/4) to very light gray (N8), fine- to medium-grained, moderate to well-sorted, quartz-rich, gypsiferous in upper third, and strongly calcareous; no skeletal allochems or trace fossils were noted; cross-stratification is abundant, low-angle cross beds in the lower ½, upper portion composed of planar to low-angle planar laminations; prominent ledge-former; sharp basal contact and laterally continuous.
undifferentiated			
2	0.10	1.75	Mudstone, gray olive (5Y 3/2) to dark reddish brown (10R 3/4), very weakly calcareous to calcareous; no body or trace fossils were noted; massive to paper-laminated in appearance; sharp basal contact; laterally continuous.
3	0.30	2.05	Limestone, yellowish gray (5Y 7/2) to medium light gray (N6); micritic mudstone; arenaceous and strongly calcareous, detrital quartz sand; convoluted fabric (?burrows) in lower third, possible intraclasts; no body fossils were noted; spar-filled wispy fractures are abundant; sharp basal contact; laterally continuous. **PCS-12.25, *PCS-9.2, PCS-9.2-1***
4	0.40	2.45	Limestone, medium light gray (N6); microbial boundstone; strongly calcareous; partially silicified (30-50%); basal 5 cm of the unit is argillaceous with fine microbial laminations; the boundstone consists of columnar and digitate stromatolites up to 13 cm in height and 1-2 cm in diameter; these stromatolites coalesce to form large domal heads up to 30 cm in diameter; the heads display 7-9 cm of relief; a layer of microbial laminates, oncoids, and

			intraclasts cover the domes and composed the interdomal areas; silicification is most prevalent in the middle of the stromatolites; unit thickness varies from 20-40 cm, sharp basal contact and laterally continuous over 1500 m. **PCS-12.5a, PCS-12.5b, *PCS-12.5a-1, PCS-12.5a-2, PCS-12.5B, PCS-U4***
5	0.10	2.55	Mudstone, dark greenish gray (5GY 4/1) to greenish gray (5GY 6/1), strongly calcareous; commonly deformed around the domal stromatolites of the lower unit; fissile appearance; no body or trace fossils were noted; variable thickness of 5-15 cm; sharp basal contact, laterally continuous.
6	0.25	2.80	Limestone, medium light gray (N6); microbial laminate to micritic mudstone; strongly calcareous; partially silicified; microbial laminates restricted to lower half of unit; intraclasts and charophytes present in upper part; minor spar filled porosity; polygonal desiccation cracks; unit thickness varies up to 5 cm; sharp basal contact and laterally continuous over the exposure.
7	0.10	2.90	Mudstone, dark greenish gray (5GY 4/1) to greenish gray (5GY 6/1), strongly calcareous; no body or trace fossils were noted; massive appearance; sharp basal contact, unit pinches and swells from 0-10 cm thick.
8	0.25	3.15	Limestone, medium light gray (N6); microbial laminate to micritic mudstone; strongly calcareous; microbial laminates restricted to lower half; charophytes present in upper part; minor spar filled porosity; sharp basal contact; laterally discontinuous over 30 m. **PCS-13.0, *PCS-13.0***
9	0.60	3.75	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); slightly calcareous; no body or trace fossils were noted; massive appearance, sharp basal contact, laterally continuous.
10	1.10	4.85	Sandstone to siltstone, pale brown (5YR 5/2) to medium light gray (N6); fine-grained, moderately sorted sublitharenite; no body or trace fossils were noted; four distinct sandstone beds grade laterally into siltstone; the unit as a whole has a lens-like geometry and a gradational basal contact; laterally continuous over the exposure.
11	0.10	4.95	Mudstone, light greenish gray (5GY 8/1), greenish gray (5GY 6/1), and grayish red (10R 4/2); no body or trace fossils were noted; massive appearance, sharp basal contact, laterally continuous.
12	0.25	5.20	Sandstone, pale brown (5YR 5/2) to medium light gray (N6); very fine-grained, quartz-rich; moderately sorted, sublitharenite; two distinct beds (lower = 5 cm; upper = 20 cm); lower bed contained a high number of trace fossils relative to the upper bed, ripple marks are also present in the lower bed; mudstone rip-up clasts weathering out of upper bed; both beds have a massive appearance; sharp basal contact; laterally continuous.

13	0.15	5.35	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); no body or trace fossils were noted; massive appearance, sharp basal contact, laterally continuous.
14	0.30	5.65	Sandstone, pale brown (5YR 5/2) to medium light gray (N6); very fine-grained, moderately sorted sublitharenite; quartzitic texture; calcareous; bioturbated fabric, trace fossils are common, particularly at the base of the unit (up to 1-2 cm in diameter); ichnofossils are primarily feeding traces; sharp basal contact and laterally continuous over the exposure.
15	1.30	6.95	Mudstone, grayish red (10R 4/2) to olive gray (5Y 3/2); possible *Gryphaea* (marine or non-marine) found, but no trace fossils were noted; massive appearance, sharp basal contact; laterally continuous over the exposure.
16	0.70	7.65	Mudstone, grayish red (10R 4/2) to moderate reddish brown (10R 4/6); pedogenic slickensides present; possible root traces, mottles (large, distinct, common) present; massive appearance; gradational basal contact and laterally continuous over the limited exposure.
17	0.40	8.05	Limestone, medium gray (N5); micritic mudstone; arenaceous; no body or trace fossils were noted; heavily weathered and very poorly exposed; sharp to gradational basal contact and laterally continuous over the limited exposure. **PCS-18,** ***PCS-18***

Figure A.3. Stratigraphic section measured at the Highway 287 outcrop.


MORRISON FORMATION
LYTLE FORMATION
LAS
Eg

Highway 287 (H)

The H section is a roadcut along U.S. 287 located approximately 1.5 km north-northeast of Ted's Place, Colorado, which is north of Fort Collins. The section is located at a latitude of 40°40.432'N and a longitude of 105°11.319'W.

Unit	T (m)	CT (m)	Description
			Basal portion not exposed.
MORRISON FORMATION			
1	0.20	0.20	Mudstone, light olive gray (5Y 5/2); slightly silty and strongly calcareous; 2-3 mm gypsum stringers in upper 3 cm of unit; massive, structureless bed; no trace of body fossils noted; extremely poor exposure; basal contact not exposed, lateral continuity unknown.
2	1.50	1.70	Limestone, light olive gray (5Y 6/1) to olive gray (5Y 4/1); 3 major limestone beds with a thin (~5 cm) mudstone interbed between limestone bed 1 and 2; limestone beds are 30, 70, and 45 cm, respectively from bottom to top; limestone and mudstone are both very strongly calcareous; mudstone is slightly silty and lacks trace or body fossils; possible mm-scale ?organic fragments; limestones are charophyte packstones; lower limestone unit has laminations in basal 5 cm and grades upward into intraclast and peloids; abundant charophyte fragments; silicified portions weathers with slight positive relief; subhorizontal spar-filled fractures; the middle limestone unit has horizontal stylolites and very faint, low-angle cross-laminations; abundant charophytes and spar-filled voids; upper limestone displays subvertical stylolites and minor silicification similar to lower unit; internal contacts between beds are sharp; basal contact of the unit is sharp; limited lateral continuity (< 5 m) due to poor exposure. **H-0.25, H-0.4a & b, H-0.6, H-1.2, H-1.24-1.4, H-1.7, *H-0.25, H-0.4a, H-0.6, H-1.2, H-1.25, H-1.7***
	4.50	6.20	Covered Interval.
3	1.40	8.60	Mudstone, pale red (5R 6/2) to grayish red (10R 4/2); slightly silty and strongly calcareous; no peds were noted; mottles are present (faint, coarse, and rare [light greenish gray]); no trace or body fossils; the unit is massively bedded and grades upward over 3 cm into an interval of carbonate nodules, yellowish gray (5Y 8/1) to light olive gray (5Y 6/1), which cap the upper part of this unit; the nodular carbonate interval is up to 10 cm thick; the carbonate appears micritic and mottled (red-green), and lacks allochems; basal contact of this unit is not exposed; laterally continuous over the limited exposure. **H-8.6, *H-8.6-1, H-8.6-2***
4	1.50	10.10	Mudstone, pale red (5R 6/2) to grayish red (10R 4/2); strongly calcareous; probable peds, no trace or body fossils; mottles are faint, coarse, and few; massively bedded; sharp basal contact; laterally continuous over the limited exposure.
5	0.50	10.60	Mudstone, yellowish gray (5Y 8/1) to light olive gray (5Y 6/1); very strongly calcareous, almost marly in appearance; no trace or body fossils; massively bedded; gradational basal contact and laterally continuous over the limited exposure.

6	3.15	13.75	Mudstone, pale red (5R 6/2) to grayish red (10R 4/2); strongly calcareous; probable ?blocky peds; no body fossils noted; calcareous rhizoconcretions from 13.0-13.2 m; the rhizoconcretions are diffuse; the unit is massively bedded and grades upward into a grayish yellow green (5GY 7/2) to greenish gray (5GY 6/1) mudstone that is silty and strongly calcareous in the upper 20-30 cm; the unit is generally a slope-former except where the carbonate is present; the unit has a sharp basal contact and is laterally continuous. **H-13.2, *H-13.2-1, H-13.2-2***
7	0.50	14.25	Sandstone, light greenish gray (5GY 8/1) to moderate yellow (5Y 7/6); very fine-grained, moderately sorted sublitharenite; strongly calcareous; mudstone rip-up clasts are present and strongly bioturbated, burrows are up to 40 cm deep and have an average diameter of 1 cm; the burrows are highly weathered but appear to have an original infilling of greenish gray mudstone; massively bedded; the upper surface is irregular with ~3 cm of relief; sharp basal contact; the unit pinches out laterally over 30 m to the southwest. **H-14**
8	0.15	14.40	Mudstone, dusky yellow green (5GY 5/2); slightly silty and calcareous; no trace or body fossils; very poorly exposed slope-former with a sharp basal contact; lateral continuity limited due to poor exposure.
9	2.20	16.60	Mudstone, pale red (5R 6/2) to grayish red (10R 4/2); calcareous; carbonate nodules and a sandstone lens are present; large m-scale arcuate pedogenic slickensides and blocky peds are present; mottles in the lower third are small to coarse, distinct, and common, while mottles in the upper two-thirds are fine-medium, faint, and few; carbonate nodules are generally <1-2 cm in diameter; the sandstone lens is petrographically similar to Unit 7 but lacks burrows and is more discontinuous (15 cm thick and pinches out over 30 cm); this unit has a sharp basal contact and is laterally continuous over the exposure.
10	0.60	17.20	Sandstone, medium dark gray (N4) to medium gray (N5), and siltstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); the sandstone is fine- to medium-grained, moderately sorted sublitharenite; both are calcareous to strongly calcareous; rare gypsum stringers in the upper 10 cm; no body fossils; ?dinoturbation or ?soft-sediment deformation; unit appears well-bedded to highly convoluted mass (50 cm x 130 cm); siltstone is present between convoluted sandstone areas; gradational basal contact; laterally discontinuous over ~ 30 m. **H-17.0**
11	0.90	18.10	Mudstone, very dusky red (10R 2/2); silty and weakly calcareous to calcareous; carbonate nodules are common as well as gypsum stringers along subhorizontal fractures; carbonate nodules are micritic to marly with minor porosity; no body or trace fossils; massively bedded; gradational to diffuse lower contact and laterally continuous over the exposure. **H-17.5**
12	0.90	19.00	Mudstone, greenish gray mudstone (5GY 6/1); silty to calcareous; carbonate nodules are present at lower contact and decrease in abundance upward; no body fossils; ?rhizoconcretions in upper 25 cm; mottles are very rare; massively

			bedded; gradational lower contact and laterally continuous.
13	1.10	20.10	Siltstone and mudstone, greenish gray (5GY 6/1) to light greenish gray (5GY 8/1); very strongly calcareous (especially at the base); unit composed of thin to medium siltstone and massive mudstone beds with minor (<5 cm thick) marly limestone interbeds; limestone interbeds have gradational upper and lower contacts; no trace or body fossils; unit displays a gradational basal contact and grades laterally into a red bed paleosol.
14	1.40	21.50	Sandstone and mudstone, light olive gray (5Y 6/1) to greenish gray (5GY 6/1), and limestone, medium gray (N5); the sandstone is fine- to medium-grained, moderately sorted sublitharenite; weakly calcareous (sandstone) to strongly calcareous (limestone); no trace or body fossils are present in the sandstone or mudstone; the limestone is a marly to arenaceous, micritic mudstone and appears convoluted (?soft-sediment deformation); laterally discontinuous for 10-15 m due to cross-cutting sandstone and mudstone; non-convoluted bedding is thin to medium and irregular to nodular where deformed; the unit as a whole has a sharp basal contact and is laterally continuous. **H-20.9**
15	1.80	23.30	Mudstone, very dusky red (10R 2/2), composed of two subunits; the lower subunit is ~ 1 m thick, strongly calcareous, and has weakly developed peds and ?pseudoanticlinal structures; the lower subunit lacks carbonate nodules; the upper subunit is ~ 0.75 m thick and strongly calcareous with micritic rhizoconcretions; this upper subunit has moderately developed peds (angular to platy) and becomes less reddened, weakly calcareous, and more variegated upward; mottles are present (few, faint and coarse); similar in appearance to Unit 11; sharp contact between the two subunits; unit as a whole is poorly exposed and has a gradational lower contact; laterally continuous over the outcrop. **H-22.5**
16	1.20	24.50	Interbedded limestone, light olive gray (5Y 6/1) to green-gray (5GY 6/1), and mudstone, medium light gray (N6) to dark greenish-gray (5GY 4/1); four thin limestones (25, 15, 10, 10 cm) interbedded with three mudstones (30, 15, 15); limestones are largely micritic mudstones devoid of skeletal allochems, although intraclasts are present in the upper 2 carbonate interbeds; limestones are strongly to very strongly calcareous; mudstones are non- to weakly-calcareous, massive, and lack trace or body fossils; bedding is generally irregular to nodular and the thickness of individual interbeds varies laterally; sharp basal contact; unit as a whole is laterally continuous. **H-23.5, H-23.9, H-24.25, H-24.45, *H-23.5, H-23.9, H-24.25, H-24.45***
17	1.00	25.50	Mudstone, very dusky red (10R 2/2), strongly calcareous with poorly developed peds and well-developed ?columnar stacked carbonate nodules (3 cm in diameter and up to 10 cm long); green-gray and Fe-stained mottles are abundant, coarse, and faint to distinct; massively bedded; last major paleosol prior to main lacustrine carbonate interval; sharp basal contact and laterally continuous over the exposure. **H-25**

18	1.10	26.60	Limestone, dark yellowish orange (10YR 6/6) to medium light gray (N6); thin interstitial areas (< 1-5 cm) filled with greenish gray (5GY 6/1) mudstone; the limestone and mudstone are very strongly calcareous; the limestone is micritic with intraclasts and microspar-filled karstic porosity in the upper 10 cm; nodular to massively bedded with sharp internal contacts between beds; sharp lower contact; this unit is laterally continuous over the exposure. **H-25.6, H-25.9, H-26.3,** ***H-25.9, H-26.3***
19	0.40	27.00	Claystone to mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); non-calcareous to calcareous; no trace or body fossils; poorly exposed; massive bed; sharp basal contact and laterally continuous over the exposure.
20	1.30	28.30	Sandstone with limestone interbeds, both are light greenish gray (5GY 8/1); the sandstone is a fine- to medium-grained, moderately sorted sublitharenite; the sandstone is also spalling; the limestone is very marly with siliciclastic mudstone rip-up clasts and minor porosity; upper ½ of the unit is poorly exposed; massive to nodular beds; sharp basal contact and laterally continuous over the exposure. **H-27.5, H-28.1,** ***H-27.5***
21	2.10	30.40	Mudstone, light to dark greenish gray (5GY 8/1 to 4/1); clayey in parts; no trace or body fossils; massively bedded; generally a slope-forming unit with 2 indurated mottled mudstone units that exhibit slight positive weathering relief; sharp basal contact and laterally continuous over the exposure.
22	0.40	30.80	Limestone, yellowish gray (5Y 8/1) to greenish gray (5GY 4/1); intraclast wacke/packstone; strongly calcareous; green mudstone rip-up clasts/intraclasts are abundant; massively bedded with a nodular weathering appearance; ledge-former; sharp basal contact; laterally continuous over the exposure. **H-30.5, H-30.5b,** ***H-30.5, H-30.5b***
23	0.20	31.00	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); non-calcareous; no trace or body fossils; mudstone becomes darker in color (more brown) toward pinch out; massively bedded; sharp basal contact; laterally pinches out over < 30 m between Units 22 and 24.
24	0.25	31.25	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); intraclast wackestone that grades laterally over 20 m into a fenestral limestone; strongly calcareous; massively bedded with fractured appearance; unit swells from 25 to 45 cm laterally until in contact with Unit 22; sharp basal contact and laterally continuous over the exposure. **H-31.4A, H-31.4B**
25	0.80	32.05	Mudstone with limestone interbeds, dark yellowish orange (10YR 6/6) to medium light gray (N6); the mudstone is non- to weakly-calcareous, silty and massively bedded; no trace or body fossils are present; the limestone is a marly to micritic mudstone with minor spar-filled porosity; the limestones are massive to nodularly bedded and are laterally discontinuous over the outcrop; unit displays a sharp basal contact and is laterally continuous over the exposure. **H-31.9,** ***H-31.9***

26	0.35	32.40	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); strongly calcareous; skeletal wackestone; intraclasts and ?charophytes; limonite-filled fenestral porosity and pyrite nodules (< 1 mm), commonly weathering to limoite, are also present; massively bedded; sharp basal contact and laterally continuous over the exposure. **H-32.1, H-32.4, *H-32.1, H-32.4***
27	0.40	32.80	Mudstone to claystone, yellowish gray (5Y 8/1) to light greenish gray (5GY 8/1); "soft"; no trace or body fossils; massively bedded; sharp basal contact and laterally continuous over the exposure.
28	0.20	33.00	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); micritic mudstone; stained by limonitic weathering; strongly calcareous; spar-filled porosity is present; massively bedded; sharp basal contact; unit thins laterally to the southwest as Unit 29 thickens; laterally continuous over the exposure. **H-32.85, *H-32.85***
29	0.10	33.10	Mudstone, yellowish gray (5Y 8/1) to light greenish gray (5GY 8/1); very strongly calcareous; no trace or body fossils; massively bedded; sharp basal contact; laterally the unit thickens to 30 cm to the southwest; laterally continuous over the exposure.
30	0.70	33.80	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); skeletal mudstone; sponge spicules; commonly stained with limonitic weathering; intraclasts are common in upper 1/3 and pyrite nodules are common (1-20 mm diameter); massive to nodular bedding; ledge-former; sharp basal contact and laterally continuous over the exposure. **H-33.4, H-33.75, *H-33.4B, H-33.4, H-33.4/2***
31	1.00	34.80	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6), and mudstone, yellowish gray (5Y 8/1) to greenish gray (5G 6/1), interbeds; the mudstone are both 10 cm thick, non-calcareous, and lack trace or body fossils; the limestones are very strongly calcareous and marly to micritic mudstones; pyrite nodules weathering to limonite and spar-filled porosity are abundant in the lower limestone, whereas intraclasts and couplets are present in the upper limestone; the lower mudstone also appears to pinch out to the southwest with the lower limestone in contact Unit 30; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **H-33.9, H-34.8, *H-33.9, H-34.8***
32	0.60	35.40	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); non-calcareous; no trace or body fossils; massively bedded; sharp basal contact and laterally continuous over the exposure.
33	1.30	36.70	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6), grades upward to mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); Fe-staining is common; the limestone is an arenaceous, intraclast wacke/packstone with abundant green mudstone rip-up clasts (< 1 cm in diameter); very strongly calcareous; the limestone is nodularly bedded with mudstone-filled interstices between the "nodules"; the mudstone is non-calcareous and silty; the interstitial mudstone is deformed and irregularly bedded, whereas the upper mudstone is massive in appearance; the unit as a whole has a sharp irregular basal contact

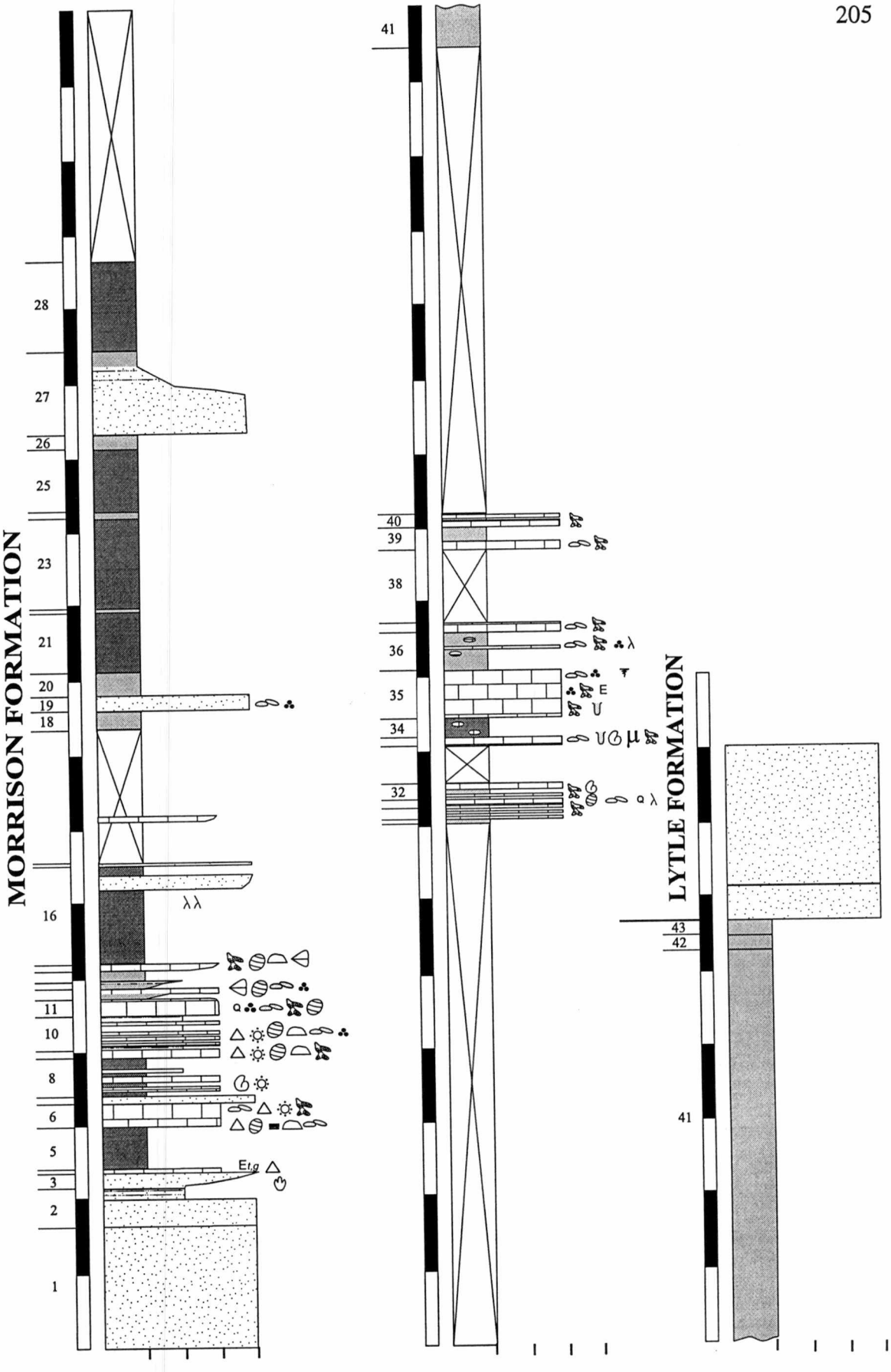
			and is laterally continuous over the exposure. **H-35.75, H-36.4, *H-35.75, H-36.4***
34	2.00	38.70	Sandstone, light brown (5YR 6/4) to yellowish gray (5Y 8/1), and mudstone greenish gray (5GY 6/1) to dark greenish gray (5GY 4/1); fine- to medium-grained, moderately-sorted sublitharenite to quartzarenite; large bone (>12 cm diameter) at the base of unit; mudstone rip-up clasts are present; Fe-concretions (?limonite after pyrite) are common also; sandstone contacts are generally sharp; the mudstone is silty; unit is characterized by laterally accretion sets and to the southwest the sandstone grades into siltstone and mudstone, with numerous gypsum stringers (1-3 mm thick); the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **H-37.3, H-OC**
35	1.05	39.75	Limestone, light brown (5YR 6/4) to medium light gray (N6); strongly calcareous; micritic mudstone; burrows are common (2-3 cm in diameter and extending up to 15 cm); large dinoturbation structure present; carbonate burrows (5 cm in diameter) also extend from the base of the unit ~ 20 cm into siltstone of Unit 33; evaporite pseudomorphs (< 5 mm long) are present as clusters; spar-filled fenestral porosity is common and unit appears to have a brecciated texture; upper 5 cm is characterized by brown, flaggy limestone with abundant pyrite nodules and gypsum (< 1 cm thick); ledge-former; massively bedded; unit has a sharp basal contact and is laterally continuous over the exposure. **H-38.7, H-39.4, H-39.45-39.7, *H-38.7, H-39.4***
36	0.65	40.40	Mudstone, light (5GY 8/1) to dark (5GY 4/1) greenish gray; non-calcareous; no trace or body fossils; sandstone interbeds present that are non- to strongly-calcareous with mudstone rip-up clasts; the interbeds are laterally discontinuous and have gradational contacts; the unit is characterized by massive beds; has a sharp basal contact; and is laterally continuous over the exposure.
37	0.70	41.10	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); strongly calcareous; intraclast wackestone; green mudstone rip-up clasts/intraclasts throughout unit; evaporite pseudomorphs in selected areas (up to 1 cm); large burrows (2-3 cm diameter, 5-10 cm in length) are present and are primarily subvertical, with minor subhorizontal component; fracture, fenestral, and moldic (evaporites) porosity present; nodularly bedded in the lower and upper ~ 10 cm, but otherwise a single massive bed; unit thins to 40 cm to the northeast; sharp basal contact and laterally continuous over the exposure. **H-40.4, H-40.7-40.9, H-41.0, *H-40.4, H-41.0a,* H-41.0b**
38	0.80	41.90	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); the lower 20 cm is characterized as a weakly calcareous, marly to arenaceous micritic mudstone, with minor porosity and gypsum stringers (3-4 mm thick) above and below the nodules; nodule interstices filled with mudstone of similar composition to Unit 36; the upper 60 cm is a strongly calcareous, intraclast wackestone with green mudstone rip-up clasts (subangular to subrounded) and pyrite nodules (2-4 mm) weathering to limonite; upper 10 cm has karstic features, including laminar fenestral porosity filled with micritic clasts, vadose silt, and spar; bedding is nodular in the basal 20 cm but otherwise is massive; sharp basal contact and laterally continuous over the exposure. **H-41.2, H-41.3, H-41.9, *H-41.3***

39	2.10	44.00	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1), with five limestone, yellowish gray (5Y 8/1) to medium light gray (N6), interbeds; the limestone interbeds are 10, 10, 20, 15, and 30 cm thick from bottom to top; the limestones are calcareous and very marly to arenaceous micritic mudstones to intraclast wackestones; mudstone rip-up clasts are common in the first and fourth carbonate beds; the limestones are nodularly bedded; the mudstones are calcareous, lack trace or body fossils, and are massively bedded; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **H-42.1, H-42.3, H-42.75, H-43.2, H-43.7,** ***H-42.75, H-43.2***
40	0.55	44.55	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); Fe-staining is common; strongly calcareous; micritic mudstone with ?evaporite pseudomorphs and fenestral porosity; massively bedded; unit thins to 30 cm to the northeast; sharp basal contact and laterally continuous over the exposure. **H-44.4,** ***H-44.4***
41	0.20	44.75	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1); non-calcareous and clayey; no trace or body fossils; massively bedded; sharp basal contact and laterally continuous over the exposure.
42	0.50	45.25	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); strongly calcareous; intraclast wackestone; green mudstone rip-up clasts in upper 5 cm; J-shaped ?burrows (20 cm high and 25 cm long) extend from the top of the limestone; pyrite nodules (1-30 mm in diameter); spar-filled fenestral and fracture porosity; massively bedded with a nodular weathering appearance; this unit is the last major limestone bed above the sandstone with the lateral accretion sets and prior to the clay change; sharp and irregular basal contact; laterally continuous over the exposure. **H-45**
43	2.75	48.00	Mudstone, light greenish gray (5GY 8/1) to greenish gray (5GY 6/1), and three limestone, yellowish gray (5Y 8/1) to pale reddish brown (10R 5/4) interbeds; the mudstone is non-calcareous, clayey, and massively bedded; no trace or body fossils present; the limestones are marly to arenaceous, intraclast wackestones with green mudstone rip-up clasts and nodular bedding; contacts between limestones and mudstones are gradational; the unit is poorly exposed; sharp basal contact; laterally continuous over the exposure. **H-46,** ***H-46***
44	0.25	48.25	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); intraclast wackestone; strongly calcareous with green mudstone rip-up clasts and minor bone fragments; bedding is massive; sharp basal contact and laterally continuous over the exposure. **H-48.2A, H-48.2B,** ***H-48.2B***
45	2.00	50.25	Mudstone, light to dark greenish gray (5GY 8/1-4/1), with minor limestone, interbeds and carbonate nodules; the mudstone is ?smectitic, clayey, and "soft"; no trace or body fossils; bedding appears massive; the limestones are marly micritic mudstones with nodular bedding and appear to be laterally discontinuous over several meters; the unit has a sharp basal contact and is laterally continuous over the exposure.

46	0.50	50.75	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6), with a thin (10 cm) mudstone interbed, light to dark greenish gray (5GY 8/1-4/1); the limestones are strongly calcareous, marly micritic mudstones to intraclast wackestones; green mudstone rip-up clasts are present in the upper limestone; the mudstone interbed is non-calcareous and lacks trace or body fossils; limestone bedding is nodular, whereas the mudstones are structureless; the unit has a sharp basal contact and is laterally continuous over the exposure. **H-50.7**
47	0.25	51.00	Mudstone, light to dark greenish gray (5GY 8/1-4/1); ?smectitic, clayey, and "soft"; no trace or body fossils; bedding appears massive; sharp basal contact and laterally continuous over the exposure.
48	2.30	53.30	Limestone, pale yellowish orange (10YR 8/6) to grayish yellow (5Y 8/4); very strongly to strongly calcareous; marly micritic mudstone; induration and relief due to weathering varies; gypsum stringers 1-3 mm thick are present; highly weathered appearance with abundant spar-filled fractures; the unit has an irregular but sharp basal contact and is laterally continuous over the exposure. **H-53.3, *H-53.3***
49	2.40	55.70	Mudstone, light olive gray (5Y 6/1) to olive gray (5Y 4/1); very "silty", ?tuffaceous, and hard compared to lower mudstones; distinct slight positive weathering expression; 40 cm ledge-forming interval characterized by green mudstone rip-up clasts and biotite fragments; sharp basal contact and laterally continuous.
50	3.50	59.20	Sandstone, yellowish gray (5Y 8/1); fine- to medium-grained, moderate sorted sublitharenite; non-calcareous; four distinct beds characterized by cross-beds in the lowest bed, vertebrate bones in the second (57.4 m), rip-up clasts (third bed), and bioturbation at the base of the fourth bed; sharp basal contact and laterally continuous over the outcrop.
51	2.05	61.25	Mudstone, light to dark greenish gray (5GY 8/1-4/1); non-calcareous and very silty; no trace or body fossils; massive bed; very poorly exposed; sharp basal contact and laterally continuous over the exposure.
52	2.30	63.55	Sandstone, light brown (5YR 6/4-5/6); fine- to medium-grained, moderate sorting sublitharenite; non-calcareous; lower 2 m appears tuffaceous; large Fe concretions with a diameter up to 10 cm; two major beds; the lower bed is 1.65 m thick with thin to medium beds, while the upper bed (0.65 m) has very faint low angle planar stratification; gradational to intercalated basal contact and laterally continuous over ~ 30 m.
53	1.50	65.05	Siltstone, yellowish gray (5Y 7/2); non-calcareous; no trace or body fossils; very poorly exposed; sharp basal contact and the unit grades laterally into mudstone.
54	7.45	72.50	Mudstone, pale red (10R 6/2) to dark greenish gray (5GY 4/1); non-calcareous and silty to very arenaceous in parts; no trace or body fossils; unit grades upward in color from red (3.95 m) to variegated (1 m) to green mudstones (2.5 m); variegated interval is arenaceous and weathers with a slight positive relief; upper 1 m characterized by Fe-stained subhorizontal fractures; this unit is very

			poorly exposed on the slope in general and has a sharp basal contact; lateral continuity is unknown.
55	0.25	72.75	Siltstone to sandstone, pale reddish brown (10R 5/4); brecciated fabric; very weakly calcareous; (?)fragipan to Fe-stained calcrete interval; very poorly exposed; unit weathers with a slight positive relief; sharp basal contact; laterally continuous over the exposure. **H-73**
56	5.50	78.25	Mudstone, greenish gray (5GY 6/1) to pale red (10R 6/2); non-calcareous and slightly silty; no trace or body fossils; massively bedded; gradational and irregular basal contact, laterally continuous over the exposure.
57	0.30	78.55	Sandstone, grayish yellow (5Y 8/4); fine- to medium-grained, moderately to poorly sorted sublitharenite; non-calcareous; mm- to cm-scale plant fragments; no trace fossils; massively bedded; gradational basal contact and laterally continuous.
58	2.60	81.15	Mudstone, moderate reddish brown (10R 4/6); non-calcareous; no trace or body fossils; hydroxymorphic reduction spots; mottles are Fe-stained (coarse, common, ?distinct); sharp basal contact and laterally continuous.
			~~ K-1 unconformity ~~~~~
LYTLE FORMATION			
	1.00	1.00	Sandstone, grayish yellow (5Y 8/4) to yellowish gray (5Y 7/2); fine- to medium-grained, moderately sorted sublitharenite to quartzarenite; very poorly exposed and highly weathered on the top of the hogback; present mostly as float; no trace or body fossils; sharp basal contact exposed and laterally continuous.

Figure A.4. Stratigraphic section measured at the Horsetooth Reservoir outcrop.


MORRISON FORMATION
LYTLE FORMATION
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Horsetooth Reservoir (HR)

The HR section is present southwest of Ft. Collins, Colorado, along State Road 23 near Spring Canyon Dam at a latitude of 40°31.499'N and a longitude of 105°08.662'W. This section represents the best exposure of the Morrison Formation in the reservoir area.

Unit	T (m)	CT (m)	Description
			Base not measured.
SUNDANCE FORMATION			
	2.00	2.00	Sandstone, grayish orange (10YR 7/4); fine to medium-grained, moderately sorted quartzarenite; non-calcareous; no body or trace fossils; festoon cross-stratification is common; abundant medium to thick beds; basal contact was not examined; laterally continuous across the exposure.
			~~ J-5 unconformity ~~~~~
MORRISON FORMATION			
Windy Hill Member			
1	4.10	4.10	Sandstone, grayish orange (10YR 7/4) to yellowish gray and pale greenish yellow (5Y 8/1 to 10Y 8/1); composed of three sub-units: A (1.5 m), B (0.35 m), and C (2.2 m); "A, B, and C" are fine-grained, subrounded, well-sorted quartzarenite; calcareous; "A" has massive beds that show very faint planar laminations and lacks body or trace fossils; "B" has flaggy to bioturbated beds (possible dinoturbation) with no internal stratification; "C" is characterized by low angle planar laminations and lacks trace or body fossils; the sandstone unit is also gypsiferous; sharp basal contact, laterally continuous.
2	1.30	5.40	Sandstone, grayish to moderate orange pink (10R 8/2-7/4); very fine-grained, subangular to subrounded, well-sorted quartzarenite; gypsum stringers throughout (primary or diagenetic); no trace or body fossils noted; chert nodules present at 5.1 m; thin beds are poorly defined; sandstone grades upward into a greenish gray (5GY 6/1) to pale reddish brown (10R 5/4) siltstone with small gypsum stringers; sharp basal contact, laterally continuous.
3	0.50	5.90	Siltstone grading upward to sandstone, very pale orange to pale yellowish brown (10YR 8/2-6/2); strongly calcareous; the siltstone is thinly bedded with small track-like dinoturbation structures (15 cm across and 3 cm deep) and is capped by a discontinuous, pale reddish brown (10R 5/4) to very dusky red (10R 2/2) chert layer; sandstone is very fine-grained, moderately sorted sublitharenite to quartzarenite; no body fossils are present; sharp basal contact, laterally continuous.
4	0.15	6.05	Limestone; micritic mudstone; light gray (N7) to brownish gray (5YR 4/1); no obvious allochems or detrital quartz grains; grades laterally into micritic mudstone with abundant red chert stringers; brecciated weathering appearance; sharp basal contact and laterally continuous. **HR-6.0, HR-6.0A,** ***HR-6.0, HR-6.0A-1***
5	1.45	7.50	Mudstone; lower 0.70 cm is primarily dusky yellowish green (5GY 5/2) to reddish brown (5YR 4/4); silty and calcareous to strongly calcareous, with rare (<1%) organic fragments; gley mottles are coarse, abundant, and distinct; very weakly developed pedogenic slickensides; minor gypsum as 2-4 mm interbeds;

			massively bedded; upper 0.75 cm is a grayish olive green (5GY 3/2), silty, calcareous mudstone; carbonate nodules are present as discontinuous layers and laterally pinch and swell to form beds up to 20cm thick within the mudstone; sharp basal contact and laterally continuous over the exposure. **HR-7.2, HR-7.2A**
6	0.75	8.25	Limestone; yellowish gray (5Y 8/1) to olive gray (5Y 4/1); skeletal mudstone-wackestone; four distinct beds (A, B, C, D); all beds are strongly calcareous; "A" has minor amounts of discontinuous red chert nodules and detrital quartz; no allochems were noted; "B" is characterized by only very rare chert nodules, detrital quartz, and gyrogonites; "C" is massive with ?faint laminations and contains charophytes and discontinuous red chert nodules; "D" (~30 cm) is characterized by the presence of gyrogonites and discontinuous layers of red chert nodules; contacts between beds are sharp; sharp basal contact; the unit is laterally continuous. **HR-7.5-7.65, HR-7.75, HR-7.85, HR-7.95, HR-8.2,** ***HR-7.5-7.65A, HR-7.5-7.65B, H-7.75, H-7.85, H-7.95, H-8.2***
7	0.25	8.50	Sandstone, pale greenish yellow (10Y 8/2); fine-grained, moderately sorted sublitharenites; strongly calcareous; no trace or body fossils; nodular weathering appearance, massive bed with no internal stratification; sharp basal contact, laterally continuous. **HR-8.35**
8	1.30	9.80	Mudstone, limestone and siltstone interbeds; 8.50-8.65 m - greenish gray (5GY 6/1) to pale reddish brown (10R 5/4), calcareous mudstone characterized by mottles; 8.65-8.81 m - limestone, skeletal mudstone, gradational basal contact with mudstone, laterally continuous; 8.81-9.01 m - non-calcareous siltstone (same color as first mudstone); 9.01-9.26 m - limestone, charophyte and gastropod mudstone-wackestone, two distinct beds (10 cm and 15 cm); sharp basal and upper contacts; 9.75-9.80 m - greenish gray (5GY 6/1) to pale reddish brown (10R 5/4), calcareous mudstone with mottles and discontinuous layers of carbonate nodules; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **HR-8.8, HR-9.1, HR-9.3, HR-9.5**
9	0.30	10.10	Limestone, light olive gray (5Y 6/1) to yellowish gray (5Y 8/1); skeletal wackestone; strongly calcareous; charophytes; discontinuous red chert layers and nodules; sharp basal contact; the unit is laterally continuous. **HR-10.0,** ***HR-10.0***
10	1.15	11.25	Siltstone with discontinuous interbeds of arenaceous limestone; yellowish gray (5Y 8/1) to pale reddish brown (10R 5/4); siltstone is very strongly calcareous, and mottled in portions; the limestone is an micritic mudstone, and is laterally discontinuous over 30 m; detrital quartz sand; sharp basal contact; unit as a whole is laterally continuous. **HR-10.6, HR-11,** ***HR-10.2, HR-10.5***
11	0.60	11.85	Limestone; light olive gray (5Y 6/1) to yellowish gray (5Y 8/1); micritic mudstone; calcareous with no silicification; ?oncoids; porosity infilled with spar; sharp to gradational basal contact and the unit pinches out laterally. **HR-11.25, HR-11.7,** ***HR-11.25***

12	0.35	12.20	Mudstone grading upward into limestone; the mudstone is greenish gray (5GY 6/1) and very strongly calcareous; lacks body or trace fossils; the limestone, light olive gray (5Y 6/1) to yellowish gray (5Y 8/1), is an intraclast wackestone; lower contact with mudstone is gradational and irregular with 3-4 cm of relief; the unit as a whole has a sharp basal contact and is laterally continuous. **HR-12.15, *HR-12.15***
13	0.25	12.45	Mudstone grading upward into siltstone, greenish gray (5GY 6/1); silty in parts and very strongly calcareous; no body or trace fossils; generally massive with possible ?relict beds (2 cm thick); very poorly exposed as a slope former; sharp basal contact and laterally continuous.
14	0.35	12.80	Mudstone, medium dark gray (N4) to brownish black (5YR 2/1); very strongly calcareous; no mottles or pedogenic slickensides; no body fossils; rhizoconcretions (1-2 cm in diameter; 5-8 cm in length) are common; massively bedded; sharp basal contact, laterally continuous. **HR-12.5-12.8**
15	0.20	13.00	Limestone, light olive gray (5Y 6/1) to yellowish gray (5Y 8/1); skeletal mudstone; possible ostracodes and charophytes; massive to nodularly bedded; sharp to gradational basal contact; thins laterally to the north and south, laterally discontinuous over the outcrop. **HR-12.8, HR-12.9, *HR-12.9***
16	3.30	16.30	Mudstone, greenish gray (5G 6/1) at the base to dusky red purple (5RP 2/2), dark gray (N3), and grayish red (5R 4/2); unit as a whole is very strongly calcareous; 13.0-13.2: greenish gray mudstone with no body or trace fossils; 13.2 -15.6: reddish mudstone with carbonate nodules (13.5-13.8 m, 14.25-14.6 m, 15.4 m), rhizoconcretions (14.75-15.2 m), and relict bedding (14.25-14.6 m); 15.6-16.0 m: minor sandstone interbed; sandstone is very fine-grained, moderately sorted quartz-rich; very strongly calcareous; hematitic in areas; pedogenically altered; very poorly exposed, laterally discontinuous to the south; 16.0-16.3 m: red mudstone with mottles, pale yellowish green (10GY 7/2), and lacking carbonate nodules or traces; pedogenic slickensides were not observed in this unit; internal subunit contacts are gradational; unit as a whole is a slope-former with a sharp basal contact and is laterally continuous. **HR-13.5-15.5, HR-15, *HR-15-1, HR-15-2/3***
17	0.10	16.40	Sandstone, yellowish gray (5Y 8/1) to dark greenish gray (5G 4/1); fine-grained, moderately sorted sublitharenite; very strongly calcareous; no body or trace fossils present; massive bed; very poorly exposed; gradational basal contact, laterally continuous. **HR-16.4**
	4.50	20.90	Mostly covered with greenish gray mudstone very poorly exposed limestone at 18.0 m. **HR-18.0**
18	0.60	21.50	Mudstone, greenish gray (5GY 6/1); very strongly calcareous and silty; no trace or body fossils; basal contact not exposed, lateral continuity unknown.

19	0.50	22.00	Sandstone, yellowish gray (5Y 8/1) to medium light gray (N6); fine-grained, moderately sorted sublitharenites; very weakly calcareous; quartzitic texture; no trace or body fossils; sharp basal contact, laterally continuous over the exposure. **HR-21.8,** ***HR-21.8***
20	0.80	22.80	Mudstone, dusky yellow green (5GY 5/2); silty and calcareous; no body or trace fossils; massive to indurated carbonate-rich intervals at 22.4 m; slight ferruginous weathering stains; generally poorly exposed, but sharp basal contact and laterally continuous. **HR-22.4,** ***HR-22.4***
21	2.00	24.80	Mudstone, pale brown (5YR 5/2) to blackish red (5R 2/2); silty and very weakly calcareous to calcareous; mottles (coarse, faint to distinct and common; green to ferruginous yellow); no trace or body fossils; very poorly exposed on slope; basal contact is mottled; laterally continuous.
22	0.15	24.95	Mudstone, greenish gray (5GY 6/1); very strongly calcareous; densely packed carbonate nodules; nodules are micritic with ~2% porosity; small fault with ~ 30 cm of offset; possible pseudoanticlines; no mottles of pedogenic slickensides; gradational basal contact, laterally discontinuous over 15 m. **HR-24.9,** ***HR-24.9-1, HR-24.9-2***
23	3.00	27.95	Mudstone, pale brown (5YR 2/2) to gray-very dusky red (10R 3/2); strongly calcareous; mottles are medium to coarse, faint, and rare; no pedogenic slickensides, traces, or body fossils noted; structureless to massive; irregular but sharp basal contact; laterally continuous.
24	0.25	28.20	Mudstone, greenish gray (5GY 6/1) and yellow to light olive gray (5Y 6/2); calcareous; no trace or body fossils; mottles are weakly developed (few, medium, faint); no pedogenic slickensides; abundant micritic carbonate nodules; massively bedded; sharp lower contact and laterally continuous. **HR-28.1**
25	2.10	30.30	Mudstone, pale brown (5YR 2/2) to brownish gray (5YR 4/1); silty and strongly calcareous; no pedogenic slickensides, traces, or body fossils; mottles (greenish gray) are rare, medium, and distinct; no carbonate nodules; sharp lower contact and laterally continuous.
26	0.50	30.80	Mudstone, dusky yellow green (5GY 5/2); silty and strongly calcareous; no trace or body fossils; massive bedding; gradational basal contact and laterally continuous.
27	2.80	33.60	Sandstone, yellowish gray (5Y 8/1) to pale brown (5YR 5/2), grading upward into siltstone and mudstone, light olive gray (5Y 5/2); the sandstone is a fine-grained, moderately sorted sublitharenite; calcareous; the sandstone has thin to medium beds; faint trough cross beds and mudstone rip-up clasts in the lower sandstone beds; the sandstone grades into a siltstone at 32.75 m and then rapidly fines into a mudstone at ~32.8 m; the mudstone is silty and calcareous to strongly calcareous; weak development of pedogenic slickensides; unit as a whole is poorly exposed; sharp basal contact and laterally discontinuous.

28	3.00	36.60	Mudstone, pale brown (5YR 5/2) to brownish gray (5YR 4/1); silty in part and strongly calcareous; no trace or body fossils; mottles are very coarse (50 mm), distinct, and few; pedogenic slickensides are present (?angular); sandstone, yellowish gray (5Y 8/1) to pale brown (5YR 5/2), is present at 33.75-33.95 m; the sandstone is fine to medium-grained, strongly calcareous, and displays a gradational upper and lower contact with the mudstone; the sandstone is burrowed (subvertical, 1 cm diameter, ~ 4 cm depth); the sandstone has a channel-like geometry and is laterally discontinuous over 5 m; the unit as a whole has a gradational basal contact and is laterally continuous.
	26.00	62.60	Covered Interval
29	0.15	62.75	Mudstone, dark greenish gray (5GY 4/1); very strongly calcareous with minor silt; no trace or body fossils; massive bed; basal contact not exposed; laterally continuous over the limited exposure.
30	0.45	63.20	Limestone with alternating mudstone interbeds, both are medium light gray (N6) and light olive gray (5Y 6/1), very strongly calcareous; the mudstone units (5-10 cm thick) lack trace or body fossils and are massively bedded; limestones are micritic mudstones; no trace or body fossils; massive beds; poorly exposed; sharp basal contact and laterally continuous over 10 m. **HR-63**
31	0.20	63.40	Limestone, yellowish gray (5Y 8/1) to medium light gray (N6); intraclast wackestone; strongly calcareous; massively bedded; gradational basal contact; laterally continuous over the exposure. **HR-63.35, *HR-63.35***
32	0.55	63.95	Mudstone and limestone, light olive gray (5Y 6/1); mudstone occurs from 63.4-63.55 m and 63.65 - ~ 63.75/63.85 m; mudstone is very strongly calcareous; no trace or body fossils; massive with sharp contacts with the limestone units; limestones are massively bedded; the lower limestone has gastropods and is laterally discontinuous; the lower contact of the upper limestone displays up to 10 cm of relief with the underlying mudstone; unit as a whole has a sharp basal contact and is laterally continuous. **HR-63.6, HR-63.9**
	1.25	65.20	Covered Interval
33	0.30	65.50	Limestone, medium light gray (N6) to yellowish gray (5Y 8/1); intraclast wackestone; calcareous; intraclasts as well as green mudstone rip-up clasts are present on the upper bedding place; large cylindrical traces that bifurcate downward and extend up to a depth of 15 cm below the upper surface of the limestone are present; these traces open to the top of the limestone and are filled with mudstone, greenish gray (5GY 5/1), similar to the overlying mudstone; the base of the limestone appears to have a laminar-like fabric; porosity is common and filled with spar or green mudstone; the upper 5-10 cm of this unit is brecciated and has sheet cracks filled with spar and vadose silt; the unit has a sharp basal contact and laterally continuous over 20 m. **HR-65.2, *HR-65.2***

34	0.65	66.15	Mudstone, dark greenish gray (5GY 5/1); clayey and non-calcareous; carbonate nodules are present at 65.6 and 66.0 m; the nodules are marly to arenaceous, and very strongly calcareous; the nodules lack allochems; the reddened interval within the mudstone is present at 65.85 m; unit is very poorly exposed; sharp basal contact and laterally continuous. **HR-65.6**
35	1.50	67.65	Limestone, medium light gray (N6) to yellowish gray (5Y 8/1); micritic mudstone to marl; very strongly calcareous; the lower limestones have burrows similar but smaller than those in Unit 33; the upper surface of the limestones at 67.65 m contains reddened mottles; the limestone is nodularly bedded with the interstices filled by green mudstone; two thin mudstone intervals (~7-10 cm thick) are also present; the mudstone is clayey, non-calcareous to very weakly calcareous, and lacks pedogenic slickensides as well as trace or body fossils; the unit as a whole has a gradational basal contact and is laterally continuous over the limited exposure. **HR-66.2, HR-66.5, HR-66.8, HR-67.1, HR-67.5, *HR-66.5, HR-67.1***
36	1.35	69.00	Mudstone, greenish gray (5GY 6/1), with carbonate interbeds, medium light gray (N6) to yellowish gray (5Y 8/1); the mudstone is very strongly calcareous and lacks trace or body fossils; the carbonate interbeds occur at 68.5 and 68.75 m and carbonate nodules occur at 68.2 m; all carbonate is primarily micritic mudstone; the lower carbonate interbed is arenaceous with mudstone rip-up clasts and the upper interbed is marly; the limestones are generally nodularly bedded with interstices filled with mudstone; the limestones also are laterally discontinuous, pinching out over 2-5 m; sharp basal and internal contacts; unit as a whole is laterally continuous over the exposure. **HR-68.2, HR--68.5, HR-68.75, *HR-68.5***
37	0.30	69.30	Limestone, yellowish gray (5Y 8/1) to dark greenish gray (5GY 4/1); micritic mudstone to intraclast wackestone; very strongly calcareous; intraclasts with minor porosity; sharp basal contact and laterally continuous over the exposure. **HR-69-69.3A, HR-69-69.3B, *HR-69-69.3a***
	2.50	71.80	Covered Interval
38	0.30	72.10	Limestone, medium light gray (N6) to yellowish gray (5Y 8/1); intraclast wackestone; very strongly calcareous; minor intraclasts and porosity; nodularly bedded; sharp basal contact and lateral continuous over the limited exposure.
39	0.50	72.60	Mudstone, dark greenish gray (5GY 4/1); weakly calcareous, "soft"; no trace or body fossils; massively bedded; very poorly exposed; sharp basal contact and laterally continuous over the limited exposure.
40	0.40	73.00	Limestone, medium light gray (N6) to yellowish gray (5Y 8/1), with interbedded mudstone, dark greenish gray (5GY 4/1); limestone interbeds are thin (5, 5, and 2 cm, from bottom to top); limestones are micritic mudstones and strongly calcareous; the middle limestone contains pyrite nodules (~ 1 mm in diameter) weathering to limonite; the limestones are nodularly bedded; the mudstone is strongly calcareous; lacks trace or body fossils; internal unit contacts are sharp; basal contact is sharp; lateral continuity is unknown. **HR-72.6, HR-72.8, HR-72.9**

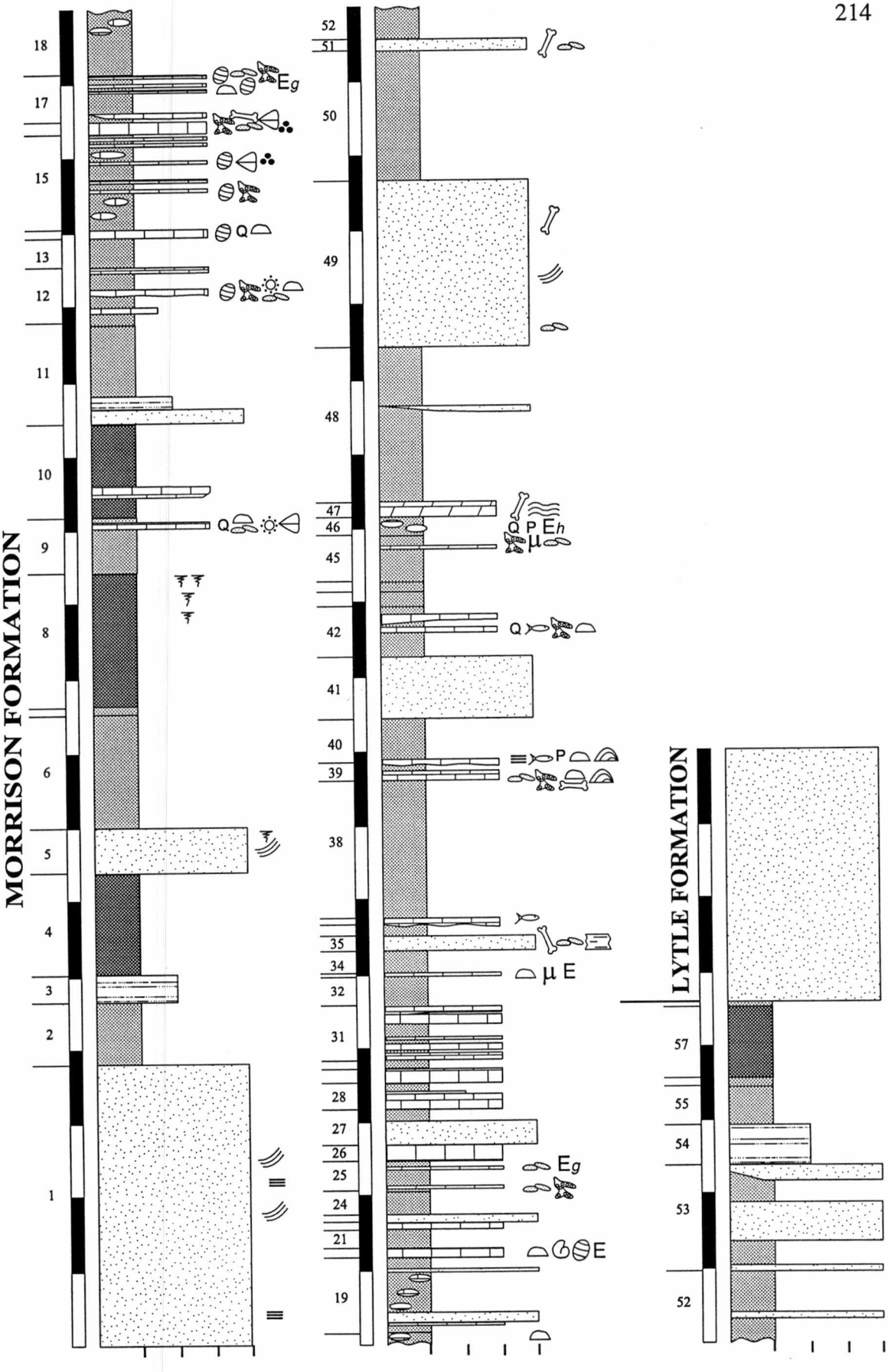
	15.60	88.60	Covered Interval
41	14.65	103.25	Mudstone, pale greenish yellow (10Y 8/2) to dark greenish gray (5GY 4/1); non-calcareous and ?tuffaceous; silty and hard/slakey; generally massively bedded with rare well-indurated beds (15-30 cm thick) weathering with positive relief; carbonized plant fragments are present at ~ 90 m and 94 m; the basal contact is not exposed; laterally continuous over the limited exposure. **HR-U41, HR-96**
42	0.50	103.75	Mudstone to claystone, grayish blue (5PB 5/2) and grayish to very dusky purple (5P 3/2); silty and non-calcareous; no trace or body fossils; no pedogenic slickensides; not "hard" as unit below; massively bedded; very poorly exposed; gradational basal contact and laterally continuous over the limited exposure.
43	0.50	104.25	Mudstone, greenish gray (5GY 6/1) to yellowish gray (5Y 8/1); silty and non-calcareous; no trace or body fossils; no pedogenic slickensides; massively bedded; sharp basal contact and laterally continuous over the limited exposure.

~~~~~ K-1 unconformity ~~~~~

LYTLE FORMATION

	3.00	3.00	Sandstone, light to moderate brown (5YR 5/4) to moderate reddish orange-brown (10R 6/6-4/6); medium-grained to conglomeratic, poorly sorted sublitharenite to quartzarenite; chert pebbles up to 3 cm (long axis); massive to thick beds; channel scours and cross-beds are present; sharp erosional basal contact and laterally continuous.
~~~~~

Figure A.5. Stratigraphic section measured at the Interstate 70 outcrop.


MORRISON FORMATION
LYTLE FORMATION
Eg
Q
Q P Eh
μ
P
μ E
Eg
E

I-70 (I70)

The I70 section is a large roadcut located on the south side of I-70, west of Denver, Colorado, near Exit 259. The section is located at a latitude of 39°42.122'N and a longitude of 105°12.196'W.

Unit	T (m)	CT (m)	Description
			Base not exposed
RALSTON CREEK FORMATION			
	10.70	10.70	Sandstone, light reddish brown (5YR 5.5/2.5) to pinkish gray (5YR 7/2); unit grades upward from sandstones to increasingly more prevalent siltstone and rare mudstone; the sandstones are very fine- to fine-grained, moderately sorted subarkoses and are calcareous; planar laminations are present in the basal beds and with cross-beds becoming more abundant upward; scour-and-fill channel forms; mudstone rip-up clasts are common; medium to thick beds; bedding plane contacts are typically sharp; laterally continuous over the exposure.
	0.40	11.10	Siltstone, grayish red (5Y 4/2); calcareous; no trace or body fossils; minor reddening and possible mottles; thin beds; sharp basal contact; unit grades laterally into a very fine-grained grayish sandstone.
			~~ J-5 unconformity ~~~~~
MORRISON FORMATION			
1	9.50	9.50	Sandstone, grayish orange (10YR 7/4); very fine- to medium-grained, poorly- to moderately-sorted, subarkose to sublitharenite; calcareous; bone clasts are present near the conglomeratic basal portions; the sandstones contain planar laminations and cross-beds, mudstone rip-up clasts, and may be bioturbated; erosive scour-and-fill structures are present; bedding is thin to thick; general fining upward trend with siltstone interbeds in the uppermost 2 m; sharp basal contact and laterally continuous over the exposure.
2	2.10	11.60	Mudstone, grayish red (10R 4/2) to light olive gray (5Y 5/2) and pale olive (10Y 6/2); calcareous and silty near the base; no trace or body fossils; massively bedded; sharp basal contact and laterally continuous over the exposure.
3	1.00	12.60	Siltstone, light olive gray (5Y5/2) to yellowish gray (5Y7/2); calcareous; rare red mottled intervals; no trace or body fossils; massive bedding; grades laterally into very fine-grained sandstone; sharp basal contact; laterally continuous over the exposure.
4	3.40	16.00	Mudstone, upper portion is grayish red (10R 4/2) to very dusky red (10R 2/2) and lower part is dusky to grayish yellowish green (5GY 6/2) to dusky yellowish green (5GY 5/2); very silty near base; calcareous; no trace or body fossils; fissile near the base; gypsum stringers at 15.5 m; red-green mottles and sandstone nodules (pedogenic regolith?) in upper 25 cm; massively bedded; gradational basal contact and laterally continuous over the exposure.
5	1.50	17.50	Sandstone, yellowish gray (5Y 7/2) to dusky yellow (5Y 6/4); very fine- to medium-grained, poorly- to moderately-sorted sublitharenite to subarkose; very weakly calcareous; rare small (<2 mm) bone fragments and mudstone rip-up clasts in basal 30 cm; upper 50 cm is cross-bedded and red mottling is present

			in mid-portion; irregular thickness; sharp, scoured and erosive basal contact and laterally continuous over the exposure.
6	3.80	21.30	Mudstone, dusky red (10R 3/4); calcareous and very silty in the basal portions; no trace or body fossils; massive bedding; slope-former; sharp basal contact; laterally continuous over the exposure.
7	0.30	21.60	Mudstone, dark gray (2.5Y 4/1.5) to dark grayish brown (2.5Y 4/2); non- to very weakly calcareous and silty; red mottles are few, medium, and faint to distinct; the gradational basal contact is mottled and laterally continuous over the exposure.
8	4.50	26.10	Mudstone, reddish brown (5YR 4/3) to dark reddish brown (2.5YR 3/3); very weakly to strongly calcareous; discontinuous siltstone interbeds present at 22.25 and 23.30 m; no trace or body fossils; mottling is present within the siltstones and along the upper contact; mottles are rare-few, coarse, and distinct; horizontal calcite veins are present; massive to thin beds; sharp basal contact and laterally continuous over the exposure.
9	1.85	27.95	Mudstone, greenish gray (5GY 6/1); discontinuous limestone interbeds are present; the mudstone is silty, calcareous, and lacks trace or body fossils; the limestone is a marly micritic mudstone with nodular to irregular bedding; the unit as a whole has a gradational basal contact and is laterally continuous over the exposure. **I70-27.6, I70-27.9, *I70-27.6***
10	3.15	31.10	Mudstone, dusky red (10R 3/2) to reddish gray (10R 5/1); calcareous with minor silt; no trace or body fossils; a discontinuous limestone (40 cm thick) interbed is present at 28.6 m; the limestone is a micritic to intraclastic mudstone and is calcareous and arenaceous; mudstone rip-ups clasts are present; a weak ledge-former; the limestone-mudstone contacts are gradational; the unit as a whole has a gradational basal contact and is laterally continuous over the exposure. **I70-28.6**
11	3.35	34.45	Mudstone, pale yellow (5Y 8/3) to olive (5Y 5/4), siltstone, reddish gray (2.5YR 6/1) to dark reddish brown (5YR 3/2), and sandstone, light greenish gray (5GY 7/1) to greenish gray (5GY 5/1); the mudstone is calcareous and silty, and contains rare carbonate nodules; the sandstone is a very fine-grained, moderately sorted sublitharenite that grades upward into siltstone; the mudstone has a brecciated appearance; coarse crystalline carbonate veins cross-cut the mudstone at approximately 32.25 m; bedding is massive to thin; sharp basal contact and laterally continuous over the exposure.
12	1.90	36.35	Mudstone, greenish gray (5GY 5/1), with numerous limestone interbeds, light gray (5Y 7/1) to olive gray (5Y 5/2); the mudstone is calcareous and massively bedded, and lacks trace or body fossils; the limestones are calcareous and marly to arenaceous micritic mudstones (8-25 cm thick); the limestones are nodularly bedded and laterally discontinuous over several meters, commonly pinching and swelling; the limestones have irregular, gradational lower contacts and generally sharp upper contacts with the mudstone; this unit is capped by a 25 cm micritic mudstone containing vertical spar-filled fractures;

			the unit as a whole has a gradational basal contact and is laterally continuous over the exposure. **I70-35.2, I70-36.3, *I70-36.3***
13	1.00	37.35	Siltstone to mudstone, light brown (7.5YR 6/4) to brown (7.5YR 4/4) and pale yellow (5Y 8/3) to yellow (5Y 8/6); calcareous; weathers with a distinctive "felted" texture and "cross-beds"; fines upward; massive thick bed; gradational to sharp basal contact and laterally continuous over the exposure.
14	0.25	37.60	Limestone, pale olive (5Y 6/3); marly micritic mudstone; calcareous; no body or trace fossils; nodularly bedded; unit thins to 20 cm laterally; gradational basal contact and laterally continuous over the exposure. **I70-37.5, *I70-37.5***
15	3.20	40.80	Mudstone, yellowish gray (5Y 7/2) to dusky yellow (5Y 6/4), with numerous limestone interbeds, greenish gray (5GY 6/1) to pale olive (10Y 6/2); the mudstone is silty, calcareous, and massively bedded; the mudstone lacks trace or body fossils; the limestones are marly micritic mudstones with rare trace fossils (described in Unit 26) with nodular beds; the limestones are laterally discontinuous over several meters to continuous over the exposure and at least 10 limestone horizons are present (5-30 cm thick); the limestone contacts are generally gradational along the base and become sharper upward; the unit as a whole has a sharp and irregular basal contact, and is laterally continuous over the exposure. **I70-38.3, I70-38.9, I70-39.8, I70-40.4, *I70-38.9, I70-39.8, I70-40.4***
16	0.40	41.20	Limestone, light yellowish brown (2.5YR 6/3) to medium light gray (N6); calcareous; micritic mudstone; possible skeletal allochems; abundant fenestral and fracture porosity filled with calcite; massive medium bed; sharp basal contact; laterally continuous over the exposure. **I70-40.9, I70-41.2, *I70-40.9, I70-41.2***
17	1.60	42.80	Mudstone, greenish gray (10Y 6/1), with siltstone, very pale brown (10YR 7/3) and light yellowish brown (2.5Y 6/4), and limestone interbeds, light gray (2.5Y 7/2) to olive (5Y 5/3); the mudstone is non-calcareous, silty, and massively bedded with no trace or body fossils; the siltstone is calcareous with no trace or body fossils and occurs as discontinuous lenses or small channel forms; the limestones range from 4-20 cm in thickness and are mostly marly micritic mudstones; the limestones occur at 4 horizons and are nodularly to massively bedded; contacts between the interbeds are generally sharp; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **I70-42.2, I70-42.5, I70-42.7, *I70-42.2, I70-42.7***
18	2.60	45.40	Mudstone, greenish gray (5GY 5/1), with minor limestone interbeds/nodules, light gray (2.5Y 7/2) to olive (5Y 5/3); the mudstone is calcareous, ranges from silty near the base to claystone and is massively bedded; limestone nodule zones or interbeds (at 44.3 and 44.5-44.70 m) are <20 cm thick and laterally discontinuous; the limestones are marly micritic mudstones; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **I70-44.3**

19	2.55	47.95	Mudstone, dark greenish gray (5GY 4/1) to greenish gray, 10Y 5.5/1), with sandstone interbeds, yellowish red (5YR 5/8) to light gray (N7.5); the mudstone is very weakly calcareous to calcareous, silty, and massively bedded; carbonate nodules and "coalesced" nodule zones are present at 45.4-45.6, 46.25-46.5, 47.1-47.35 m; the carbonate nodules are typically <8 cm; sandstone interbeds occur at 45.7-46.1 and 47.75-47.95 m; the lower sandstone interval is very calcareous and laterally grades into an arenaceous limestone; this interval is massively bedded; the upper sandstone interval consists of thin beds to laterally discontinuous lenses of sandstone; the unit as a whole has a gradational basal contact and is laterally continuous over the exposure. **I70-45.7, I70-46.25-5** (nodules), **I70-47.4,** ***I70-45.7***
20	0.30	48.25	Limestone, pale olive (5Y 6/3) to light gray (5Y 7/2); micritic mudstone; marly and calcareous; fenestral porosity filled with limonitic cement; massively bedded; sharp basal contact and laterally continuous over the exposure. **I70-48.0, I70-48.2,** ***I70-48.0***
21	0.65	48.90	Mudstone, greenish gray (5GY 6/1); calcareous and silty; gastropods; no trace fossils; rare (<2 cm) carbonate nodules; sharp basal contact and laterally continuous over the exposure.
22	0.20	49.10	Limestone, olive gray (5Y 5/2) to light gray (N7); calcareous; micritic mudstone; limonitic cement in fenestral porosity; fracture porosity filled with spar; minor (3-4 cm), discontinuous mudstone lens in the middle of the limestone; nodular to massive beds; gradational basal contact over 3-4 cm; laterally continuous over the exposure.
23	0.30	49.40	Sandstone, very pale brown (10YR 8/3); fine- to coarse-grained, very poorly-sorted sublitharenite; calcareous; limestone and mudstone rip-up clasts (1-3 cm); minor cross-beds; unit grades laterally into a very calcareous sandstone lacking cross-beds; wood fragments (up to 3 cm long axis) present; massive medium bed; sharp basal contact and laterally continuous over the exposure. **I70-49.25**
24	0.75	50.15	Mudstone, greenish gray (10Y 5/1) to dark greenish gray (10Y 4.5/1); non-calcareous and silty along base; no trace or body fossils; massive bedding; gradational basal contact and laterally continuous over the exposure.
25	1.05	51.20	Mudstone, greenish gray (10Y 5/1), with two distinct limestone interbeds, pale olive (5Y 6/3) to white (N8); the mudstone is silty and calcareous, and lacks trace and body fossils; the mudstone has rare carbonate nodules near the basal portion of the upper limestone and the mudstone is massively bedded; the limestones are marly to arenaceous, micritic mudstones (45 and ~20 cm thick); no trace or body fossils; the limestones are highly weathered with a brecciated appearance; the limestones are nodularly to irregularly bedded; mudstone to limestone contacts are gradational; the unit as a whole has a sharp basal contact; laterally continuous over the exposure. **I70-50.3, I70-51.0,** ***I70-50.3***

26	0.55	51.75	Limestone, pale olive (5Y 6/3) to white (N8); calcareous; micritic mudstone; root traces or burrows (7-10 cm in length) are present and are filled with green mudstone; sheet/horizontal desiccation cracks; vertical fractures and moldic porosity filled with calcite cement is common; massive thick bedding; irregular but sharp basal contact and laterally continuous over the exposure. **I70-51.5, I70-51.7,** ***I70-51.7***
27	1.20	52.95	Sandstone, yellowish gray (5Y 8/1); grades upward into mudstone, dusky yellowish green (5GY 5/2); the sandstone is fine-grained, moderately-sorted, sublitharenite; the sandstone is calcareous, highly weathered, friable, and lacks trace or body fossils; possibly ?gypsiferous; unit grades up into a silty and non-calcareous mudstone (~ 50 cm) lacking trace or body fossils; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **I70-U27**
28	0.85	53.80	Limestone, pale olive (5Y 6/3) to white (N8), and siltstone to mudstone, light olive gray (5Y 6/1) to moderate red (5R 5/4); the limestone is a micritic mudstone and is calcareous with abundant fenestral, fracture, and moldic porosity; the limestone has irregular lower and upper surfaces with up to 5-10 cm of relief; the limestone is overlain by a 10 cm thick siltstone layer that grades rapidly upward into a silty and calcareous mudstone; no trace or body fossils were noted in the mudstone and siltstone; carbonate nodules and purple mottling is rare in the mudstone; internal contacts are sharp; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **I70-53-53.15**
29	0.50	54.30	Limestone, pale olive (5Y 6/3) to light gray (5Y 7/2); calcareous; micritic mudstone; no body fossils; burrows or root traces? (7-10 cm in length) filled with green mudstone (similar to traces in unit 26 and at section H, unit 42); abundant fenestral and fracture porosity infilled with limonitic to ?altered sparry cement; massive bedding; minor ledge-former; sharp irregular contact and laterally continuous over the exposure. **I70-53.9, I70-54.2**
30	0.30	54.60	Mudstone, dark greenish gray (10Y 4/1); non-calcareous and very minor silt; no trace or body fossils; massive bedding; sharp basal contact and laterally continuous over the exposure.
31	1.80	56.40	Limestone, pale olive (5Y 6/3) to light gray (5Y 7/2), with mudstone interbeds, greenish gray (5GY 6/1) to moderate red (5R 5/4); the mudstone is the minor component and is calcareous, massively bedded, and exhibits soft-sediment deformation around the limestone beds; the mudstone lacked trace or body fossils but red mottling is present above limestone "C"; there are five limestone beds (A, B, C, D, and E); all are micritic mudstones and calcareous; "A" is 25 cm thick with flaggy bedding; "B" is 25 cm thick with minor vertical fractures; "C" is 10 cm thick with porosity filled with ?limonitic cement and is laterally discontinuous; "D" is 30 cm thick with possible gastropods; "E" is 30 cm thick with vertical fractures; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **I70-54.7, I70-55, I70-55.7, I70-56, I70-56.3,** ***I70-55.3, I70-56.3***

32	1.05	57.45	Mudstone, greenish gray (10Y 5/1); non-calcareous to very weakly calcareous; no trace or body fossils; weak red (10R 4/2) to dusky red (10R 3/2) mottles are few, medium, and distinct; massive bedding; sharp basal contact; laterally continuous over the exposure.
33	0.10	57.55	Limestone, moderate greenish yellow (10Y 7/4) to pale olive (10Y 6/2); micritic mudstone; calcareous; no trace or body fossils; nodular bedding; sharp basal contact and laterally continuous over the exposure. **I70-57.5,** ***I70-57.5***
34	0.75	58.30	Mudstone, greenish gray (10Y 5/1); non-calcareous to very weakly calcareous; no trace or body fossils; weak red (10R 4/2) to dusky red (10R 3/2) mottles are common, medium, and distinct; carbonate and mudstone rip-up clasts; minor black chert; unit appears to coarsen upward; bedding is massive and thick; sharp basal contact and laterally continuous over the exposure.
35	0.30	58.60	Sandstone, dusky yellow (5Y 6/4) to moderate greenish yellow (10Y 7/4); fine- to medium-grained, moderately sorted sublitharenite; calcareous; no trace or body fossils; no stratification; very thin to thin beds; very poorly exposed; sharp basal contact and laterally continuous over the exposure. **I70-58.5,** ***I70-58.5***
36	0.60	59.20	Mudstone, greenish gray (5GY 6/1); calcareous; no trace or body fossils; massive, structureless, thick bed; thickness varies from 50-60 cm; sharp basal contact; laterally continuous over the exposure.
37	0.20	59.40	Limestone, medium light gray (N6) to pale olive (10Y 6/2); non-calcareous to very weakly calcareous (?dolomitic); no trace or body fossils; abundant fenestral porosity; very nodularly bedded; unit thickens to 30 cm; sharp basal contact; laterally continuous over the exposure. **I70-59.3,** ***I70-59.3***
38	4.65	64.05	Mudstone, greenish gray (5GY 6/1); weakly calcareous; "hard" with brecciated appearance; no trace or body fossils; mottles present from ~61-62.25 m; thin to massive thick beds; sharp basal contact and laterally continuous over the exposure.
39	0.70	64.75	Limestone, pale olive (10Y 6/2), with minor mudstone interbed; the mudstone interval is present from 64.3-64.5 m; the mudstone is calcareous and has gradational upper and lower contacts with the limestone beds; pyrite nodules are present within the mudstone; the two limestones beds are both 25 cm thick; the lower bed is a skeletal mudstone-wackestone and contains bone fragments; the upper bed is a skeletal wackestone; conchostracans, charophytes, and ostracodes are present as well as pyrite nodules; bedding is thin and medium (limestones) to massive (mudstone); the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **I70-64.1, I70-64.2, I70-64.25, I70-64.7,** ***I70-64.1, I70-64.2, I70-64.25, I70-64.7***
40	1.35	66.10	Mudstone, greenish gray (5GY 6/1); non-calcareous; no trace or body fossils; Fe-stain "spots" in lower 30 cm; thin beds; massively bedded; sharp basal

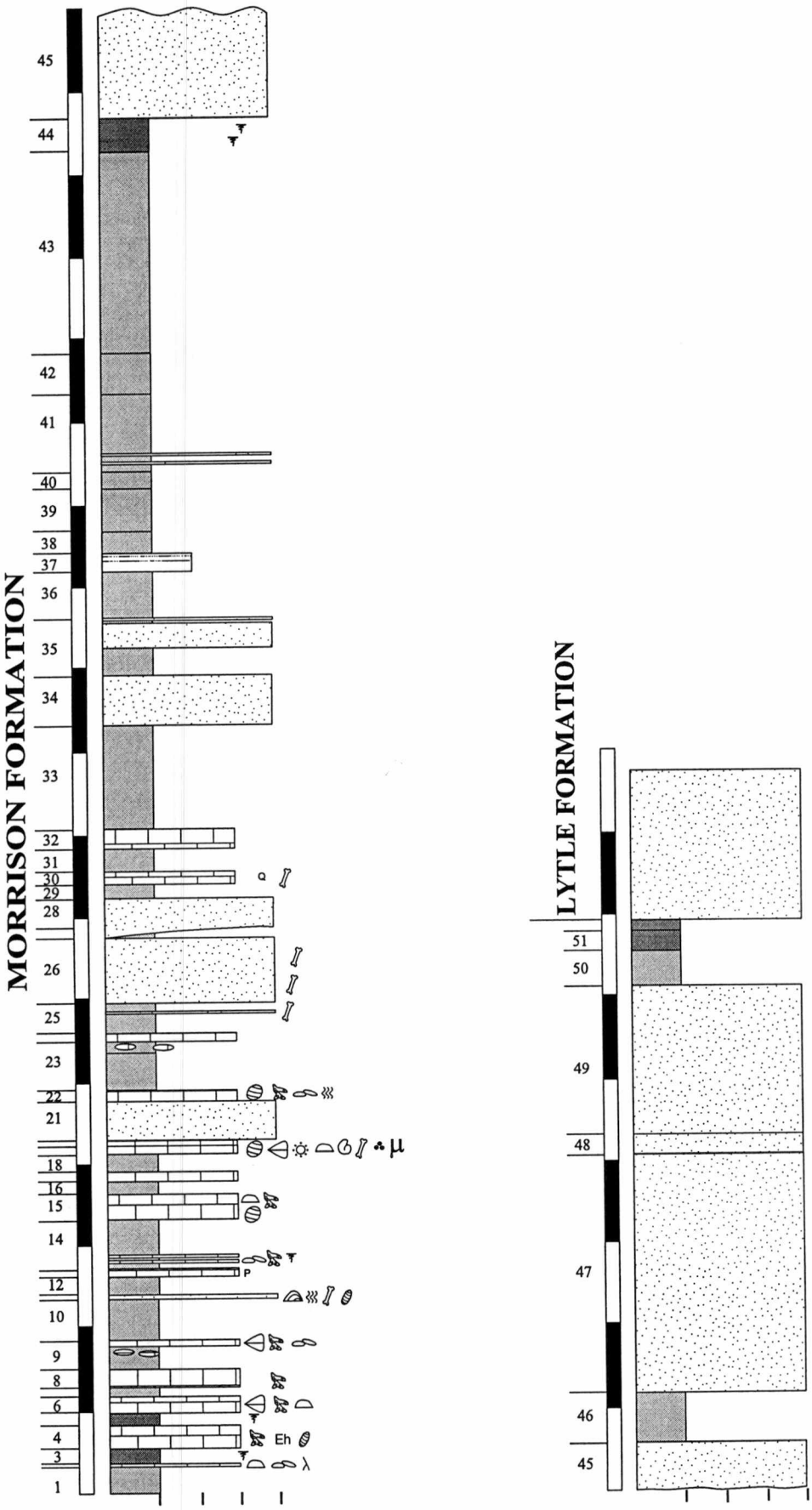
contact and laterally continuous over the exposure.

41	2.10	68.20	Sandstone, light gray/white (5Y 7.5/1); fine- to medium-grained, moderately-sorted sublitharenite; non-calcareous to very weakly calcareous and possibly ?gypsiferous; three distinct beds are present (A, B, C); "A" is 70 cm thick and consists of thin interbeds of sandstone, siltstone, and mudstone; "B" is characterized by lateral accretion sets , is heavily bioturbated, and scours down into "A"; "C" is characterized by cross-beds and capped by a reverse fault (corrected for minor displacement); beds are generally thick; the unit as a whole has a gradational contact and is laterally continuous over the exposure.
42	1.70	69.90	Limestone, light olive gray (5Y 6/2) to yellowish gray/white (5Y 8/1), and mudstone, greenish gray (5GY 6/1) interbeds; the two limestone interbeds are 20 and 30 cm thick; the limestones are micritic mudstones to intraclast wackestones and calcareous; the lower limestone is arenaceous and contains meniscate burrows (1 cm diameter; 2 cm length); fenestral porosity is common; the three mudstone interbeds are 80, 20, and ~25 cm thick; the mudstones are non-calcareous and silty; the lowermost mudstone is well-indurated and the upper mudstone contains faint mottles; no trace or body fossils were noted in the mudstones; the mudstones are characterized by massive medium to thick beds; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **I70-69.2,** ***I70-69.2***
43	0.50	70.40	Limestone, light greenish gray (5G 8/1) to greenish gray (10GY 6/1); micritic mudstone; very weakly calcareous to dolomitic; no trace or body fossils; pyrite nodules (1-2 cm); tuffaceous; minor porosity; unit coarsens upward; massive medium bed; ledge-former; thickness varies laterally with unit up to 90 cm; irregular but sharp basal contact and laterally continuous over the exposure.
44	0.30	70.70	Welded tuff with mudstone interbeds, light greenish gray (5G 8/1) to greenish gray (10GY 6/1); non-calcareous; no trace or body fossils; thinly bedded; very poorly exposed; sharp basal contact and laterally continuous over the exposure.
45	1.55	72.25	Mudstone, greenish gray (5GY 6/1); silty and non-calcareous; no trace or body fossils; massive thick beds; thin (~5 cm thick), discontinuous dolostone lenses present at 71.8 m; the unit as a whole has a gradational basal contact and is laterally continuous over the exposure. **I70-71.8,** ***I70-71.8***
46	0.65	72.90	Mudstone, greenish gray (5GY 6/1) to moderate red (5R 4/6); non-calcareous and silty to tuffaceous; no trace or body fossils; massive beds; discontinuous dolostone lenses (~5 cm thick) are present at 72.3, 72.7, and 72.8 m and are marly to arenaceous; the unit as a whole has a gradational basal contact and is laterally continuous over the exposure. **I70-72.8,** ***I70-72.8***
47	0.50	73.40	Dolostone, grayish orange (10YR 7/4) to very light gray (N8); intraclast wackestone; very weakly calcareous; tuffaceous; mudstone rip-up clasts are present in the lower 30 cm; wavy to distorted laminations (?calcrete); pyrite nodules are common in the upper 15 cm; minor spar-filled porosity; massive medium bed; ledge-former prior to the major sandstone unit; gradational basal

			contact over 10 cm; the unit is laterally continuous over the exposure. **I70-73.1, I70-73.4, *I70-73.3***
48	5.20	78.60	Mudstone, olive gray (5Y 5/1); non-calcareous to very weakly calcareous; no trace or body fossils; massive to structureless bedding; small (10 cm thick), a laterally discontinuous sandstone lens is present at 76.25 m; the sandstone is a very fine- to fine-grained, moderately-sorted quartzarenite with sharp upper and lower contacts; mottling is present in the upper 50-60 cm of the mudstone and is faint, few, and medium to coarse; the unit as a whole has a gradational basal contact; laterally continuous over the exposure. **I70-78.3, *I70-78.3***
49	5.57	84.17	Sandstone, pale yellow (2.5Y 8/2) to reddish brown (2.5YR 5/4); fine- to coarse-grained, poorly- to moderately-sorted subarkose to sublitharenite; non-calcareous; bone fragments are present at 81.5 m and mudstone rip-up clasts occur at the base of the unit and along the base of channel forms; scour-and-fill channel forms present with trough cross-beds; dinoturbation within the upper sandstone beds at ~ 84.0 m; bedding is thin to thick; two minor mudstone interbeds, gray (5Y 5/1) to olive gray (5Y 5/2), are present in the upper 1.2 m; the mudstone is non-calcareous, massively bedded, and very poorly exposed; the unit as a whole is a major ledge former; sharp basal contact and laterally continuous over the exposure.
50	4.33	88.50	Mudstone, greenish gray (10GY 5/1); non-calcareous, "hard", and slakey; no trace or body fossils; discontinuous reddened intervals are weak red (10R 4/2) to reddish black (10R 2.5/1) and present in the upper 30 cm; the red mudstones contain abundant pedogenic slickensides; a discontinuous sandstone interbed is present at 85.0 m; the sandstone is fine-grained with minor chert and mudstone rip-up clasts; very weakly calcareous; pyrite nodules are present at the base of the sandstone; the unit has massive to medium beds; sharp basal contact and laterally continuous over the exposure.
51	0.40	88.90	Sandstone, moderate yellowish brown (10YR 5/4) to pale red (10R 6/2); fine- to very coarse-grained, very poorly sorted sublitharenite; calcareous; mudstone rip-up clasts and large bone fragments (15 x 8 cm) are common; sharp irregular basal contact; laterally discontinuous to the north over 3 m but the unit thickens to >4 m to the south with a distinct channel geometry.
52	3.50	92.40	Mudstone, dark greenish gray (10GY 3.5/1) to dark olive gray (5Y 3/2), with minor sandstone interbeds, moderate yellowish brown (10YR 5/4); the mudstone is very weakly calcareous with massive beds and lacks trace or body fossils; the sandstone interbeds are medium- to coarse-grained, very poorly- to moderately-sorted subarkoses to sublitharenites; the sandstones are very weakly calcareous and consist of thin to medium beds; the sandstones are very poorly exposed; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
53	3.60	96.00	Mudstone, dark greenish gray (5GY 4/1), interbedded with sandstone, light brown (5YR 5/6) to moderate reddish orange (10R 6/6); the mudstone (2 main beds) is non-calcareous and "hard", and lacks trace or body fossils; the mudstone consists of massive thick beds; the sandstone (3 main beds) are very fine- to coarse-grained, very poorly- to moderately-sorted graywackes to

			sublitharenites, non-calcareous to very weakly calcareous, and argillaceous; tubular to nodular structures are present in the middle sandstone (6 cm diameter x 7 cm depth); ?pedogenic slickensides along the basal part of the middle sandstone as well as Fe-O/pyrite nodules (2-4 cm); chert; sandstone beds are medium to thick; sharp basal contact and laterally continuous over the exposure.
54	1.30	97.30	Siltstone, light greenish gray (10Y 7/1) to greenish gray (10Y 5/1); non-calcareous; no trace or body fossils; highly variegated; unit coarsens upward to a very fine sandstone; massive bedding; gradational basal contact and laterally continuous over the exposure.
55	1.30	98.60	Mudstone, dark greenish gray (5GY 4/1) and weak red (10R 4/3); silty and non-calcareous; no trace or body fossils; highly variegated; massively bedded; gradational basal contact and laterally continuous over the exposure.
56	0.30	98.90	Mudstone, dark greenish gray (5GY 4/1); silty and non-calcareous; no trace or body fossils; massively bedded; gradational basal contact and laterally continuous over the exposure.
57	2.40	101.30	Mudstone, weak red (10R 4/3) to dusky red (10R 2/4); silty and non-calcareous; no trace or body fossils; mottles are few, faint to distinct, and medium to coarse; very weak developed of pedogenic slickensides; massively bedded; gradational basal contact and laterally continuous over the exposure.
58	0.20	101.50	Mudstone, greenish gray (10GY 5/1) to dark gray (5Y 4/1) in the upper portion; silt to rare detrital sand-size grains; non-calcareous; no trace or body fossils; massively bedded; gradational basal contact and laterally continuous over the exposure.
			~~ K-1 unconformity ~~~~~
LYTLE FORMATION			
	3.00	3.00	Sandstone, very pale brown (10YR 8/4) to pale yellow (2.5Y 8/2) and pink (5YR 7/4); very fine- to medium-grained, moderately- to well-sorted quartzarenite to sublitharenite; non-calcareous; mudstone rip-up clasts at the base; planar-tabular cross-beds to planar laminations; wispy subhorizontal veins also near the base; bedding is massive to medium and thick; sharp erosive basal contact and laterally continuous over the exposure.

Figure A.6. Stratigraphic section measured at the West Alameda Parkway outcrop.


MORRISON FORMATION
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West Alameda Parkway (WAP)

The WAP roadcut is the type section for the Morrison Formation as described by Waldschimdt and LeRoy (1944). This section is located within Dinosaur Ridge National Historic Landmark, approximately 2.5 km north of Morrison, Colorado, at a latitude of 39°40.625'N and a longitude of 105°11.813'W.

Unit	T (m)	CT (m)	Description
			Basal portion covered by colluvium.
MORRISON FORMATION			
1	0.80	0.80	Mudstone, light olive gray (5Y 6/1); calcareous; no trace or body fossils; massively bedded; very poorly exposed; basal contact not exposed and lateral continuity limited due to exposure.
2	0.07	0.87	Limestone, yellowish gray (5Y 8/1) to light gray (N7); skeletal mudstone; gyrogonites and other skeletal allochems; strongly calcareous; nodularly bedded; very poorly exposed; sharp basal contact and laterally continuous over the limited exposure. **WAP-0.8-0.87, *WAP-0.8-0.87***
3	0.48	1.35	Mudstone, pale olive (10Y 6/2) to pale red (10R 6/2); very weakly calcareous; no trace or body fossils; red mottles are fine, faint, and few to common; massively bedded; sharp basal contact; laterally continuous over the exposure.
4	0.70	2.05	Limestone, yellowish gray (5Y 8/1) to light gray (N7); argillaceous, micritic mudstone; lower 30 cm contains abundant greenish gray mudstone; unit as a whole is weakly calcareous to calcareous; no trace or body fossils; fractures are filled with green mudstone and coarse calcite spar; nodular to very poorly, organized medium beds; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **WAP-1.4, WAP-1.85, *WAP-1.4, WAP-1.85***
5	0.35	2.40	Mudstone, dusky yellowish green (5GY 5/2) to dusky red (5R 3/4); non-calcareous to very weakly calcareous; no trace or body fossils; red mottles in portions; sharp basal contact and laterally continuous over the exposure.
6	0.50	2.90	Limestone, light olive gray (5Y 6/1) to moderate yellowish brown (10YR 5/4); micritic mudstone; strongly calcareous; massive thick bed; sharp but irregular basal contact; unit thickness varies by 3-7 cm laterally but is continuous over the exposure. **WAP-2.4, WAP-2.8, *WAP-2.4, WAP-2.8***
7	0.30	3.20	Mudstone, greenish gray (5GY 6/1); very weakly calcareous; no trace or body fossils; massively bedded; slope-former; sharp basal contact and laterally continuous over the exposure.
8	0.55	3.75	Limestone, light olive gray (5Y 6/1) to moderate yellowish brown (10YR 5/4); micritic mudstone; very strongly calcareous; weathering into "nodules" between fractures; massive to irregular nodular beds; ledge-former; sharp basal contact and laterally continuous over the exposure. **WAP-3.35, WAP-3.5, *WAP-3.35***

9	0.85	4.60	Mudstone, greenish gray (5GY 6/1), to limestone, light olive gray (5Y 6/1) to medium gray (N5); unit grades from mudstone upward into marly limestone and limestone; the unit is calcareous to strongly calcareous upward; the mudstone lacks trace or body fossils; the limestone is a marly, micritic mudstone; bedding grades upward from massively bedded mudstone and nodularly bedded limestone to a massive medium limestone bed; the unit has a sharp basal contact and is laterally continuous over the exposure. **WAP-4.25, WAP-4.6,** ***WAP-4.25***
10	1.25	5.85	Mudstone, dark greenish gray (5GY 4/1), to limestone, light olive gray (5Y 6/1) to medium gray (N5); unit is composed of 4 mudstone-limestone couplets with beds typically <10-15 cm; the mudstone is weakly calcareous to calcareous, is massively bedded and lacks trace or body fossils; the limestones are micritic mudstones to intraclast wackestones and are strongly calcareous; minor green mudstone rip-up clasts; limestone bedding is irregular to nodular due to soft sediment deformation in the mudstones; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **WAP-4.95, WAP-5.2**
11	0.15	6.00	Sandstone, dark greenish gray (5GY 4/1) to yellowish gray (5Y 7/2); grades upward from arenaceous mudstone to sandstone; the sandstone is a fine- to medium-grained, moderately- to well-sorted sublitharenite; very strongly calcareous; lined, cylindrical burrows are present (~1 cm wide and 3 cm deep); the sandstone appears well-cemented but the unit is a slope-former; bedding is massive; gradational basal contact and laterally continuous over the exposure. **WAP-5.0, UNIT 11,** ***WAP-5.0***
12	0.55	6.55	Mudstone, pale olive (10Y 6/2) to yellowish gray (5Y 7/2) upward; non-calcareous with a very minor silt content; no trace or body fossils; orange limonite weathering appearance in upper part; lower interval (pale olive) weathers with a paper-laminated appearance but is actually a massive thick bed; sharp basal contact and laterally continuous over the exposure.
13	0.25	6.80	Limestone, pale olive (10Y 6/2) to dusky yellow (5Y 6/4); micritic mudstone; strongly calcareous and argillaceous; unit appears "grainy"; nodular beds; very poorly exposed; sharp basal contact and laterally discontinuous over 10 m. **WAP-6.6,** ***WAP-6.6***
14	1.50	8.30	Mudstone, greenish gray (5GY 5/1), with thin limestone interbeds, dark yellowish orange (10YR 6/6) to light olive gray (10Y 6/1); the mudstone is non-calcareous and massively bedded, and lacks trace or body fossils; the limestones are intraclast wackestones with mottles and are laterally discontinuous; the unit is very poorly exposed on the slope; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **WAP-7.05, WAP-7.15,** ***WAP-7.05, WAP-7.15***
15	0.75	9.05	Limestone, pale to light brown (5YR 5/2-5/6) to pale yellowish brown (10YR 6/2); intraclast wackestone; peloids and intraclasts; bioturbated to disturbed fabric in upper 20 cm; fenestral, fracture, and dissolution porosity common, some infilled with karstic debris on upper surface; upper surface also

			characterized by 1-2 cm chalky weathered carbonate; moderate ledge-former; medium to thick beds; sharp basal contact; unit thins to 55 cm laterally but continuous over the exposure. **WAP-8.35, WAP-8.5, WAP-8.85, WAP-9.0, *WAP-8.35, WAP-8.85***
16	0.42	9.47	Mudstone, greenish gray (5GY 6/1) and pale to dark yellowish orange (10YR 6/6-6/8); very weakly calcareous and minor silt content; minor ?organic fragments; very poorly exposed and highly weathered; massive thick bed; laterally to the southeast carbonate nodules are present; sharp basal contact and laterally continuous over the exposure. **WAP-9.45**
17	0.28	9.75	Limestone, grayish orange (10YR 7/4) to light gray (N7); micritic mudstone to wackestone; very weakly calcareous to calcareous; green mudstone filled horizontal and vertical fractures (~1-5 mm wide) and trace fossils (burrow/root trace?); massive bed; sharp basal contact; laterally continuous over the exposure. **WAP-9.7**
18	0.55	10.30	Mudstone, dusky yellowish green (5GY 5/2); very weakly calcareous; silty; small (<0.1 mm) black grains (?organic or allochem fragments); massive thick bed; sharp basal contact and laterally continuous over the exposure.
19	0.25	10.55	Limestone, pale yellowish brown (10YR 6/2) to light olive gray (5Y 6/1); micritic mudstone; calcareous to dolomitic in part; unit capped by 2-3 cm weathered chalky layer; pyrite nodules (mm-cm scale) are present near the top; two medium beds; small ledge former; sharp basal contact and laterally continuous over the exposure. **WAP-10.3, WAP-10.45, WAP-10.5, *WAP-10.3, WAP-10.4, WAP-10.45, WAP-10.5***
20	0.15	10.70	Limestone, grayish orange (10YR 7/4), to mudstone, greenish gray (5GY 6/1); interval characterized by 2-3 cm of chalky carbonate, 3 cm of very marly, micritic limestone, and 9 cm of mudstone; the carbonate intervals are laterally discontinuous and appear to lack trace or body fossils; the mudstone is non-calcareous and lacks trace or body fossils; the unit as a whole has a gradational basal contact and is laterally continuous over the exposure. **WAP-10.6**
21	1.20	11.90	Sandstone, pale to dark yellowish orange (10YR 6/2-6/6); medium- to coarse-grained, poorly- to moderately-sorted subarkose; calcareous and very friable; no trace or body fossils; poorly bedded and a poor ledge-former; the upper and lower 50 cm are well-cemented and weather with a positive relief (30-40 cm) relative to the middle argillaceous portion; sharp basal contact and laterally continuous over the exposure. **WAP-10.95, WAP-U21**
22	0.35	12.25	Limestone, pale yellowish brown (10YR 6/2) to light olive gray (5Y 6/1); micritic mudstone; calcareous with abundant spar-filled porosity and ?burrows on the upper surface; arenaceous green mudstone in area between discontinuous limestones; small-ledge former; bedding is massive to nodular and discontinuous; sharp basal contact and laterally discontinuous to the

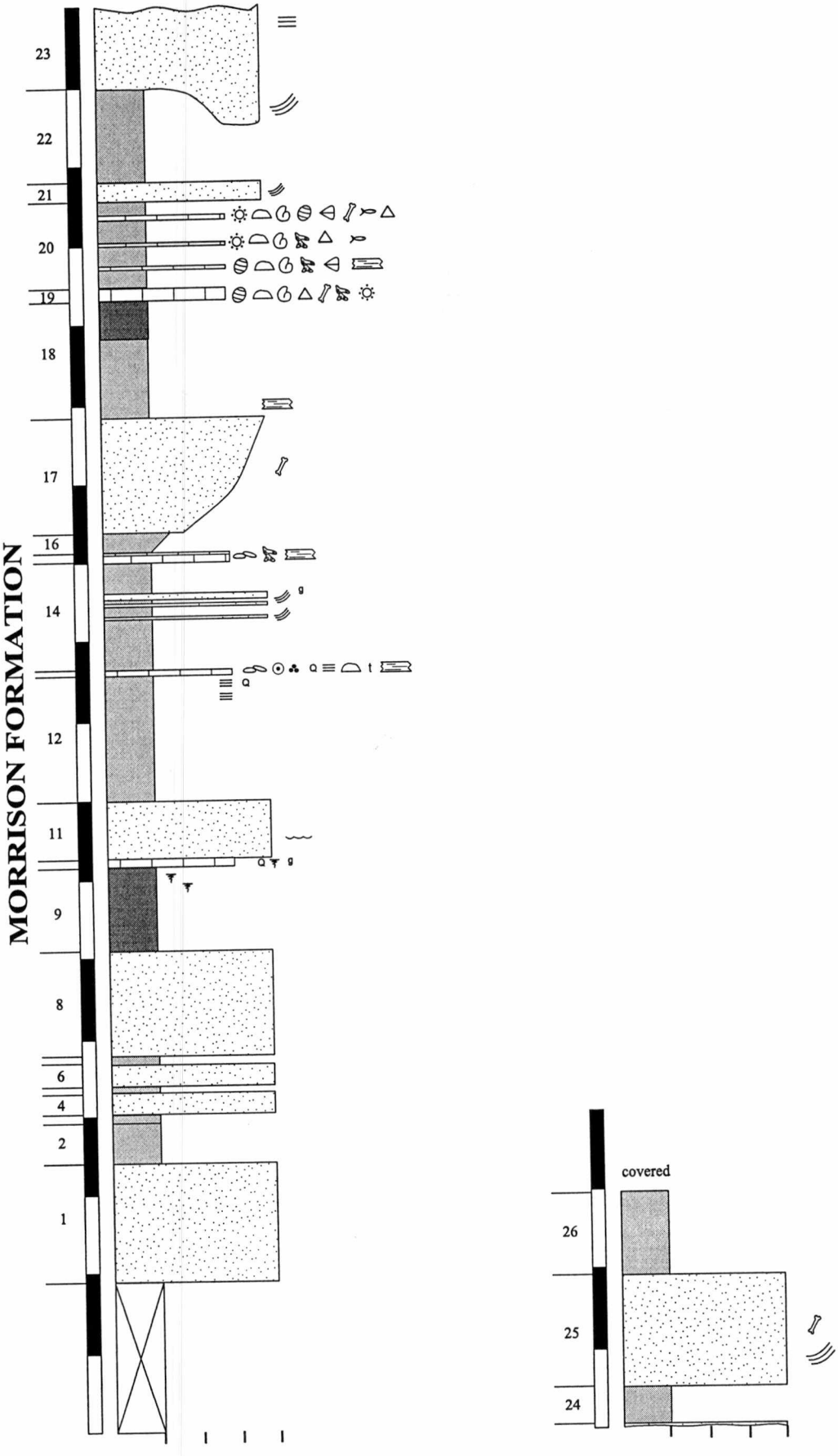
			southeast over 10 m. **WAP-11.9A, WAP-11.9B, *WAP-11.95***
23	1.15	13.40	Mudstone, greenish gray (5GY 6/1); strongly calcareous becoming very weakly calcareous upward; no trace or body fossils; sandy interbeds present along the basal 0-30 cm and middle 65-70 cm; "felted" texture associated with arenaceous intervals; sharp basal contact at first prominent limestone of Unit 24; laterally continuous over the exposure.
24	0.60	14.00	Mudstone, pale to dark yellowish orange (10YR 6/2-6/6), with limestone nodules; the mudstone is strongly calcareous and typically <7-9 cm thick between carbonate nodules; the mudstone displays soft sediment deformation around and between the carbonate nodules; the limestones are strongly calcareous, micritic mudstones consisting of nodular to irregularly bedded units (60 cm long and 30 cm wide); mudstone and carbonate nodules grade laterally into a 30-40 cm well-bedded, micritic limestone near the dinosaur quarry; sharp basal contact and laterally the unit thins toward the southeast (quarry). **WAP-13.45, WAP-13.6, WAP-13.7, WAP-13.8, *WAP-13.6, WAP-13.8***
25	0.90	14.90	Mudstone, greenish gray (5GY 6/1); non-calcareous; no trace or body fossils; two interbeds of fine-grained sandstone (4-5 cm thick) in upper 30 cm of the unit; massively bedded with a paper-laminated appearance in upper 20 cm; sharp basal contact and laterally continuous over the exposure. **WAP-14.7, *WAP-14.7***
26	2.00	16.90	Sandstone, yellowish gray (5Y 8/1) to moderate yellowish brown (10YR 5/4); medium- to coarse-grained, poorly sorted angular to subrounded sublitharenite; black and red chert clasts and mudstone rip-up clasts; very weakly calcareous; lower 1.75 m contains abundant dinosaur bones (level of the main quarry and tourist attraction); unit generally fines upward; channel scour in parts; massive thick beds; sharp erosive basal contact and laterally continuous for over 100 m.
27	0.30	17.20	Mudstone, greenish gray (5GY 6/1); minor silt and non-calcareous; no body fossils; burrows or root traces (5 mm diameter) are present; massively bedded; sharp basal contact; the unit pinches out laterally due to channel scour from the overlying Unit 28.
28	0.90	18.10	Sandstone, yellowish gray (5Y 8/1) to moderate yellowish brown (10YR 5/4); medium- to coarse-grained sublitharenite; black and red chert grains; calcareous; mudstone rip-up clasts and trough cross-beds; unit scours down into Unit 27; massive thick beds; sharp erosive basal contact and laterally continuous over the exposure (>100 m).
29	0.40	18.50	Mudstone, light olive gray (5Y 5/2); non-calcareous; no trace or body fossils; arenaceous in parts; massive bedding; sharp (but very poorly exposed) basal contact; the unit thins laterally to the northwest where it is contact with Unit 30.
30	0.40	18.90	Limestone, light olive gray (5Y 6/1); micritic mudstone; calcareous (?dolomitic in part); possible burrows; massive thick bed; sharp irregular basal contact and laterally continuous over the exposure. **WAP-18.8, *WAP-18.8***

31	0.70	19.60	Mudstone, greenish gray (5GY 6/1); non-calcareous; silty; no trace or body fossils; massive bed; sharp basal contact; laterally continuous over the exposure.
32	0.60	20.20	Limestone, dark yellowish orange (10YR 6/6) to light olive gray (5Y 6/1); three distinct beds (A-C, from bottom to top); "A" is a 15 cm thick, calcareous micritic mudstone; approximately 3-4 cm of siliciclastic greenish gray mudstone separate "A" and "B", with sharp lower and upper contacts, respectively; "B" is a 15 cm thick, calcareous micritic mudstone with numerous thin (<0.2 mm) vertical fractures; "C" is a 20-25 cm thick, non-calcareous, distinctively pale greenish yellow (10Y 8/2), arenaceous ?dolostone with conchostracans; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **WAP-19.6, WAP-19.7, WAP-20.0, WAP-CC, *WAP-19.6, WAP-19.8***
33	3.10	23.30	Mudstone, light olive gray (5Y 6/1) to greenish gray (5GY 6/1); non-calcareous; two mudstone beds; the lower 1.5 m bed is arenaceous and characterized with a "felted" texture; the bed grades upward into a 1.6 m bed that is predominately greenish gray with grayish red (10R 4/2) mottles, which are very indistinct, large, and abundant; massively bedded; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
34	1.50	24.80	Sandstone, light brown (5YR 5/6) to dark yellowish orange (10YR 6/6); fine- to medium-grained, moderately-sorted subarkose; non-calcareous; no trace or body fossils; lower 40 cm is argillaceous and the upper 110 m has white stringers (?gypsum); last prominent sandstone prior to dinoturbation in Unit 45; gradational basal contact; the unit pinches out laterally to the southeast.
35	1.75	26.55	Mudstone, greenish gray (5GY 6/1), and interbedded sandstone, light brown (5YR 5/6) to dark yellowish orange (10YR 6/6); three beds are present: 0-80 cm and 161-175 cm is mudstone; 81-160 cm is sandstone; the mudstone is non-calcareous, silty, and mottled (grayish red [10R 4/2], very indistinct, large; present only in the lower mudstone bed); the sandstone is fine-grained, moderately-sorted sublitharenite; the sandstone is also very weakly calcareous, green mudstone rip-up clasts are present, and the first 15 cm contains contorted beds (?soft-sediment deformation); massive medium to thick beds for the mudstone and very thin to thin beds in the sandstone; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
36	1.40	27.95	Mudstone, greenish gray (5GY 6/1); non-calcareous and silty; grayish red (10R 4/2) mottles are rare, large, and indistinct; no trace or body fossils; a thin (<10 cm), sandstone interbed is present and is laterally discontinuous over 1 m; the sandstone is calcareous and highly argillaceous with abundant mudstone rip-up clasts; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
37	0.60	28.55	Siltstone to mudstone, pale olive (10Y 6/2) to dark yellowish orange (10YR 6/6); non-calcareous and very silty; no trace or body fossils; small grains weathering to a limonitic product (tuffaceous microphenocrysts?); unit weathers with slight positive relief; conchoidal fracture; massive thick bed; gradational basal contact and laterally continuous over the exposure.

38	0.65	29.20	Mudstone, dark yellowish orange (10YR 6/6) to greenish gray (5GY 6/1); non-calcareous and silty; "hard"; no trace or body fossils; variegated; massive thick bed; gradational basal contact and laterally continuous over the exposure.
39	1.25	30.45	Mudstone, pale olive (10Y 6/2) to dark yellowish orange (10YR 6/6); non-calcareous and tuffaceous; microphenocrysts; no body fossils; rhizoliths vertically cross-cut most of the unit, which terminate against the upper surface of unit; brecciated weathering appearance; massive bed with slight positive relief; gradational basal contact; laterally continuous over the exposure. **WAP-29.2**
40	0.55	31.00	Mudstone, light olive gray (5Y 5/2); non-calcareous; no trace or body fossils; massive thick bed; very poorly exposed as a slope-former; sharp basal contact and laterally continuous over the exposure.
41	2.35	33.35	Mudstone, grayish brown (5YR 3/2), with two sandstone interbeds (32.45-32.63 m and 32.78-32.88 m); the mudstone is non-calcareous and silty (minor) with gley (pale olive [10Y 6/2]) mottles at 31.7 m; the mottles are few-common, medium, and distinct; no trace or body fossils; the sandstone interbeds are fine-grained and very weakly calcareous with a quartzitic texture; the sandstone interbeds appear to be laterally continuous with a 1.4 m thick sandstone channel the pinches out laterally toward the sandstone interbeds; the sandstone contacts are sharp; thin to massive thick beds; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **WAP-32.35,** ***WAP-32.45***
42	1.20	34.55	Mudstone, dark yellowish orange (10YR 6/6) to greenish gray (5GY 6/1); non-calcareous and silty; no trace or body fossils; variegated; massive thick bed; sharp basal contact and laterally continuous over the exposure.
43	6.10	40.65	Mudstone, light gray (N7) to light grayish olive (10Y 5/2) and reddish brown (10R 4/4) in the upper 1.5 m; non-calcareous to very weakly calcareous; no trace or body fossils; "hard" and silty in parts; well-indurated intervals weather with positive relief; unit as a whole alternates from slope to ledge-former depending on the degree of induration; bedding is generally massive and structureless in the lower part to poorly defined medium and thick beds in the upper part; gradational basal contact; laterally continuous over the exposure.
44	1.00	41.65	Mudstone, dusky yellowish green 5GY 5/2) to moderate brown (5YR 4/4); color varies laterally; non-calcareous and silty in parts; no trace or body fossils; horizontal mottles are common (within reddened intervals), medium to coarse and distinct; massive bedding; gradational basal contact and laterally continuous over the exposure.
45	4.80	46.45	Sandstone, pale greenish yellow (10Y 8/2) to grayish orange (10YR 7/4); fine-grained, moderately- to well-sorted, sublitharenite; non-calcareous; lower 20 cm contains abundant gleyed areas and is moderate red (5R 4/6); lower 1.0 m is well-bedded (thin to medium), whereas bedding in the upper 3.8 m is disturbed by dinoturbation (> 11 individual tracks); minor rip-up clasts at 3.8 m; medium beds dominated the upper part; major ledge former; sharp basal contact and laterally continuous over the exposure. **WAP-41.6,** ***WAP-41.7***

46	1.50	47.95	Mudstone, light gray (N7) and medium dark gray (N4) to grayish red (10R 4/2) and dark reddish brown (10R 3/4); non-calcareous; no trace or body fossils; unit contains three subunits based on color: 0-70 cm ("red"), 71-110 cm ("green"), and 111-150 cm ("red"); bedding is massive; unit thickness varies slightly laterally; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
47	7.25	55.20	Sandstone, yellowish gray (5y 8/1) to light brown (5YR 6/4) and grayish orange (10YR 7/4); fine-grained, well-sorted, subrounded sublitharenite; non-calcareous; no trace or body fossils; green mudstone rip-up clasts; faint cross-beds are present; concretions (within lower 2 m) and fractures lined with Fe oxides are common; not well-cemented/friable; unit is not a prominent ledge-former; massive thick beds with channel forms; unit has a sharp erosive basal contact; variable thickness laterally.
48	0.60	55.80	Sandstone, yellow to light olive gray (5Y 6/2) to dusky red (5R 3/4); fine-grained, poorly- to moderately-sorted sublitharenite to graywacke; non-calcareous and argillaceous; minor pedogenically-altered (rubified) regions; very poorly exposed to covered on a slope; massive thick bed; sharp basal contact and laterally continuous over the exposure.
49	4.50	60.30	Sandstone, grayish orange pink (5YR 6/2) to very pale orange (10YR 8/2); fine- to medium-grained, moderate- to well-sorted sublitharenite; non-calcareous; no trace or body fossils; faint planar-tabular and trough cross-beds become more prominent upward; upper 50 cm characterized by abundant Fe-oxides and hardpan layer; last major ledge former prior to the Lytle Formation; massive, irregular medium to thick beds; channel forms present; sharp erosive basal contact and the unit thins to <1 m laterally to the northwest.
50	1.10	61.40	Mudstone, light olive gray (5Y 6/1); non-calcareous with abundant silt; no trace or body fossils; massively bedded; poorly exposed; sharp basal contact and laterally continuous over the exposure.
51	0.60	62.00	Mudstone, dark reddish brown (10R 3/4); non-calcareous and silty; no trace or body fossils; rare, yellowish gray (5Y 7/2) mottles at the basal contact; massively bedded; sharp basal contact; laterally continuous over the exposure.
52	0.35	62.35	Mudstone, grayish red purple (5RP 4/2) to pale gray red purple (5RP 5/2); non-calcareous with minor silty content; platey structure ("E" horizon); no carbonate nodules; fragile impressions of conifer needles in the upper 5-10 cm; gradational basal contact and laterally continuous over the exposure.
			~~ K-1 unconformity ~~~~~
LYTLE FORMATION			
	5.00	5.00	Sandstone, very pale orange (10YR 8/2) to white (N9); fine- to medium-grained, moderately to well-sorted, subrounded to rounded quartzarenite; non-calcareous; cross-beds are common; minor thin lignite beds; bedding is medium to thick; massive cliff-forming unit; sharp erosive basal contact and laterally continuous over the exposure.

Figure A.7. Stratigraphic section measured at the Marsh-Felch Quarry outcrop.


MORRISON FORMATION
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24

Marsh-Felch Quarry (MFQ)

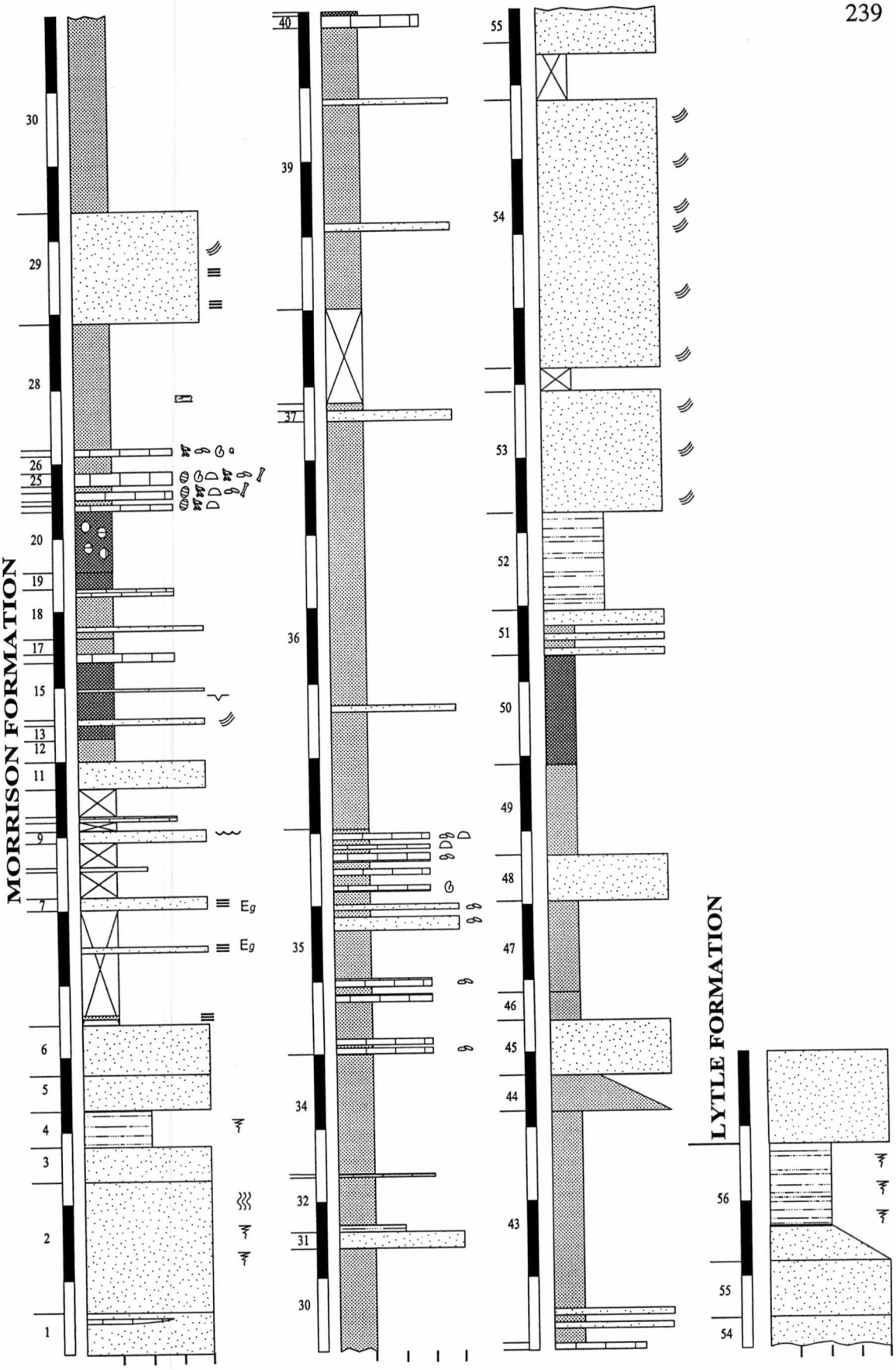
The MFQ section is located within the Garden Park Paleontological Area, approximately 14 km north of Cañon City, Colorado, west off of State Road 9. The area is managed by the Bureau of Land Management (BLM) and permission should be obtained prior to access if samples will be collected. The quarry is located at a latitude of 38°32.136'N and a longitude of 105°13.305'W but the section begins near the bridge abutment near Four Mile Creek. The lower part of MFQ section is based upon an unpublished measured section by E. Evanoff (University of Colorado, 1993). My detailed stratigraphic descriptions begin approximately 18 m above the J-5 unconformity according to Evanoff's unpublished section and my unit numbers and sample labels also reflect this.

Unit	T (m)	CT (m)	Description
			Basal portion not measured.
MORRISON FORMATION			
9	2.60	17.90	Mudstone, light greenish gray (5GY 7/1) to dark reddish brown (2.5YR 3/3); calcareous; silt content greatest near the base; no body fossils; mottles are common distinct to prominent, and medium to coarse in upper 10-20 cm; possible slickensides; thin (2-3 cm) interbeds of siltstone and sandstone; sandstone are fine-grained, moderately sorted sublitharenite; highly variegated appearance; nodular weathering appearance with best exposure near Four Mile Creek; sharp basal contact and laterally continuous over the exposure.
10	0.30	18.20	Limestone, light greenish gray (10Y 7/1) to greenish gray (5GY 6/1) and dusky red (2.5YR 3/2); no trace or body fossils; highly mottled; nodular weathering appearance; nodular to medium bed; gradational basal contact and laterally continuous over 30 m. **MFQ-18, MFQ-18.2, MFQ-18.3,** ***MFQ-18, MFQ-18.2***
11	1.80	20.00	Sandstone, moderate yellowish brown (10YR 5/4) to moderate yellow (5Y 7/6); medium- to coarse-grained, poorly-sorted, conglomeratic sublitharenite; granitic clasts are common; calcareous; no trace or body fossils; ripple marks in sandstone float material; irregular and medium beds; very poorly exposed except along cliff face; sharp basal contact; the unit pinches out laterally.
12	3.95	23.95	Mudstone, brownish black (5YR 2/1) to pale olive (5Y 6/4); smectitic, calcareous (in parts) and very silty near the base; no trace fossils; minor ?plant fragments; soft-sediment deformation of laminations or varves?; ?cross-laminations; laminated to very thinly bedded; sharp basal contact with poor exposures; laterally continuous along Four Mile Creek cliff face. **MFQ-U12,** ***MFQ-U12A, MFQ-U12B***
13	0.20	24.15	Limestone, medium gray (N5); skeletal wackestone; calcareous; ostracodes, charophytes, and intraclasts are present as well as crystallaria; alternating couplets of micrite and siliciclastic-rich intervals composed of ooids and sand-size quartz, feldspar and lithic fragments, many with crystallaria growths of calcite; micrite part of the couplets contain evaporite pseudomorphs of ?trona; the couplets are not regular planar but somewhat irregular to wavy; upper portion appears laminated; sharp basal contact; laterally continuous over 100 m. **MFQ-23.9-24.1A, MFQ-23.9-24.1B,** ***MFQ-23.9, MFQ-24.1***
14	3.40	27.55	Mudstone, pale olive (5Y6/4) to dark greenish gray (10Y 4/1); minor silt and non-calcareous to very weakly calcareous; the mudstones are massively bedded;

			three sandstone interbeds are present and are fine- to medium-grained, moderately-sorted sublitharenites; the sandstones are approximately 20 cm thick, very weakly calcareous to calcareous and commonly cross-bedded; a 5-8 cm gypsum bed is present at the base of the upper sandstone; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
15	0.30	27.85	Limestone, medium gray (N5); micritic mudstone; calcareous; no trace or body fossils; minor black grains and minor porosity; nodular to bulbous weathering appearance; slight ledge-former; massive bed; sharp basal contact and laterally continuous over the exposure for at least 40 m. **MFQ-27.5A**
16	0.65	28.50	Mudstone, dark greenish gray (5GY 4/1); high silt content at the base which decreases upward; calcareous; no trace or body fossils; massive to structureless bedding; sharp basal contact and laterally continuous over the exposure.
17	3.60	32.10	Sandstone, moderate yellowish brown (10YR 5/4) to moderate yellow (5Y 7/6); fine- to medium-grained, moderately-sorted sublitharenite; calcareous; bone fragments are present, level of *Haplocanthosaurus*/Cleveland quarry; cross-bedding is present; sharp basal contact; major ledge-former near Four Mile Creek but the unit pinches out laterally over the exposure.
18	3.70	35.80	Mudstone, greenish gray (5GY 6/1); silty and calcareous; ?plant fragments in the lower mudstone; reddened interval at 34.0 m serves as an excellent marker bed for the area; carbonate intervals are present at 35.1 m that may grade laterally into a sandstone; the mudstone is generally massive and the interbeds are thinly bedded; the unit as a whole has sharp basal contact and is laterally continuous over the exposure. **MFQ-35.1, MFQ-35.6**
19	0.40	36.20	Limestone, light brownish gray (5YR 6/1) to light olive gray (5Y 6/1); skeletal wackestone; calcareous; charophytes, gastropods, and ostracodes (commonly silicified), and large bone fragments (platy and up to 4 cm wide); medium bed; porosity filled with spar; sharp basal contact; laterally continuous over >300 m. **MFQ-35.9, MFQ-36.0B, MFQ-36, MFQ-36C, MFQ-36.1B,** ***MFQ-35.9, MFQ-36.0A, MFQ-36.1D***
20	2.70	38.90	Mudstone, grayish olive (10Y 4/2), with three distinct limestone interbeds (A, B, C); the mudstone is very weakly calcareous to calcareous and silty; massive structureless beds; mudstone-limestone contacts are all sharp; the limestone interbeds are all calcareous and very poorly exposed; "A" is a ~ 5 cm thick, intraclast wackestone with minor mudstone rip-up clasts (~ 2 cm long x 1 cm wide), horizontal and vertical burrows; this interbed thickens over 2 m to 15 cm; "B" is 6-10 cm thick, skeletal wackestone with ostracodes, charophyte "ropes" and ?bone fragments; "B" has horizontal burrows, chert replacement of some allochems, and nodular beds; "B" also thickens and thins laterally; "C" is a 5-10 cm, micritic mudstone with minor chert replacement and black allochems; "C" appears to pinch out laterally; this unit as a whole has a sharp basal contact and is laterally continuous over 100 m; best exposure near Marsh-Felch quarry and on the spur. **MFQ-36.7, MFQ-37.0A, MFQ-37.0B, MFQ-37.5A, MFQ-37.5B,** ***MFQ-36.7, MFQ-37.0A, MFQ-37.0A1, MFQ-37.0B, MFQ-37.25, MFQ-37.5a***

21	0.60	39.50	Sandstone, moderate yellowish brown (10YR 5/4) to moderate yellow (5Y 7/6); fine- to medium-grained, moderately sorted sublitharenite; strongly calcareous; cross-beds are present; sharp basal contacts; laterally discontinuous over 30 m. **MFQ-39.0,** ***MFQ-39.0***
22	3.00	42.50	Mudstone, greenish gray (5GY 6/1); strongly calcareous and silty; black plant or bone fragments (<2 mm); gypsum stringers along subhorizontal to subvertical fractures; massively bedded; sharp basal contact and laterally continuous over the exposure.
23	2.60	45.10	Sandstone, moderate yellowish brown (10YR 5/4) to moderate yellow (5Y 7/6); fine- to medium-grained, moderately sorted sublitharenite; strongly calcareous; mudstone rip-up clasts and dinosaur bones are present; lateral accretion sets and trough cross-beds are also present; large channel form; thickens to a maximum thickness of 4.5 m; sharp erosive basal contact; unit is laterally continuous over the exposure but thins to the east.
24	1.20	46.30	Mudstone, moderate greenish yellow (10Y 7/4); calcareous; no trace or body fossils; massive bedding; very poorly exposed; sharp basal contact and lateral continuous over the exposure.
25	3.50	49.80	Sandstone, moderate yellowish brown (10YR 5/4) to moderate yellow (5Y 7/6); fine- to medium-grained, moderately sorted sublitharenite; very weakly calcareous to calcareous; cross-beds; dinosaur bones; level of Felch quarry; thin to thick beds; sharp erosive basal contact and laterally continuous over 100 m.
26	2.60	52.40	Mudstone, very dark red (5R 2/6); non-calcareous and very brittle; tuffaceous; no trace or body fossils; lower contact poor exposed; laterally continuous over the exposure.
			Remaining Morrison Formation is covered.

Figure A.8. Stratigraphic section measured at the Cope's Nipple outcrop.


MORRISON FORMATION
LYTLE FORMATION
Eg
Eg

Cope's Nipple (CN and CQ)

The section at Cope's Nipple is located within the Garden Park Paleontological Area, approximately 14 km north of Cañon City, Colorado, at a latitude of 38°32.934'N and a longitude of 105°13.797'W. This is area contains numerous classic dinosaur quarries and is managed by the Bureau of Land Management (BLM) in Cañon City. The BLM monitors the area closely and permission should be granted by the BLM prior to initiation of any geological studies. Measurements for units 52-56 are based on an unpublished measured section from F. Peterson.

Unit	T (m)	CT (m)	Description
			Basal portion not measured.
WANAKAH FORMATION			
	4.60	4.60	Sandstone, pale yellowish brown (10YR 6/2) to moderate red (5R 4/6); medium- to coarse-grained, conglomeratic arkose; feldspars are up to 5 cm in length with euhedral crystal faces; very weakly calcareous to calcareous; no body fossils; minor rhizoliths; massive to medium beds display graded bedding, shallow (< 30 cm) channel forms, sharp basal contact and laterally continuous over exposure; only part of the section measured. **WF-0.9**
			~~ J-5 unconformity ~~~~~
MORRISON FORMATION			
1	1.40	1.40	Sandstone, light gray (7.5YR 7/1) to pale brown (10YR 6/3); fine- to medium-grained, subrounded, sublitharenite to subarkose; calcareous; possible dinoturbation at base; scalloped, medium to thick beds; limestone, gray (10YR 5/1) to light brown (7.5YR 6/4), present as interbed at 1.2 m; limestone is a micritic mudstone with minor detrital quartz and feldspar; the limestone bed is laterally discontinuous over ~ 50 m, very thinly bedded with sharp upper and lower contacts; the limestone is up to 12 cm thick; the sandstone unit as a whole has a very sharp basal contact and is laterally continuous. **CQ-1.2**
2	4.35	5.75	Sandstone, light olive gray (5Y 6/2) to light reddish brown (5YR 6/3); fine- to medium- and coarse-grained, subrounded to subangular, poorly to moderately sorted subarkose; apparent bimodal grain size distribution(<0.1 mm and >~ 0.5 mm); coarse detrital quartz and feldspar; strongly calcareous; medium to thick beds; slope- to poor ledge-former; unit is conglomeratic in places; low angle to planar cross-stratification in lower half of unit, with graded bedding(?); stratification is disrupted by abundant burrows (1-2 cm in diameter, 1-4 cm in length, meniscate(?)) and as well as by minor reddened mottles; mottles become more pronounced in upper 30-50 cm; mottles are dark olive brown (2.5YR 3/3) to light greenish gray (10Y 7/1), medium to coarse (0.5 to 3.0 cm in diameter), and distinct; reddening primarily in upper part of unit; gradational basal contact and laterally continuous. **CQ-1.4**
3	1.30	7.05	Sandstone, reddish brown (5YR 4/3); fine- to coarse-grained (< 6 mm), poorly to moderately sorted, sublitharenite to subarkose; lithic rock fragments are common; calcareous; no trace or body fossils; flaggy bedding grades upward into thin beds; sharp basal contact and laterally continuous.

4	1.15	8.20	Siltstone, light greenish gray (5 GY 7/1) to reddish brown (5 YR 4/3); calcareous, with a basal sandy portion; massive bed; minor carbonate nodules at 7.75 and 8.0 m; no obvious body fossils; mottles are abundant (~30%), distinct, and medium to coarse (up to 3-5 cm in diameter); gradational basal contact; laterally continuous over the exposure.
5	1.20	9.40	Sandstone, reddish brown (5 YR 4/3) to light brown (7.5YR 6/4) and gray (10YR 5/1); medium- to very coarse-grained, with angular to subangular, poorly-sorted arkose; detrital quartz, feldspar, and lithic rock fragments are easily identified; calcareous; large carbonate clasts (up to 10 cm in length) are present; clasts derived from nodular limestone (<10 cm thick) at the base; nodular limestone is medium light gray (N6), contains detrital quartz and feldspar, lacks fossil material, and is laterally discontinuous over 50 m; the sandstone has minor planar-tabular cross-beds and it is a ledge-former, the unit as a whole has a gradational to sharp basal contact and is laterally continuous. **CQ-8.2A, CQ-8.2B, CQ-8.6**
6	1.73	11.13	Sandstone, light gray (7.5YR 7/1); medium-grained, subangular to subrounded, subarkose; calcareous; no trace or body fossils; massive to medium beds; poorly exposed; sharp basal contact, laterally continuous over 100 m. **CQ-10.9**
	3.91	15.04	Covered Interval 11.25 m - Mudstone (0.10 m), grayish black (N2), with calcareous mm-scale laminae; *very* poorly exposed, laterally continuity limited due to exposure quality. 13.6 m - Sandstone with interbeds of limestone and gypsum (0.18 m); sandstone is very fine- to fine-grained, moderately-sorted, sublitharenite; calcareous with minor planar laminations; interbeds are very thin to thinly bedded; the limestone has brecciated fabric with intraclasts and minor laminations; the gypsum has planar to contorted irregular beds (4-20 mm); tee-pee structures are present on uppermost surface. **CQ-13.6**
7	0.46	15.50	Sandstone, dusky to grayish yellow (5Y 7/4); very fine- to medium-grained, moderately sorted, subarkose; very thin to thinly bedded with interbeds of gypsum (2-5 mm); planar-tabular cross-beds in upper 10 cm; very poorly exposed; basal contact not exposed, laterally discontinuous.
	0.86	16.36	Covered Interval
8	0.18	16.54	Siltstone, dark greenish gray (5GY 4/1); weakly calcareous; no body or trace fossils; very poorly exposed; basal contact not exposed, laterally discontinuous.
	0.82	17.36	Covered Interval
9	0.36	17.72	Sandstone, grayish to dusky yellow (5Y 7/4); fine- to medium-grained, subangular to subrounded, well-sorted sublitharenite to subarkose; calcareous; 3-D ripples (amplitude = 5 cm; λ = ~10 cm); basal contact not exposed; laterally continuous for at least 50 m.

	0.32	18.04	Covered Interval
10	0.14	18.18	Limestone, light bluish gray (5B 7/1); micritic mudstone, weakly calcareous, no allochems or sedimentary structures noted; very poorly exposed; basal contact not exposed; laterally discontinuous. **CQ-18.18**
	0.93	19.11	Covered Interval: gypsum float is common.
11	0.89	20.00	Sandstone, grayish to dusky yellow (5Y 7/4); fine- to medium-grained well-sorted sublitharenite to subarkose; calcareous; no trace or body fossils; thin to medium beds become more poorly exposed upward; sharp basal contact, laterally continuous; last major ledge-former prior to Unit 29.
12	0.75	20.75	Mudstone, greenish gray (10BG 5/1); calcareous; no body or trace fossils; no mottles; very poorly exposed; base not exposed; laterally continuous.
13	0.45	21.20	Mudstone, weak red (2.5YR 5/2); calcareous; no body or trace fossils; platy structure or relict bedding (~ 1 cm thick); gradational basal contact, laterally continuous.
14	0.20	21.40	Sandstone, dusky yellow (5Y 5/4); fine- to medium-grained well-sorted subarkose; calcareous; no body or trace fossils; flaggy bedding grades laterally into planar-tabular cross-beds in small channel form; unit pinches and swells; sharp lower contact, laterally discontinuous.
15	1.90	23.30	Mudstone, dark reddish brown (2.5YR 3/3) to dark greenish gray (5G 4/1); grades upward to become increasingly more calcareous and reddened; rare mudcracks in upper portion; no body or trace fossils; minor sandstone interbed from 22.3-22.35 m; sandstone is fine-grained, quartz-rich, laminated, and very poorly exposed; lower mudstone is more variegated, with a platy structure; basal contact is not exposed, unit as a whole is laterally discontinuous. **CQ-22.9, *CQ-22.9***
16	0.30	23.60	Limestone; light bluish gray (5B 7/1); micritic mudstone; no allochems, trace fossils, or detrital grains; marly to argillaceous; nodular bedding, which thins laterally to 5-6 cm; gradational basal contact, laterally discontinuous. **CQ-23.4**
17	0.50	24.10	Mudstone, dark greenish gray (5G 4/1); calcareous with a marly fabric; silty; no body or trace fossils; conchoidal fracture; very poorly exposed; gradational basal contact, laterally discontinuous. **CQ-24.1**
18	1.65	25.75	Mudstone, dark greenish gray (5G 4/1); silty and calcareous; minor carbonate nodules; thin interbeds of sandstone (5 cm) at 24.45 m and limestone (10 cm) at 25.65 m; gradational contacts between interbedded units; the sandstone is fine-grained, quartz-rich, and has a pale reddish brown (10R 5/4); the limestone is an argillaceous micritic mudstone with plant fragments(?); the unit as a whole has a gradational basal contact and is laterally discontinuous. **CQ-25.75**

19	0.55	26.30	Mudstone, weak red (2.5YR 5/2); silty and calcareous; no mottles or carbonate nodules; pedogenic slickensides are present; very thinly bedded; sharp basal contact and laterally continuous.
20	2.13	28.43	Mudstone, weak red (2.5YR 5/2) to dark greenish gray (5G 4/1); lower and uppermost portions are greenish-gray, silty, and non-calcareous, no trace or body fossils; the middle portion is a red, calcareous mudstone, with carbonate nodules and pedogenic slickensides; the unit as a whole is very poorly exposed; the gradational basal contact and laterally discontinuous.
21	0.18	28.61	Limestone; greenish gray (10Y 6/1); skeletal wackestone; charophytes, ostracodes, and gastropods; marly in portions; porosity is commonly filled with spar; basal contact is poorly exposed, laterally discontinuous. **CQ-28.6**
22	0.17	28.78	Mudstone, dark greenish gray (5G 4/1); strongly calcareous; no body or trace fossils; very thinly bedded; very poorly exposed basal contact; laterally discontinuous.
23	0.28	29.06	Limestone; greenish gray (10Y 6/1); intraclast wackestone; pink clasts (?feldspar); calcareous; minor fenestral and vuggy porosity filled with spar; medium beds have a nodular appearance; gradational basal contact and laterally continuous over 30 m. **CQ-29.0,** ***CQ-29.0-1, CQ-29.0-2***
24	0.18	29.24	Mudstone, dark greenish gray (5G 4/1); strongly calcareous; no body or trace fossils; very thinly bedded; very poorly exposed basal contact; laterally discontinuous.
25	0.45	29.69	Limestone; dark gray (10YR 4/1); skeletal wackestone; calcareous; silicified gastropods and charophytes; moldic and other types of porosity are present and filled with spar and silica cement; sharp basal contact and laterally continuous over 300 m. **CQ-29.6A, CQ-29.6B,** ***CQ-29.6A, CQ-29.6B***
26	0.55	30.24	Mudstone, greenish black (10Y 5.5/1); strongly calcareous; no body or trace fossils; fissile to nodular bedding; conchoidal fracture; sharp basal contact, laterally continuous. **CQ-30**
27	0.20	30.44	Limestone; pale purple (5P 6/2) to dark gray (10YR 4/1); micritic mudstone; no body or trace fossils; silty to argillaceous but strongly calcareous; grades laterally into sandstone; sharp basal contact, laterally continuous over 100 m. **CQ-30.4**
28	4.17	34.61	Mudstone, dark greenish gray (10Y 4/1); calcareous to slightly calcareous in uppermost 1 m; smectitic(?); possible fine plant fragments (typically < 1 mm) present; minor amounts of lithic rock fragments and quartz grains; thin sandstone interbed at 32.4 m; the sandstone is fine-grained, calcareous, thickens to ~ 55 cm to the south, and has diffuse contacts within mudstone; unit displays a sharp basal contact and is laterally continuous over 300 m.

29	3.73	38.34	Sandstone, light gray (5Y 7/2); very fine- to coarse-grained, poorly sorted, subangular to subrounded sublitharenite; calcareous; three major thick beds; rare carbonate clasts in lower bed; no trace or body fossils; cross-stratification is commonly and includes planar-tabular and low angle planar laminations; soft sediment deformation (i.e. contorted layering) is also present in the lowermost bed; graded bedding is present in the uppermost bed; sharp erosive basal contact and laterally continuous for over 300 m.
30	10.09	48.43	Mudstone, dark greenish gray (5GY 4/1), light olive gray (5GY 6/2), and black (5Y 2.5/1) to very dusky red (10R 2.5/2) in the upper 60 cm; non-calcareous to very weakly calcareous; silty to arenaceous with < 10 cm thick sandstone interbeds; rare red chert bands are laterally discontinuous (2-3 cm length and 1-2 mm thick); massive bedding; sharp basal contact and laterally continuous.
31	0.51	48.94	Sandstone, pale yellow (5Y 8/2), very fine-grained, moderately sorted, sublitharenite; weakly calcareous; massive without internal stratification; nodular outcrop appearance; gradational basal contact and laterally continuous over 30 m.
32	1.86	50.80	Mudstone, greenish gray (10Y 6/1); non-calcareous to weakly calcareous; very silty in the basal 60 cm that fines upward; red mottles are rare; (?) bioturbation; minor vugs with calcite spar; no body fossils; gradational basal contact and lateral continuous. **CQ-50.7**
33	0.08	50.88	Limestone, mudstone, light gray (N7); calcareous; no trace or body fossils; massive bedding; geodes associated with this unit; sharp basal contact and laterally continuous over 100 m. **CQ-50.8, CQ-50.8G, CQ-50.8B**
34	4.11	54.99	Mudstone, greenish gray (10Y 6/1) to dark bluish gray (10B 3/1); non-calcareous to strongly calcareous; silty intervals 20-30 cm thick in the lower portion; an interbed of argillaceous limestone is also present in the middle of this unit; the limestone is brownish black (5YR 2/1), ?organic rich, and has a thin lens-like geometry (5-6 cm in length, 3-4 cm thick); no identifiable body or trace fossils in the limestone; interbeds display gradational contacts; both units are massively bedded; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **CQ-51.6**
35	7.66	62.65	Mudstone, greenish gray (5GY 5/1) and dark bluish gray (5B 3/1); the mudstone units are fine to silty and very weakly calcareous to calcareous; no body or trace fossils were observed from the mudstone units; interbeds of limestone and sandstone are common (labeled a-m in fieldbook); the interbeds typically alternate with the mudstone every 30-100 cm; the limestone units are calcareous, argillaceous micritic mudstones with minor intraclasts; no body or trace fossils were noted except ?ostracodes in the uppermost beds (k-m); red chert is also present in the uppermost beds (l-m); the sandstone units are fine- to medium-grained, moderately sorted and quartz-rich; the sandstone units are calcareous and contain minor intraclasts (2-3 cm); a thin gypsum layer (1-2 cm thick) and laminations are present in sandstone "g"; limestone and sandstone

			units are both primarily massively bedded; unit "h" is nodularly bedded; interbed contacts are generally sharp; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **CQ-55.0, CQ-55.1, CQ-57.2, CQ-57.4, CQ-57.8, CQ-59.0, CQ-60.7, CQ-61.6, CQ-61.7, CQ-62.3**
36	13.63	76.28	Mudstone, greenish gray (5Y 4/1) to dark reddish brown (2.5YR 2.5/3); the mudstone is non-calcareous to calcareous; silty; massively bedded; red mottles are present; no fossil material present; basal contacts with interbeds (<10-15 cm) of sandstone and limestone are sharp; the sandstone is very pale orange (10YR 8/2); the very fine- to fine-grained, subarkose is a small ledge former with a nodular massive appearance; the sandstone has rare green mudstone rip-up clasts and is commonly reddened in part; the limestone is dusky red (10R 3/2) to dark reddish brown (2.5YR 2.5/3); silty to argillaceous micritic mudstone; calcareous; no skeletal was noted; minor green mudstone filled vertical tubes; nodular appearance; very poorly exposed; laterally continuous over 50 m; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **CQ-65.25, CQ-67.6, CQ-68.1, 68.4, CQ-68.55, CQ-68.8, CQ-69.1, CQ-70.1**
37	0.36	76.64	Sandstone, pale yellow (5Y 8/2), fine- to medium-grained, poorly to moderately sorted, subangular grains sublitharenite; abundant lithic fragments; calcareous; no body or trace fossils; very poorly exposed; sharp basal contact and laterally continuous over 20 m.
38	0.24	76.88	Mudstone, greenish gray (5Y 4/1) to dark reddish brown (2.5YR 2.5/3); non-calcareous to calcareous; silty; massively bedded; no fossil material; sharp basal contact and laterally continuous over 30 m.
	3.16	80.04	Covered Interval
39	9.50	89.54	Mudstone, dark reddish gray (2.5YR 3/1) to dark greenish gray (5GY 4/1); non-calcareous to very weakly calcareous; silty with minor sandstone interbeds (< 20 cm thick); contacts with the sandstone units are generally sharp; the sandstone units are greenish gray (10Y 5/1) to dark reddish brown (2.5 YR 2.5/3), very fine-grained, moderately sorted, and quartz-rich; calcareous; massive to laminated; the unit as a whole is laterally continuous over 30 m and the base is not exposed. **CQ-82.7, CQ-86.9**
40	0.35	89.89	Limestone, mudstone; light gray (N7); calcareous; no body or trace fossils; tuffaceous (?); massive with nodular to bulbous appearance; highly fractured; sharp basal contact and laterally continuous over 30 m. **CQ-90.0a, CQ-90.0b**
41	0.30	90.19	Mudstone, dusky red (2.5 YR 3/2); calcareous; no trace or body fossils; platy fabric; sharp basal contact and laterally continuous over 30 m.
42	0.25	90.44	Limestone, mudstone; light gray (N7); calcareous; no body or trace fossils; nodular to thin beds; sharp basal contact; laterally continuous over 40 m. **CQ-90.3**

43	7.60	98.04	Mudstone, dark reddish brown (10R 3/4) to greenish gray (5GY 6/1); non-calcareous to very weakly calcareous; silty with 3 minor sandstone interbeds (10-20 cm thick); no body or trace fossils; the sandstone beds are fine-grained, moderately sorted, and quartz-rich; massive beds with minor very low-angle cross-stratification; the mudstone is also massively bedded; the unit as a whole has a sharp basal contact and in laterally continuous over the exposure.
44	1.20	99.24	Sandstone, very dark brown (7.5 YR 2.5/3); very fine-grained, moderately sorted, sublitharenite; non-calcareous; argillaceous; pedogenically modified with an angular blocky fabric(?); unit grades upward into greenish gray (5GY 6/1) siltstone and tuffaceous mudstone; the unit as a whole has a sharp basal contact and laterally continuous over the exposure.
45	1.80	101.04	Sandstone, very pale orange (10YR 8/2); very fine-grained, moderately sorted, subangular to subrounded sublitharenite to subarkose; minor feldspar and black (?)chert fragments; non-calcareous to very weakly calcareous; minor (< 2 cm) siltstone intercalations; no body or trace fossils; very thin to medium beds that are commonly laminated; minor green mudstone rip-up clasts in the basal portion; minor ledge-former; gradational basal contact; laterally continuous over 30 m.
46	1.00	102.04	Mudstone, dark reddish brown (2.5 YR 3/8); non-calcareous to very weakly calcareous; silty; no trace or body fossils; very thin to thinly bedded (?); small (1-2 cm diameter) gleyed horizontal structures; grades upward into siltstone and sandstone; the sandstone is very pale orange (10YR 8/2); very fine-grained, moderately sorted, and quartz rich; very weakly calcareous; massively bedded; the unit as a whole has a sharp basal contact and laterally continuous over the exposure.
47	3.00	105.04	Mudstone, dark reddish brown (2.5YR 3/3); silty intervals and the unit grades up into a siltstone in the upper 20 cm; non-calcareous to very weakly calcareous; no trace or body fossils; massively bedded; gradational basal contact and laterally continuous over the exposure. **CQ-106.5**
48	1.50	106.54	Sandstone, very pale orange (10YR 8/2); fine- to medium-grained, moderately sorted sublitharenite; non-calcareous to very weakly calcareous; green mudstone rip-up clasts; lower sandstone beds are massive; low-angle cross-stratification present at the base of the upper bed; distinctive ledge-former; medium to thick beds (25-50 cm); sharp basal contact and laterally continuous over 300 m.
49	3.00	109.54	Mudstone, olive (5Y 4/) to grayish green (5G 4/2); non-calcareous; silty; dinosaur bone fragments are common; no trace fossils; massively bedded; major slope-former; grades into a thinly bedded siltstone in the upper 20 cm; this unit is the basal mudstone of Cope's Nipple; sharp basal contact and laterally continuous.
50	3.35	112.89	Mudstone, dark reddish brown (2.5YR 2.5/3); non-calcareous to very weakly calcareous; silty intervals weathering with slight positive relief at 113.9 m possible coprolite(?); no body fossils; generally massive beds; gradational basal contact and laterally discontinuous over the exposure.

51	1.65	114.54	Mudstone, dusky red (10R 3/2) to dark gray (N3); very weakly calcareous; massively bedded; silty with distinct sandstone interbeds; the sandstone units represent the tip of Cope's Nipple; the sandstone is very fine-grained, moderated sorted, and quartz-rich; non-calcareous to very weakly calcareous; massive to medium beds; low angle planar tabular cross-stratification in the uppermost sandstone; the lower sandstone is massive with a nodular appearance; sharp basal contact; laterally discontinuous.
52	3.13	117.67	Siltstone, weak red (10R 4/3); very weakly calcareous; bioturbated (?); massively bedded; very poorly exposed; sharp basal contact that correlates to the top of Cope's Nipple; laterally discontinuous. **CQ-U21**
53	4.00	121.67	Sandstone, light brown (5YR 5/6); fine- to medium-grained, moderately sorted sublitharenite; very weakly calcareous; no body or trace fossils; abundant cross-stratification; conglomeratic in places with pebbles up to 3-4 cm; friable; major cliff former; sharp basal contact; laterally continuous over the exposure.
	0.75	122.42	Covered Interval
54	8.75	131.17	Sandstone, very pale brown (10YR 7/4); fine- to coarse-grained, moderately sorted sublitharenite; very weakly calcareous; no body or trace fossils; abundant cross-stratification; 10-30 cm conglomeratic channel forms with a coarse basal lag are present; pebbles up to 3-4 cm; friable; major cliff former; sharp basal contact and laterally continuous over the exposure.
	1.88	133.05	Covered Interval
55	1.90	134.95	Sandstone, light greenish gray (10Y 8/1); fine-grained, moderately sorted sublitharenite; non-calcareous; no body or trace fossils; friable; two medium beds; sharp basal contact and laterally continuous over the exposure.
56	3.75	138.70	Siltstone to sandstone, dusky red (5R 3/4) to very dark red (5R 2/6); non-calcareous; the siltstone is punctuated by 0.5-1 m scale sandstone intervals that weather with a positive relief; the sandstone is fine-grained, moderately sorted sublitharenite; hematite cement is abundant; minor green mudstone rip-up clasts and quartz clasts (1-2 cm) in the siltstone; minor gleying (light greenish gray) and mottles in the upper portion; very friable; basal contact sharp but poorly exposed; laterally continuous over the exposure. **CQ-Unit 28-1, CQ-Unit 28-2**

~~~~~ K-1 unconformity ~~~~~

LYTLE FORMATION

	3.00	3.00	Sandstone, light bluish gray (10B7/1); fine- to medium-grained, moderately sorted quartzarenite; conglomeratic with clasts up to 3-5 cm; non-calcareous; no trace or body fossils; cross-stratification marked by chert pebbles and coarser grains along foresets; massive to thick beds; very friable; sharp irregular basal contact and laterally continuous. **CCLF-0.0**
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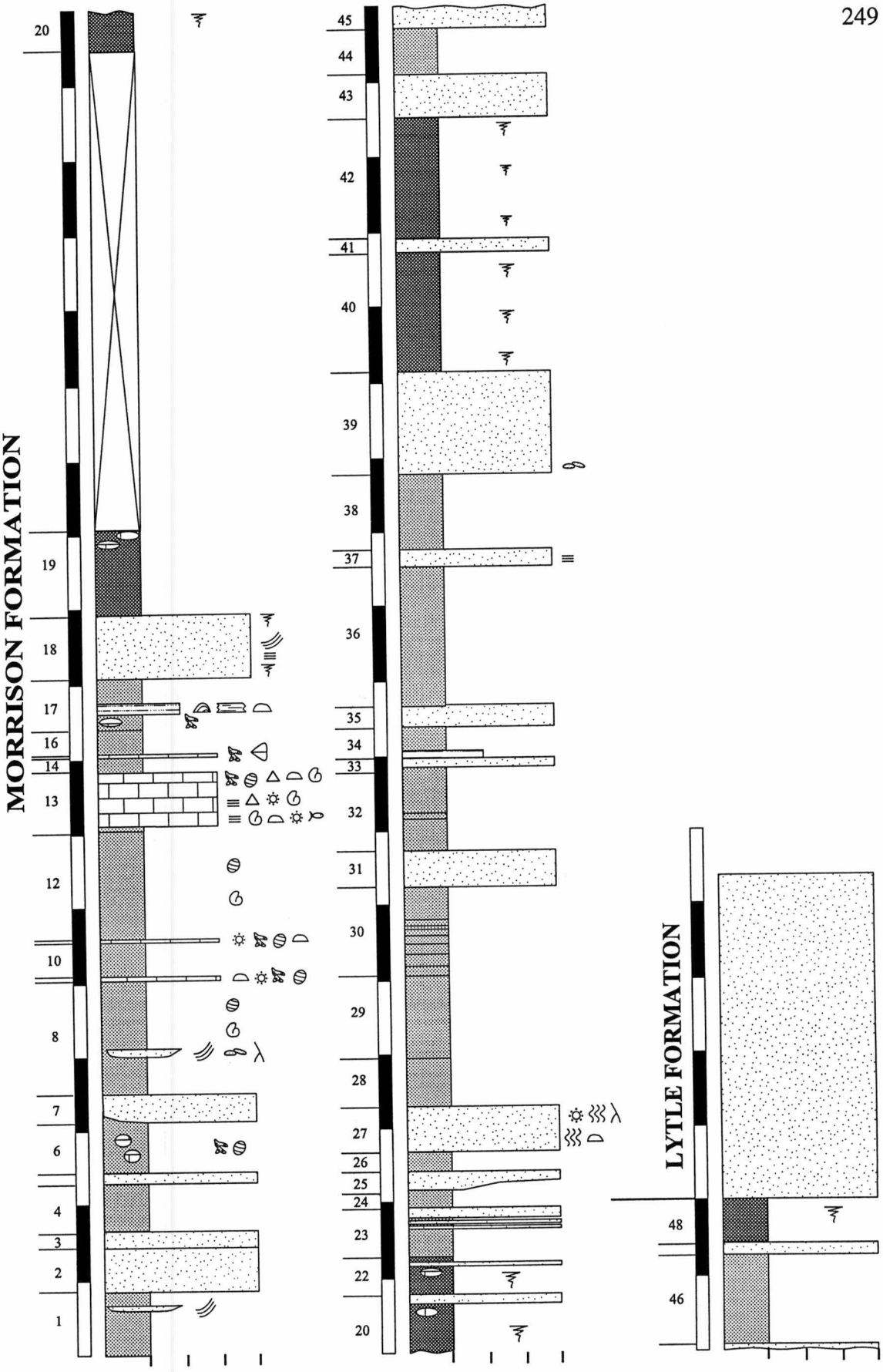
Figure A.9. Stratigraphic section measured at the Skyline Drive outcrop.


MORRISON FORMATION
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Skyline Drive (SD)

This section is located along Skyline Drive on the west side of Cañon City, Colorado, just north of the old State Penitentiary at a latitude of 38°28.215'N and a longitude of 105°15.339'W. The SD section outcrops along a road built on top of a hogback held up by sandstones of the Lytle Formation.

Unit	T (m)	CT (m)	Description
			Basal portion not measured.
RALSTON CREEK FORMATION			
	4.50	4.50	Sandstone, reddish brown (5Y 4/3); fine- to coarse-grained, poorly-sorted, angular to subrounded sublitharenite; conglomeratic; very weakly calcareous to calcareous; no trace or body fossils; faint mottles and reddened intervals are present in the upper 1.5 m; lower 2 m has trough to planar-tabular cross-beds and lithic fragments (metamorphic and igneous) are commonly imbricated; unit fines upward; medium to thick beds; laterally continuous over the exposure. **RC-2**
			~~ J-5 unconformity ~~~~~
MORRISON FORMATION			
1	2.10	2.10	Mudstone, dark yellowish gray (10Y 3/1); calcareous; silty in lower 10 cm; gastropod in float at 0.75 m; laminated in upper 25 cm; discontinuous sandstone lens at 1.75 m; the sandstones (~ 10 cm thick; 1-2 m wide) are medium- to coarse-grained, poorly- to moderately-sorted litharenites with laminations; the unit as a whole has very thin beds with a gradational basal contact over 15-20 cm; laterally continuous over the exposure.
2	1.50	3.60	Sandstone, greenish gray (10Y 6/1); very fine- to fine-grained, moderately sorted, subangular to subrounded sublitharenite to subarkose; minor feldspar and red chert; calcareous; upper 20 cm is bioturbated (burrows are <1 cm in diameter and 3-4 cm in length); massively bedded; sharp basal contact; the unit thins to 1.2 m laterally over 50 m.
3	0.60	4.20	Sandstone, greenish gray (10Y 6/1); very fine- to fine-grained, moderately sorted sublitharenite; black to orange chert grains; strongly calcareous; no trace or body fossils; bulbous to nodular weathering appearance; medium beds; sharp basal contact and laterally continuous over the exposure.
4	1.55	5.75	Mudstone, greenish gray (5GY 5/1); silty; calcareous; no trace or body fossils; friable with a nodular to bulbous weathering appearance; massive bedding; gradational lower contact and laterally continuous over the exposure.
5	0.40	6.15	Sandstone, pale yellowish brown (10YR 6/2); fine- to medium-grained, moderately sorted sublitharenite; calcareous to strongly calcareous; no trace or body fossils; cross-stratification includes trough cross-beds and climbing ripples; appears to coarsen upward; medium beds; sharp basal contact and laterally continuous over the exposure.
6	1.65	7.80	Mudstone, greenish gray (5GY 5/1); silty; calcareous; friable at the base; carbonate nodules are present from 7.25 to 7.35 m ; no body fossils; massive bedding; sharp basal contact; laterally continuous over the exposure. **SD-7.25-7.35,** ***SD-7.25-7.35, SD-7.25-7.35 Unit 6***

7	0.95	8.75	Sandstone, pale yellowish brown (10YR 6/2); very fine- (upper only) to medium-grained, poorly- to moderately-sorted sublitharenite; calcareous; bioturbated basal part (burrows are <1 cm in diameter, vertical to horizontal); mudstone rip-up clasts at 8.25 m; trough cross-beds in upper ½; medium to thick beds; sharp erosive basal contact and laterally discontinuous over 5 m.
8	3.85	12.60	Mudstone, light to dark greenish gray (10Y 4/1-7/1), with sandstone, pale yellowish brown (10YR 6/2) lenses; the mudstone is silty and calcareous; fines upward; charophyte gyrogonites and gastropods (at 11.25 m) are present; no trace fossils; the mudstone displays massive bedding; contact with sandstone lenses is gradational at the top and sharp along the base; the two sandstone lenses (~25 cm thick) are fine- to coarse-grained, poorly-sorted sublitharenites; they contain mudstone rip-up clasts, trace fossils (root trace [tapering, 2 cm in diameter; 3-4 cm depth] and burrows [2-3 cm in length; 5 mm in diameter]) with sandstone infill; gypsum stringer (1-3 mm thick) in upper 25 cm; unit as a whole has a gradational basal contact; laterally continuous over the exposure.
9	0.15	12.75	Limestone, yellowish gray (5Y 8/1) to pinkish gray (5YR 8/1); skeletal mudstone; gastropods are present; vertical and horizontal fenestral are common and spar-filled (coarse, pink crystals); nodular weathering appearance; very poorly exposed on slope; thickness varies laterally by up to 5 cm; sharp basal contact and laterally continuous over 60 m. **SD-12.75A, SD-12.75B, *SD-12.75B***
10	1.15	13.90	Mudstone, greenish gray (10Y 6/1); very weakly calcareous with a slight silt content; no body or trace fossils; massive and structureless bedding; sharp basal contact and laterally continuous over the exposure.
11	13.90	14.00	Limestone, yellowish gray (5Y 8/1) to pinkish gray (5YR 8/1); calcareous; micritic mudstone; no trace or body fossils; porosity includes spar-filled moldic and fenestral; thin bedding; nodular weathering appearance; largely covered on slope; sharp basal contact and laterally continuous over 30 m. **SD-13.9, *SD-13.9***
12	3.65	17.65	Mudstone, greenish gray (10Y 6/1); very weakly calcareous; minor silt in basal part; minor gastropods (planorbids) and charophyte gyrogonites; arenaceous interval at 15.2-15.25 m; gypsum stringer at 17.5 m; massive and structureless to faint thin beds; sharp basal contact; laterally continuous over the exposure.
13	1.98	19.63	Limestone, yellowish gray (5Y 8/1) to pinkish gray (5YR 8/1), with a basal claystone to mudstone bed (10 cm thick), light greenish gray (10Y 7/1); the basal claystone to mudstone is very strongly calcareous with no trace or body fossils; the lowermost bed also appears to have very thin beds; the limestone portion of this unit may be subdivided into 4 subunits; subunit 1 grades upward from the claystone-mudstone to a marly skeletal mudstone that is calcareous, very friable, and has very thin to medium beds; this subunit has minor gastropods and vuggy porosity; subunit 2 is characterized by an irregular, wavy laminated fabric near the base capped by 3 cm of a similar texture; this subunit is a peloidal-skeletal mudstone with gastropods as well as abundant vuggy porosity filled with coarse, pink spar; the primarily subvertical vugs are up to 5 cm long and 2 cm wide and cut across bedding; subunit 3 has a blocky to

			highly fractured and brecciated fabric and is composed on 4 irregular to medium beds of skeletal mudstone (20, 5, 10, 10 cm, respectively); subunit 3 has gastropods, ?gyrogonites, and ?ostracode fragments and the irregular vertical to horizontal fenestral and channel porosity infilled with coarse pink spar; subunit 4 is composed of 3 distinct beds (medium thickness); subunit 4 is a skeletal mudstone with gastropods, "ropy" charophyte stems and abundant fenestral and moldic porosity; discontinuous, wavy silicification is also common in the uppermost 3-4 cm as well as silicified gastropods and charophyte stems; unit as a whole has a gradational basal contact and is laterally continuous over 1 km. **SD-18.15-18.35, SD-18.5, SD-19-19.1, SD-19.5,** ***SD-18.15, SD-18.35(4), SD-18.35(4a), SD-18.5, SDS-0.1-0.2-B, SDS-1.2, SDS-1.2-2, SDS-1.45***
14	0.47	20.10	Mudstone, greenish gray (5GY 6/1); silty; calcareous; no trace or body fossils; massive bedding; sharp basal contact; laterally continuous over the exposure.
15	0.10	20.20	Limestone, yellowish gray (5Y 8/1); calcareous to very strongly calcareous; micritic mudstone; skeletal material is present (?unionid bivalves); chalky and nodular weathering appearance; bedding is irregular to nodular; sharp basal contact and laterally discontinuous over 5-10 m. **SD-20.1A, SD-20.1B, SD-20.1C**
16	0.80	21.00	Mudstone, greenish gray (5GY 6/1); very minor silt content; calcareous; reddened mottles near upper part; no trace or body fossils; weathers with a blocky appearance; massive bedding; sharp basal contact; laterally continuous over the exposure.
17	1.70	22.70	Mudstone to claystone, brownish yellow (10YR 6/8) to greenish gray (10Y 5/1), with limestone nodule and siltstone interbeds; claystone interval from 21.6 to 22.5 m weathers a distinctive moderate yellow (5Y 7/6) to grayish orange (10YR 7/4); unit is generally very weakly calcareous to calcareous; the mudstone is silty and massively bedded; the limestone nodules at 21.4 m are brecciated with possible skeletal fragments and silicification; the siltstone interbed at 21.5-21.7 m has abundant conchostracans and plant remains; bedding for the siltstone is very thin to laminated; gypsum nodules are also present and up to 5 cm in diameter (diagenetic?); this unit has a gradational basal contact and is laterally continuous over the exposure. **SD-21.6, SD-21.7,** ***SD-21.6***
18	2.15	24.85	Sandstone, light gray (N7) to white light gray (2.5Y 7.5/1); very fine- to fine-grained, moderately-sorted subarkose; no trace or body fossils; light reddish brown (2.5YR 6/3) mottles in the upper and lower 40-50 cm; commonly laminated to cross-laminated; highly weathered and very poorly exposed as a slope-former primarily; very friable; gradational basal contact and laterally continuous over the limited exposure.
19	2.85	27.70	Mudstone, dusky red (2.5YR 3/2) to weak red (2.5YR 4/2) and greenish gray (10Y 6/1); weakly calcareous to calcareous and silty in the basal 1 m; no trace or body fossils; a sandstone lens present at 25.0 m; "chalky" nodules present at 27.5 m; chalk nodules have septarian cracks; bedding varies from very thin to structureless; gradational basal contact and laterally continuous over limited exposure.

SD-27.5

	16.15	43.85	Covered Interval
20	2.80	46.65	Mudstone, dark reddish brown (5YR 3/3) to olive (5Y 5/3); very weakly calcareous to calcareous; silty in parts; no body or trace fossils; horizontal and vertical mottles are common in reddened intervals; variegated weathering appearance; carbonate nodules are present at 46.5 m; basal contact not exposed; unit appears to be laterally continuous over the limited exposure.
21	0.35	47.00	Sandstone, light greenish gray (5GY 8/1) to olive (5Y 6/4); very fine- to fine-grained, poorly sorted graywacke to sublitharenite; argillaceous and non-calcareous; no body or trace fossils; laminations are present; sandstone grades laterally into a weak red (10R 4/2) sandstone, siltstone, and mudstone; sharp basal contact and laterally continuous over the exposure.
22	1.25	48.25	Mudstone, dark reddish brown (2.5YR 3/3); calcareous; no body or trace fossils; carbonate nodules (7-15 cm in diameter) are present at 47.8 m and distributed laterally every 10-30 cm; light greenish gray (5GY 7/1) mottles are present above and below the carbonate nodules; a sandstone interbed (5-8 cm thick) is present at 48.0 m; the sandstone is a very fine-grained, moderately sorted litharenite; it is calcareous and laminated; the basal part of the unit is silty; the unit as a whole has a gradational lower contact and is laterally continuous over the exposure. **SD-47.8**
23	1.45	49.70	Sandstone, light greenish gray (5GY 8/1), with mudstone, pale olive (5Y 6/4) to weak red (10R 4/2); the sandstone is fine- to medium-grained, moderately sorted sublitharenite; the mudstone is tuffaceous and contains reddened horizons; both are calcareous; no body fossils are present; burrows are present at ~ 48.8 m; minor 1-2 cm gypsum layers are present; the mudstone is massively bedded and the sandstone consists of medium beds; possible first occurrence of tuffaceous mudstone; the unit as a whole has a sharp and irregular basal contact and is laterally continuous over the exposure.
24	0.80	50.50	Mudstone, reddish brown (5YR 4/4); non-calcareous and silty; "hard"; no body or trace fossils; vertical and horizontal mottles are distinct, common, and medium-sized; very thin to thin beds are present; sharp basal contact and laterally continuous over the exposure.
25	0.60	51.10	Mudstone to sandstone, greenish gray (5GY 6/1); non-calcareous to very weakly calcareous; the mudstone is slightly silty; the sandstone is fine-grained, moderately sorted litharenite; the mudstone and sandstone are massively bedded; the upper part of the sandstone is reddened and has a nodular weathering appearance; minor plant fragments; no trace fossils; the unit grades upward from mudstone to sandstone; the unit as a whole has an irregular sharp lower contact and is laterally continuous over the exposure. **SD-50.8**
26	0.65	51.75	Mudstone, dark yellowish brown (10YR 4/6) and reddish brown (2.5YR 4/3) to reddish gray (10R 6/1); non-calcareous to very weakly calcareous; tuff with reddened mudstone intervals present in the lower 20 cm and upper 10 cm; no

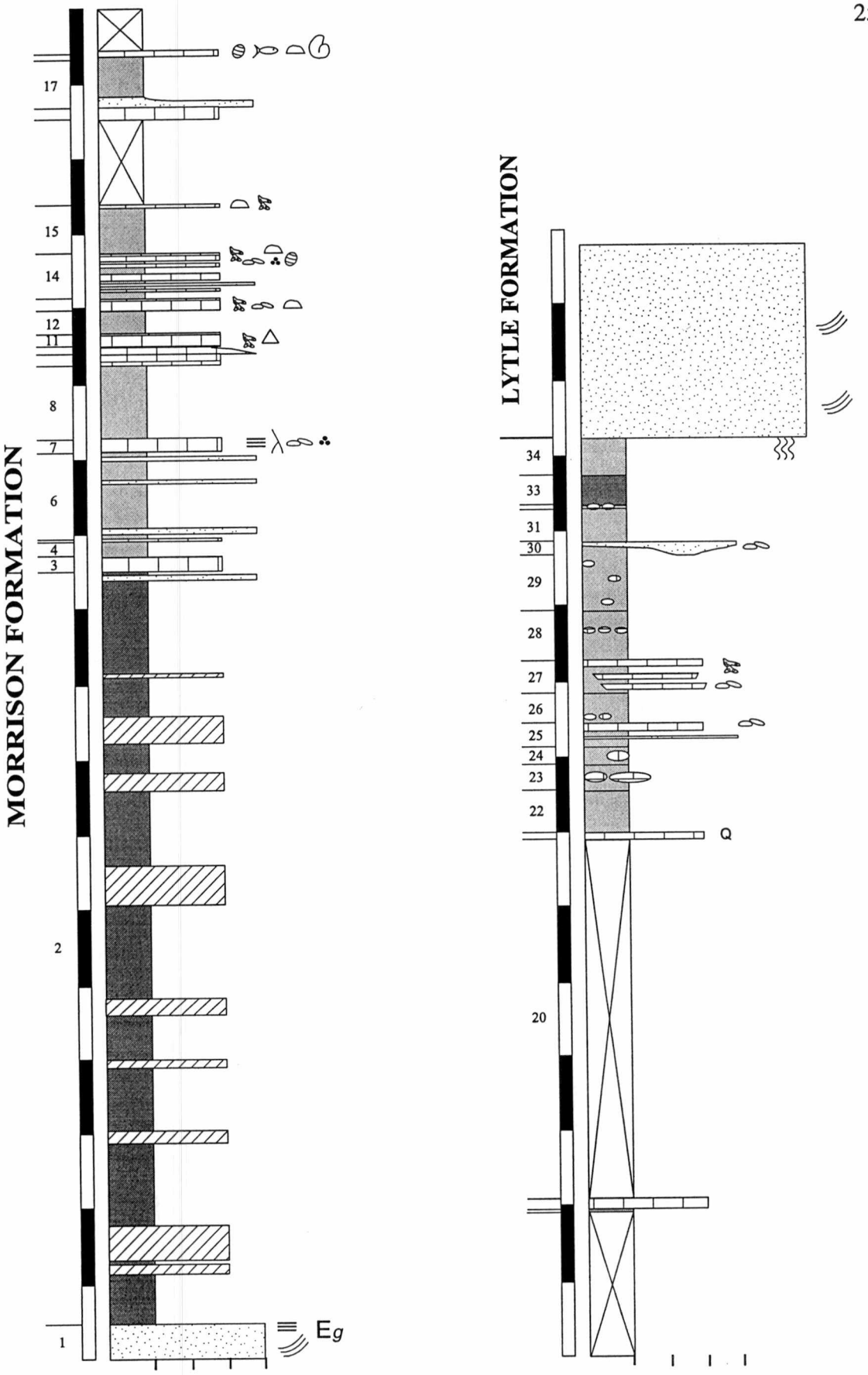
			body or trace fossils; well-developed mottles are distinct, common, and medium-sized; the tuff is laterally discontinuous; the unit as a whole has a gradational lower contact and is laterally continuous over the exposure.
27	1.55	53.30	Sandstone, light greenish gray (5GY 7/1); fine- to medium-grained, poorly sorted graywacke; argillaceous, and non-calcareous to calcareous; no body or trace fossils; the sandstone consists of thin to medium beds with interbeds of ?tuffaceous mudstone and gypsum; minor porosity filled with spar and unidentified green clay mineral; bulbous weathering appearance; ledge-former; sharp basal contact and laterally continuous over the exposure. **SD-51.3,** ***SD-51.3***
28	1.60	54.90	Mudstone, greenish gray (5GY 6/1) to very dusky red (2.5YR 2.5/2) in the upper 40 cm; non-calcareous; the mudstone is silty and tuffaceous in the upper 40 cm; no body or trace fossils; well-indurated and "hard"; slope-forming unit; sharp basal contact and laterally continuous over the exposure.
29	2.85	57.75	Mudstone, olive (5Y 5/4); non-calcareous to very weakly calcareous; no body or trace fossils; tuffaceous; blocky brecciated appearance; massively bedded with some possibly very thinly laminated areas; weathers to pale red (5R 6/2), grayish black (N2), and dark yellowish orange (10YR 6/6); gradational basal contact; laterally continuous over the exposure.
30	2.95	60.70	Mudstone, white (N9) to light greenish gray (10Y 7/1); non-calcareous to very weakly calcareous; tuffaceous; "hard"; no body fossils; possible ?dinoturbation; minor interbeds of welded tuff and rare gypsum interbeds; the welded tuffs have highly altered ?microphenocrysts, are poor ledge-formers, and have irregular but sharp contacts with the tuffaceous mudstone; the welded tuffs are characterized by medium beds, while the tuffaceous mudstones are massively bedded; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
31	1.20	61.90	Sandstone, yellowish gray (5Y 7/2); fine-grained, moderately sorted sublitharenite; non-calcareous; no body fossils; burrows are present on base of lowermost sandstone bed; thick to medium and thin beds in upper portion; unit fines upward; unit exhibits a channel-like geometry and thins laterally; ledge-former; sharp basal contact and laterally continuous over the exposure.
32	2.80	64.70	Mudstone, light gray (10YR 7/1) to greenish gray (5GY 6/1); non-calcareous to very weakly calcareous; tuffaceous in parts; no body or trace fossils; a welded tuff is present from 63.0 to 63.5 m; pyrite nodules (mm-cm scale) are present in the welded tuff; the welded tuff grades laterally into a channel sandstone up to 1.0 m thick; reddened intervals are present in the upper 1.0 m characterized by pedogenic slickensides and gypsum stringers along fractures; the tuffaceous mudstone is massively bedded and the welded tuff consists of nodular to a single massive thick bed; contacts between the tuffaceous mudstone and welded tuff are gradational; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.
33	0.30	65.00	Sandstone, yellowish gray (5Y 7/2) to light greenish gray (5GY 7/1); fine-grained, moderately sorted, sublitharenite; non-calcareous; no body or trace fossils; faint laminations; very thin to thin beds; sharp basal contact and

laterally continuous over the exposure.

34	1.00	66.00	Siltstone to mudstone, greenish gray (5GY 6/1); non-calcareous; tuffaceous in parts; no body or trace fossils; minor reddened horizons (15-20 cm thick) that are laterally discontinuous over 1 m; mottles are present in the reddened intervals and are distinct, few, and small- to medium-sized; sharp basal contact and laterally continuous over the exposure.
35	0.75	66.75	Sandstone, yellowish gray (5Y 7/2) to light greenish gray (5GY 7/1); fine- to medium-grained, moderately sorted sublitharenite; calcareous to non-calcareous in the upper part; no body or trace fossils; no internal stratification; the unit is thinly bedded in the lower 10 cm with an upper massive thick bed; gradational basal contact and laterally continuous over the exposure.
36	4.65	71.40	Mudstone, pale olive (5Y 6/2) and pinkish white (2.5YR 8/2) to reddish brown (5YR 5/3); non-calcareous; silty to tuffaceous; no body or trace fossils; mottles are present in reddened interval at 69.0 m; the mottles are few, faint, and medium-sized; minor sandstone interbed (5-9 cm thick) present at 69.9 m; the mudstone is massively bedded; sharp basal contact and laterally continuous over the exposure.
37	0.60	72.00	Sandstone, yellowish gray (5Y 7/2); fine- to medium-grained, moderately sorted sublitharenite; very weakly calcareous; no body or trace fossils; minor faint laminations; four thin to medium beds; gradational basal contact and laterally continuous over the exposure.
38	2.50	74.50	Mudstone, pale olive (5Y 6/4) to greenish gray (10Y6/1) and brown (2.5YR 5/3); non-calcareous to very weakly calcareous; tuffaceous in parts; silty in basal 20 cm; no body or trace fossils; interval with welded tuff beds (~95 cm thick) serve as minor ledge-formers; the mudstone is massively bedded and the welded tuffs are characterized by thin to medium beds; gradational basal contact and laterally continuous over the exposure.
39	3.40	77.90	Sandstone, olive brown (2.5Y 4/3) to weak red (10R 4/4); very fine- to medium-grained, moderately sorted, sublitharenite; non-calcareous to very weakly calcareous; tuffaceous in part; no body or trace fossils; rip-up clasts are present in the lowermost of the thick sandstone beds, which also displays a general coarsening upward trend; well-indurated; laminations are present in several of the sandstone beds; one thin and five medium to thick beds are present; lowermost sandstone bed has a channel like geometry; the unit as a whole is a ledge-former; the unit as a whole has a sharp basal and is laterally continuous over the exposure. **SD-76.1, SD-77.9, *SD-76.1, SD-77.9***
40	4.00	81.90	Mudstone, greenish gray (5GY 6/1) to olive (5Y 4/3), dark bluish gray (5PB 4/1), and dark reddish brown (5YR 3/2); non-calcareous and tuffaceous in parts; well-indurated; no body or trace fossils; mottles (few, distinct, and medium-sized) are present in reddened intervals; fractures along arcuate slickensides contain detrital clastics and gypsum; massively bedded; sharp basal contact and laterally continuous over the exposure.
41	0.45	82.35	Sandstone, yellowish gray (5Y 7/2) to weak red (10R 4/4); fine- to medium-

			grained, moderately sorted, sublitharenite; non-calcareous and tuffaceous; no body or trace fossils; no internal stratification; massive thick bed; well-indurated; gradational basal contact and laterally continuous over the exposure.
42	4.00	86.35	Mudstone, dark reddish gray (2.5YR 3/1) to dark greenish gray (10Y 4/1); non-calcareous and tuffaceous; no body or trace fossils; mottles are present in parts and are reddish black (2.5YR 2.5/1); the mottles are few, distinct, and medium-sized; arcuate slickensides with clastic material and gypsum; massively bedded; slope-forming unit; thickness varies slightly laterally; sharp basal contact and laterally continuous over the exposure.
43	1.45	87.80	Sandstone, yellowish gray (5Y 7/2); fine- to medium-grained, moderately sorted sublitharenite; non-calcareous and tuffaceous; no body or trace fossils; no internal stratification; massive medium to thick beds; well-indurated; sharp basal contact and laterally continuous over the exposure.
44	1.50	89.30	Mudstone, dark reddish gray (2.5YR 4/1) to light yellowish brown (2.5Y 6/4) and greenish gray (10Y 5/1); non-calcareous and tuffaceous; no body or trace fossils; silty; "hard" and well-indurated; massively bedded; gradational basal contact and laterally continuous over the exposure.
45	0.90	90.20	Sandstone, grayish orange (10YR 7/4) to moderate red (5R 4/6); fine- to medium-grained, moderately sorted sublitharenite; non-calcareous; no body or trace fossils; minor laminations in lower bed; three massive thick beds; minor ledge former; gradational lower contact; laterally continuous over the exposure.
46	3.00	93.20	Siltstone, dark reddish brown (5YR 3/3) to very dusky red (10R 2.5/2); non-calcareous to very weakly calcareous; no body or trace fossils; greenish-gray (5GY 6/1) mottles are present in lower half; the mottles are few to common, medium-sized, and distinct; the unit appears massively bedded but areas have very thin to thin beds; lower half weathers with slight positive relief and may be tuffaceous; sharp basal contact and laterally continuous over the exposure.
47	0.40	93.60	Sandstone, moderate red (5R 4/6); fine- to medium-grained, moderately sorted sublitharenite; non-calcareous and tuffaceous; no body or trace fossils; bedding is massive and pinches and swells; gradational basal contact and laterally discontinuous over the exposure.
48	1.45	95.05	Mudstone, very dusky red (10R 2.5/2) to greenish gray (5GY 5/1) in the upper 70 cm; non-calcareous; thin intervals dominated by siltstone; arenaceous in the basal 10 cm; no body or trace fossils; massively bedded; lower red interval has green mottles (few, distinct, and medium); gradational basal contact and laterally continuous over the exposure.
			~~ K-1 unconformity ~~~~~
LYTLE FORMATION			
	2.00	2.00	Sandstone, grayish yellow (5Y 8/4); fine- to coarse-grained, moderately sorted quartzarenite; non-calcareous; no body or trace fossils observed; thin interbeds of mudstone and siltstone (<30 cm thick); cross-stratification is common in the sandstones; outcrops are massive and cliff-forming; sharp erosive basal contact and laterally continuous over the exposure.

Figure A.10. Stratigraphic section measured at the Purgatoire outcrop.


MORRISON FORMATION
17
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LYTLE FORMATION
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Purgatoire (P, P2, P3)

The Purgatoire (P, P2, P3) sections represent a composite section located in Bravo Canyon, on the U.S. Army Pinion Maneuvering Grounds, approximately 44 km south-southwest of La Junta, Colorado. "P" section is present along an old uranium mining road after crossing the fence onto the maneuvering grounds. Sections P2 and P3 outcrop across the valley . The "blue agate" bed serves as a good correlating tool across the valley. Latitude and longitude data are not available for these localities. The basal 26.3 m of the composite P-P3 section is from a measured section by Peterson (unpublished data).

Unit	T (m)	CT (m)	Description
			Basal portion not exposed.
BELL RANCH / ENTRADA FORMATION			
	2.60	2.60	Sandstone, yellow (2.5Y 7/8) to reddish brown (5YR 4/4); very fine- to fine-grained, moderate to well sorted sublitharenite to quartzarenite; non-calcareous; no body fossils present; abundant, prominent, and very coarse (up to 40 cm in diameter) reddish brown mottles; faint crude cross beds; 10-15 cm desiccation polygons; medium flaggy beds; laterally continuous over the exposure.
			~~ J-5 unconformity ~~~~~
MORRISON FORMATION			
1	1.20	1.20	Sandstone, dark reddish brown (2.5YR 2.5/3) to reddish brown (2.5YR 4/3) and pinkish gray (7.5YR 7/2); very fine- to medium-grained generally with coarse-grained intervals in the lower 10 cm and individual coarse intervals up to 3 cm thick; poorly to moderately sorted sublitharenite; non-calcareous to moderately calcareous; wispy veins of gypsum (< 2 cm thick); no body or trace fossils; faint to crude cross beds; bedding consists of very thin to medium beds; unit thickens by up to 30 cm where the J-5 unconformity has cut deeper into underlying Entrada Sandstone; this unit has a sharp and irregular basal contact and is laterally continuous over the exposure.
2	25.10	26.30	Mudstone, brown (7.5YR 4/3) to dark reddish brown (2.5YR 2.5/3), with gypsum interbeds, light gray (N7) to light bluish gray (5B 7/1); major gypsum interbeds are present in this unit from 2.85-3.2, 3.3-4.45, 7.2-7.6, 9.7-10.0, 11.5-12.1, 15.2-16.5, 19-19.6, 20.6-21-5, 22.8-22.9 m; a sandstone bed is present at 26-26.2 m; the mudstone is silty, calcareous, very thinly bedded with rare gypsum nodules, and a slope former; no body or trace fossils were noted in the mudstone; the gypsum beds have a nodular weathering appearance and are ledge-formers and are laterally continuous over the exposure; larger gypsum intervals have interbeds of mudstone and siltstone; the sandstone is very fine- to fine-grained, quartz-rich, and calcareous; the sandstone also displays crude horizontal laminations; this unit as a whole has a sharp basal contact and is laterally continuous over the canyon.
3	0.50	26.80	Limestone, dark bluish gray (10B 4/1); silicified limestone (the "blue agate" bed); carbonate largely replaced by chert; no body or trace fossils; calcareous in parts; possible evaporite pseudomorphs; minor calcite in porosity; nodular outcrop appearance; sharp basal contact and laterally continuous over the area. **P2-0.5**

4	0.50	27.30	Mudstone, dark greenish gray (5GY 4/1); minor silt and very weakly calcareous; no body or trace fossils; very thinly bedded; sharp basal contact and laterally discontinuous due to poor exposure.
5	0.10	27.40	Limestone, yellowish gray (5Y 7/2); micritic mudstone; calcareous; no body or trace fossils; laminations; very poorly exposed; massive bed; sharp basal contact and laterally continuous over the exposure. **P2-1.25,** ***P2-1.25***
6	2.85	30.25	Mudstone, dark greenish gray (5GY 4/1); silty and moderately calcareous; no body or trace fossils; the mudstone has sandstone interbeds at 28.5-28.75; 29.2-29.35, and 29.95-30.1 m; the sandstones are very fine- to fine-grained, moderately sorted sublitharenites; argillaceous, calcareous to strongly calcareous, and very friable; the lower sandstone has internally graded couplets; the sandstones typically grade upward into siltstone and mudstone; the sandstones have very thin to medium nodular beds; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **P2-2.5**
7	0.45	30.70	Limestone, yellowish gray (5Y 7/2); calcareous; micritic mudstone; no body or trace fossils; very thin to laminated basal 10 cm that grades upward into thin and medium beds; sharp basal contact and laterally continuous over the exposure. **P2-4.2, P2-4.3, P2-4.5, P2-4.6,** ***P-29.3***
8	2.45	33.15	Mudstone, dark greenish gray (5GY 4/1); silty; calcareous; no body or trace fossils; carbonate nodules in the upper 10 cm; very thinly bedded; sharp basal contact and laterally discontinuous due to poor exposure.
9	0.35	33.50	Limestone, yellowish gray (5Y 7/2); calcareous; peloidal skeletal packestone; gastropods, ostracodes, and ?gyrogonites or ooids; thick massive bed; brecciated weathering appearance; sharp lower contact and laterally continuous over the exposure. **P2-7.1, P2-7.4,** ***P2-7.4***
10	0.25	33.75	Limestone grading up into sandstone, yellowish gray (5Y 7/2), and mudstone, greenish gray (5GY 6/1); all are calcareous; no body or trace fossils; the limestone is a micritic mudstone; the sandstone is very fine- to fine-grained sublitharenite; thin, flaggy beds; lower contact is gradational; laterally continuous over the exposure.
11	0.35	34.20	Limestone, yellowish gray (5Y 7/2); calcareous; intraclast wackestone; no body or trace fossils; lower 10 cm appears massive and the upper 16 cm is laminated; intraclasts and desiccation cracks are present at the top of the laminated unit; the limestone is capped by a ~9 cm thick, conglomeratic sandstone; the sandstone has a sharp lower contact with the limestone; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **P2-7.8, P2-7.93,** ***P2-7.93***

12	0.75	34.95	Mudstone, greenish gray (5GY 6/1) to light brownish gray (5YR 6/1); silty and calcareous; no body or trace fossils; thick laminations to very thin bedding; basal contact is gradation and laterally continuous over the exposure.
13	0.40	35.35	Limestone, brownish gray (5YR 4/1) to medium dark gray (N4); skeletal mudstone to microbial boundstone; calcareous; minor ostracodes and gastropods on upper bedding plane; 2 cm deep desiccation cracks; wavy to crinkly laminations (1-5 mm thick) that dome slightly upward with a diameter of < 10 cm; massive bed that is very brittle; sharp basal contact and laterally continuous over the exposure. **P2-8.85, P2-9.05-9.2,** ***P2-8.85, P2-9.05, P2-9.15***
14	1.50	36.85	Mudstone, greenish gray (5GY 6/1), with limestone, yellowish gray (5Y 7/2), and sandstone interbeds; interbeds are as follows: 35.55-35.65 (limestone), 35.74-35.82 (sandstone), 35.90-36.15 (limestone), 36.35-36.55 (limestone), 36.65-36.85 (limestone); the mudstone is silty, calcareous and lacks body or trace fossils; the mudstone is also bentonitic and well-indurated in places; the sandstone is a fine-grained, sublitharenite with unionid bivalve or conchostracan fragments; the limestones are peloid skeletal wacke/packstones; gastropods and unionid bivalves; minor ooids and microbial laminates; fenestral, vuggy, and fracture porosity are also present and filled with calcite; all units display sharp contacts with other lithofacies, except the upper limestone contacts which have 2-3 cm of relief; the mudstone is massively bedded; the limestone and sandstone consists of thin to medium beds and act as small ledge formers; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **P2-10.2a, P2-10.2b, P2-10.2c, P2-9.8, P2-10.0, P2-10.15-10.4, P2-10.5-10.7, P2-10.6-10.7,** ***P2-10.0, P2-10.2c, P2-10.25, P2-10.6-10.7***
15	1.65	38.50	Mudstone, olive (5Y 4/4) to black (10YR 2/1), and limestone, light olive brown (2.5Y 5/3); the mudstone is calcareous and lacks body or trace fossils; the mudstone is also massively bedded; the upper 10 cm consists of a silty to marly limestone that caps the mudstone; the limestone is a skeletal mudstone with charophytes; sharp lower contact with the mudstone; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **P2-12.3,** ***P2-12.3***
	2.80	41.30	Covered Interval
16	0.40	41.70	Limestone, yellowish gray (5Y 7/2); calcareous; skeletal wackestone; ostracodes, charophytes, and gastropods; allochems appear reworked; minor porosity; massive thick, spalling bed; basal contact poorly exposed; limited laterally continuity. **P3-15.3**
17	1.60	43.30	Mudstone, greenish gray (5GY 6/1) to moderate yellowish brown (10YR 5/4); silty and calcareous; no body or trace fossils; massively bedded with very thin to thin sandstone interbeds; an arenaceous interval in present in the basal 20 cm and at 42.6 m; the sandstone are very fine-grained, calcareous, and massively bedded; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.

18	0.20	43.50	Limestone, yellowish gray (5Y 7/2) to pale olive (10Y 6/2); calcareous; skeletal mud/wackestone; gastropods and ostracodes; minor porosity; thin to medium beds; gradational basal contact and laterally continuous over the exposure. **P2-17.3, *P2-17.3***
	6.30	49.80	Covered Interval
19	0.10	49.90	Tuff, dark greenish yellow (10Y 6/6) to pale olive (10Y 6/2); biotite fragments; extremely poorly exposed; basal contact covered and lateral extent uncertain; unit sampled by T.M. Demko for geochronology.
20	0.35	50.25	Sandstone, brownish gray (5YR 4/1); fine-grained, moderately sorted sublitharenite; calcareous; no body or trace fossils; very poorly exposed due to cover; sharp basal contact; lateral extent unknown.
	12.00	62.25	Covered Interval
21	0.25	63.50	Sandstone, moderate brown (5YR 3/4); very fine-grained, well-sorted sublitharenite; calcareous sandstone to silty limestone; no body or trace fossils; massive medium to thick bed; sheet-like geometry; unit thickens to 45 cm; small ledge former; sharp basal contact; laterally continuous for over 300 m. **P3-0.45**
22	0.35	63.85	Mudstone, dark reddish brown (10R 3/4); silty and non-calcareous to very weakly calcareous; no body or trace fossils; few, medium, distinct gley mottles in the basal 2 cm; sharp basal contact; laterally continuous over the exposure.
23	0.90	64.75	Mudstone, greenish gray (5GY 5/1); non-calcareous, silty, massively bedded and smectitic in the lower 40 cm; a discontinuous, nodular limestone interbed is present from 64.4-64.7 m, the limestone is a calcareous, micritic mudstone with no body or trace fossils; fenestral to channel/fissure porosity filled with calcite; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **P3-1.0, P3-1.1**
24	0.60	65.35	Mudstone, dark reddish brown (10R 3/4), and limestone, pale yellowish brown (10R 6/2); the mudstone is non-calcareous to very weakly calcareous, silty, and massively bedded; two laterally discontinuous nodular limestone interbeds are present from 64.75-64.83 and 64.95-65.15 m; both limestones display sharp contacts with the mudstone, irregular and nodular bedding, and are calcareous, micritic mudstones; no body or trace fossils were noted in the mudstone or the limestones; the unit as a whole has a diffuse to gradational contact and is laterally continuous over the exposure. **P3-1.5, P3-1.7**
25	0.80	66.15	Mudstone, yellowish gray (5Y 7/2), with sandstone, yellowish gray (5Y 7/2), and limestone, dark yellowish orange (10R 6/6); the mudstone is silty and non-calcareous, lacks body or trace fossils, and is massively bedded; the sandstone is present from 65.65-65.73 m; the sandstone is non-calcareous, very fine-grained, moderately sorted sublitharenite, and is massively bedded; the limestone is present from ~ 65.8-66.15 m and ranges in thickness from 25-35

			cm; the limestone consists of 4 thin beds (each ~ 8 cm); the limestones are calcareous, micritic mudstones with minor silicification; the limestones have sharp planar lower contacts and sharp irregular upper contacts; the unit as a whole has a gradational contact over 4 cm and is laterally continuous over the exposure. **P3-2.6, P3-2.8, *P3-2.6, P3-2.8***
26	1.00	67.15	Mudstone, dark reddish brown (10R 3/4); non-calcareous and silty; no body or trace fossils; carbonate nodules are present in the basal 5 cm; massively bedded; sharp and irregular lower contact and laterally continuous over the exposure. **P3-3.0**
27	1.10	68.25	Mudstone, greenish gray (5GY 6/1), with limestone interbeds, dark yellowish orange (10YR 6/6); the mudstone is non-calcareous, lacks body or trace fossils, and is massively bedded; three limestone interbeds are present from 67.45-67.60 (A), 67.70-67.95 (B), and 68.05-68.30 (C) m; "A" is a nodularly bedded, micritic mudstone with a bulbous appearance; "B" is a silty micritic mudstone that grades upward into a calcareous sandstone with minor fenestral porosity; "C" is an argillaceous micritic mudstone with minor porosity; A and B are laterally discontinuous over 10 m, where C is laterally continuous for at least 30 m; A, B, and C have sharp but irregular basal and upper contacts; no body or trace fossils were noted in A, B, or C; the unit as a whole has an irregular gradational lower contact and is laterally continuous over the exposure. **P3-4.25, P3-4.5, P3-4.75, P3-4.8-5.0, *P3-4.75***
28	1.60	69.85	Mudstone, greenish gray (5G 6/1) to light olive gray (5Y 6/1), with limestone, dark yellowish orange (10YR 6/6); the mudstone is non-calcareous, silty, massively bedded, and lacks body or trace fossils; the limestone is a micritic mudstone, silty, calcareous, and nodularly bedded; no body or trace fossils were noted in the limestone; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure. **P3-6.1**
29	2.20	72.05	Mudstone, dark reddish brown (10R 3/4); silty and non-calcareous; no body or trace fossils; carbonate nodules are common throughout the unit; massively bedded; sharp basal contact and laterally continuous over the exposure. **P3-unit 9**
30	0.10	72.15	Limestone, dark yellowish orange (10YR 6/6); calcareous; micritic mudstone; no body or trace fossils; horizontal fenestral porosity is common; unit thickens laterally to a maximum thickness of 30 cm; channel-like geometry; irregularly bedded; sharp basal contact and laterally discontinuous over 20 m. **P3-8.15, P3-8.4a, P3-8.4b, *P3-8.4b***
31	1.10	73.25	Mudstone, light olive gray (5Y 6/1) with sandstone light greenish gray (5G 8/1); the mudstone is non-calcareous, lacks body or trace fossils, and massively bedded; two laterally discontinuous (over 25 m) sandstone channels are present in this unit; the channels maximum thickness are 45 (lower) and 35 (upper) cm; the lower channel scours within 3-5 cm of the underlying carbonate channel; the sandstone is very fine-grained, quartz-rich but argillaceous; the unit as a whole has a sharp basal contact and is laterally continuous over the exposure.

32	0.10	73.35	Mudstone, light olive gray (5Y 6/1), impregnated with carbonate nodules, dark yellowish orange (10YR 6/6); argillaceous micritic mudstone; very weakly to moderately calcareous; no body or trace fossils; minor vertical fracture porosity; nodules are up to 30 cm in length and 30 cm in width; some nodules appear to coalesce; unit is nodularly bedded; sharp basal contact and laterally continuous over the exposure. **P3-9.6**
33	1.00	74.35	Mudstone, dusky red (5R 3/4); non-calcareous to very weakly calcareous; no body or trace fossils; carbonate nodules in the basal 10 cm; massively bedded; sharp basal contact and laterally continuous over the exposure.
34	1.25	75.60	Mudstone, light greenish gray (5GY 7/1); very weakly calcareous to calcareous; no body fossils; uppermost 10 cm in bioturbated (?termite galleries); Fe mottles along subhorizontal fractures; massively bedded; sharp basal contact and laterally continuous over the exposure.

~~~~~ K-1 unconformity ~~~~~

LYTLE FORMATION

3.00	3.00	Sandstone, grayish yellow (5Y 8/4); predominantly very fine- to medium-grained, well-sorted quartzarenite; locally conglomeratic; very weakly calcareous; no body or trace fossils noted; trough cross bedding; massive cliff-former; sharp erosive basal contact and laterally continuous over the area.
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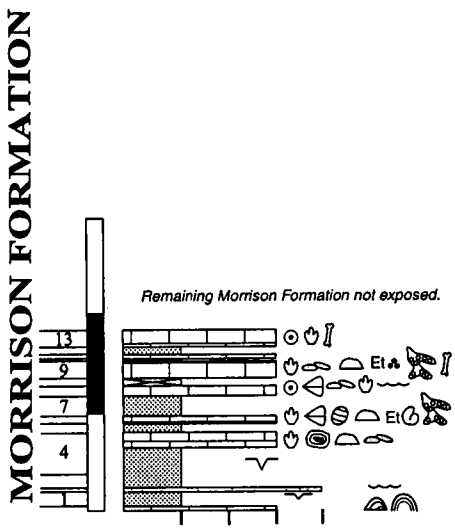
Figure A.11. Stratigraphic section measured at the Purgatoire Trackway outcrop.


MORRISON FORMATION
Remaining Morrison Formation not exposed.
13
9
7
4
Et A
Et B

Purgatoire Trackway (PT1, PT2, PT3)

The Purgatoire Trackway sections are located approximately 44 km south-southwest of La Junta, Colorado, in Picketwire Canyon, Comanche National Grasslands, which are managed by the U.S. Forest Service. Permission to enter and collect must be obtained from the U.S. Forest Service in La Junta. The trackway sections are located at a latitude of 37°37.083'N and a longitude of 103°35.783'W.

The described section below is a composite derived from three sections within 250 m of each other. The sample designations PT*x* (1, 2, or 3) refers to the three different sections. Note that the measurements of hand specimen do not correspond to the cumulative thickness of the composite section. Also, note that neither the base nor the top of the Morrison Formation is exposed at this locality. Fred Peterson (unpublished data) has suggested that the main dinosaur trackway of Lockley *et al.* (1985) at this section correlates to the distinctive silicified "blue agate" limestone in Unit 3 at the Purgatoire section.

Unit	T (m)	CT (m)	Description
			Basal portion of section not exposed.
MORRISON FORMATION			
	0.10	0.10	Limestone, light olive gray (5Y 6/1) to medium light gray (N6); skeletal mudstone; strongly calcareous; silty; conchostracans and minor microbial laminations; desiccation cracks; massively bedded; basal contact is not exposed and laterally continuity is limited to about 20 m. **PT1-[-0.1], PT3-[-0.5],** ***PT1-[-0.1], PT3-[-0.5]***
1	0.40	0.50	Mudstone, light olive gray (5Y 6/1) to light gray (N7); calcareous; no body or trace fossils; desiccation cracks penetrate from the top of this unit down 8 cm; massively bedded; sharp basal contact and laterally continuous over the exposure.
2	0.10	0.60	Sandstone, light brownish gray (5YR 6/1); medium-grained, moderately sorted sublitharenite; calcareous; no body or trace fossils; 2-D wave ripples (λ = ~20 cm); carbonate and green mudstone rip-up clasts at the base of the unit; friable; massively bedded; sharp basal contact; laterally continuous over the exposure.
3	1.05	1.65	Mudstone, light olive gray (5Y 6/1); calcareous; silty; no body or trace fossils; minor desiccation cracks are rare; massively bedded except where disturbed due to differential compaction related to dinoturbation, where compacted to thin beds; sharp to diffuse basal contact and laterally continuous over the exposure.
4	0.40	2.05	Limestone, light olive gray (5Y 6/1) to light brownish gray (5YR 6/1); skeletal wackestone; strongly calcareous and argillaceous; minor gastropods; dinoturbation is present; sharp basal contact; the unit thins and pinches out laterally over 100 m. **PT1-0.95, PT3-0.5,** ***PT3-0.5***
5	0.20	2.25	Mudstone, light olive gray (5Y 6/1); calcareous; no body or trace fossils; minor carbonate nodules; bedding disturbed due to differential compaction related to dinoturbation; generally massively bedded except around the tracks; sharp basal contact and laterally continuous over the exposure. **PT1-1.2**

6	0.20	2.45	Limestone, light olive gray (5Y 6/1) to light brownish gray (5YR 6/1); skeletal wackestone; strongly calcareous; gastropods are common with rare unionid bivalves; minor dinoturbation and polygonal desiccation cracks up to 1 cm wide; minor porosity is present; massively bedded; sharp basal contact and laterally continuous over the exposure. **PT2-1.4, PT2-1.4B, PT3-1.0, *PT2-1.4, PT2-1.4b***
7	0.50	2.95	Mudstone, light olive gray (5Y 6/1); calcareous; no body or trace fossils; disturbed due to differential compaction related to dinoturbation; massively bedded except around dinosaur tracks, where compacted to thin beds; sharp basal contact and laterally continuous over the exposure.
8	0.25	3.20	Limestone, very light gray (N8) to light brownish gray (5YR 6/1); ooid grainstone; strong calcareous; ooids with minor intraclasts and unionid bivalves; main dinosaur trackway as described in Lockley *et al.* (1986); dinoturbation thickens the limestone up to 0.65 m; cross-laminations and isolated ooid sand waves (λ = 10 cm); pink spar filled porosity; nodularly to massively bedded; sharp basal contact and laterally continuous over the exposure. **PT3-1.7, *PT3-1.7***
	0.20	3.40	Covered interval
9	0.45	3.85	Limestone, light brownish gray (5YR 6/1); micritic mudstone; strong calcareous; tuffaceous(?); arenaceous; no body fossils; dinoturbation; nodularly bedded; sharp basal contact and laterally continuous over the exposure. **PT3-2.3, *PT3-2.3***
10	0.05	3.90	Mudstone, light olive gray (5Y 6/1); calcareous; silty; no body or trace fossils; diffuse thin beds; sharp basal contact and laterally continuous over the exposure.
11	0.10	4.00	Limestone, light brownish gray (5YR 6/1); ooid packstone; strong calcareous; ooids; no body or trace fossils; massively bedded; sharp basal contact and laterally continuous. **PT3-2.5, PT3-2.5B, *PT3-2.5B***
12	0.20	4.20	Mudstone, light olive gray (5Y 6/1); calcareous; silty; no body or trace fossils; diffuse thin beds; sharp to diffuse basal contact and laterally continuous over the exposure.
13	0.45	4.65	Limestone, light gray (N7) to light brownish gray (5YR 6/1); ooid intraclast packstone; strong calcareous; ooids, intraclasts (green mudstone), and oncoids(?); dinoturbation; nodularly to massively bedded; sharp basal contact and laterally continuous over the exposure. **PT3-3.0, *PT3-3.0***

APPENDIX B:

STABLE ISOTOPE DATA

Open Lacustrine Facies (micritic matrix)

Sample	Description	$\delta^{18}O$	$\delta^{13}C$
SD-18.15-B	micrite from bioturbated and faintly laminated skeletal wackestone; contains minor dolomicrite	-9.01	-2.90
SD-18.5-A	micrite from bioturbated and faintly laminated skeletal wackestone	-8.34	-2.65
SDS-1.45-C	micrite from skeletal wackestone; possible contamination from ostracodes	-9.96	-3.33
HR-7.5-7.65B-A	micrite from skeletal mudstone; Magadi-type cherts are common	-9.03	-3.66
HR-7.85-A	micrite from skeletal mudstone between two Magadi-type chert lens	-9.26	-4.16
HR-10.0-A	micrite from skeletal mudstone below Magadi-type chert lens	-9.85	-4.33
PCS-12.5a-1-A	micrite from mudstone laminae between ostracode packstone layers above microbial buildups	-9.93	-2.78
PCS-12.5a-2-B	micrite from mudstone laminae between ostracode packstone layers above microbial buildups	-9.27	-2.57
Total (n): 8	Minimum:	-9.96	-4.33
	Maximum:	-8.34	-2.57
	Average:	-9.33	-3.30

Marginal Lacustrine Facies (micritic matrix)

Sample	Description	$\delta^{18}O$	$\delta^{13}C$
CQ-29.6A-B	micrite from skeletal wackestone to packstone; minor dolomicrite (<10%)	-10.71	-4.42
CQ-29.6B-A	micrite from skeletal peloidal wackestone to packstone; very minor dolomicrite (<10%)	-8.52	-2.99
H-23.5-A	micrite from brecciated clast in silty intraclast wackestone	-10.72	-5.96
H-23.9-A	micrite from skeletal mudstone with minor dolomicrite	-9.92	-5.75
H-24.25-A	micrite from silty skeletal mudstone	-10.09	-6.02
H-38.7-A	micrite from silty mudstone with abundant quartz	-10.49	-6.01
H-41.0b-B	micrite from clast surrounded by circumgranular crack in skeletal intraclast wackestone-packstone	-10.66	-7.03
HR-11.25-A	micrite from skeletal mudstone with abundant detrital quartz	-10.46	-4.09
HR-65.2-A	micrite from intraclast; intraclast-skeletal packstone with abundant pseudomicrokarst	-11.82	-6.19
I70-27.6-A	micrite from clayey mudstone; minor dolomicrite	-9.68	-5.36
I70-40.4-A	micrite from mudstone; minor fenestral porosity and meniscate burrows; pseudomicrokarst is common	-10.35	-5.28
I70-42.7-A	micrite from mudstone with abundant pseudomicrokarst	-8.92	-4.33
I70-51.7-A	micrite from clayey mudstone; ~2 cm from base of billet	-10.08	-6.62
I70-51.7-B	micrite from clayey mudstone; 3.5 cm from base of billet	-8.92	-5.61
I70-51.7-C	micrite from clayey mudstone; 5.8 cm from base of billet	-9.78	-5.79

I70-55.3-A	micrite from marly mudstone; 6.2 cm from base of billet (right side); possible contamination from weathered limonitic fractures	-10.77	-8.80
I70-55.3-B	micrite from marly mudstone; 2 cm from base of billet	-9.15	-8.01
I70-55.3-C	micrite from marly mudstone; 3.6 cm from base of billet	-9.67	-8.17
I70-55.3-D	micrite from marly mudstone; 6.5 cm from base of billet (left side of billet)	-9.51	-8.47
I70-64.2-A	micrite from laminated skeletal wackestone; possible contamination from ostracodes or intergranular porosity	-9.93	-6.05
MFQ-18.2-A	micrite from mudstone; abundant detrital quartz and evaporite pseudomorphs	-8.37	-2.77
MFQ-23.9-A	micrite from skeletal mudstone; ~ 1 cm from the base of the billet	-10.56	-6.82
MFQ-23.9-B	micrite from skeletal mudstone above clastic (quartz and feldspar) fining upward bed (2-3 cm); 3.5 cm from the base of the billet	-10.32	-4.53
MFQ-23.9-C	micrite from light-colored mudstone laminae; 4 cm from the base of the billet	-9.41	-4.47
MFQ-23.9-D	micrite from mudstone; 4.5 cm from the base of the billet	-9.14	-4.36
MFQ-23.9-E	micrite from mudstone laminae between coarse clastic beds; 6.4 cm from the base of the billet; possible contamination from clastic beds	-10.30	-3.98
MFQ-24.1-A	micrite from mudstone ; 5 mm from large (2 cm) pseudomorphs after evaporites; 9 cm from the base of MFQ-23.9	-10.11	-4.08
P2-1.25-A	micrite from clay-rich mudstone; pseudomorphs after evaporites present in basal 3 cm of billet; sample from 6.5 cm from base of the billet	-10.03	-7.98
P2-1.25-B	micrite from clay-rich mudstone; pseudomorphs after evaporites present in basal 3 cm of billet; sample from 3.6 cm from base of the billet	-10.21	-7.86
P2-1.25-C	micrite from clay-rich mudstone; pseudomorphs after evaporites present in basal 3 cm of billet; sample from 2.6 cm from base of the billet	-10.42	-7.67
P2-10.0-A	micrite lens from skeletal-peloid-intraclast packstone; pseudomorphs after gypsum present	-11.08	-4.40
P2-9.05-A	micrite from laminated clay-rich and silty mudstone; rhizoturbated	-9.43	-3.16
PT-[-0.1]-A	micrite from skeletal mudstone laminae within microbial laminate; Magadi-type cherts are present	-9.89	-4.49
PT3-0.5-A	micrite from skeletal mudstone below oncoid skeletal packstone	-9.07	-3.20
PCR-12.0B-A	micrite from skeletal mudstone-wackestone; abundant fenestral porosity and pseudomicrokarst; possible ostracode or fenestral porosity contamination	-12.99	-7.64
PCR-5.0-A	micrite from a bioturbated skeletal mudstone; minor detrital quartz and possible contamination from skeletal fragment	-9.68	-3.56
PCS-18-A	micrite from clayey mudstone; 2.5 cm from base of the billet near red mottling	-9.34	-2.58
PCS-18-B	micrite from clayey mudstone; 4.5 cm from base of the billet	-10.16	-3.82
SD-12.75B-A	micrite from skeletal mudstone-wackestone; minor detrital quartz and pseudomicrokarst	-8.94	-3.87
SD-7.25-.35-1-A	micrite from carbonate nodule (skeletal mudstone) in green mudstone	-8.26	-4.56

SD-7.25-.35-2-A	micrite from carbonate nodule (skeletal mudstone) in green mudstone	-10.26	-4.39
WAP-0.8-0.87-A	micrite from silty mudstone	-10.10	-5.26
WAP-5.0-A	micrite from mudstone	-8.58	-6.94
WAP-6.6-A	micrite from bioturbated mudstone with volcanic rock fragments	-9.92	-6.44
WAP-7.05-A	micrite from mudstone with abundant green mudstone rip-up clasts	-8.39	-6.12
WAP-10.3-A	micrite from skeletal mudstone	-11.94	-5.12
WAP-10.4-A	micrite from skeletal mudstone	-10.34	-6.04
WAP-18.8-A	micrite from mudstone with abundant volcanic rock fragments and detrital quartz	-11.30	-5.08
Total (n): 48	Minimum:	-12.99	-8.80
	Maximum:	-8.26	-2.58
	Average:	-9.97	-5.46

Pedogenic Carbonate

Sample	Description	$\delta^{18}O$	$\delta^{13}C$
H-13.2-1-A	micrite from pedogenic nodule	-9.24	-5.08
H-8.6-A	micrite from pedogenic nodule; < 15% dolomicrite	-11.00	-4.69
HR-15-A	micrite from pedogenic nodule with minor cracks	-10.97	-5.77
HR-24.9-1-A	micrite from pedogenic nodule with minor cracks; < 15% dolomicrite	-9.33	-4.75
Total (n): 4	Minimum:	-11.00	-5.77
	Maximum:	-9.24	-4.69
	Average:	-10.14	-5.07

Diagenetic Components

Sample	Description	$\delta^{18}O$	$\delta^{13}C$
CQ-29.6A-A	ferroan blocky calcite from intragranular gastropod void in skeletal wackestone-packstone; gastropod shell is silicified with Magadi-type chert	-8.05	-4.80
H-0.4a-A	non-ferroan drusy calcite from horizontal fracture void in skeletal peloidal packstone	-12.28	-4.11
H-1.25-A	coarse-crystalline non-ferroan drusy calcite from dissolutional void in skeletal peloidal wackestone-packstone	-14.65	-4.90
H-32.1-A	non-ferroan drusy calcite from dissolutional void in skeletal wackestone	-12.88	-10.65
HR-68.5-A	ferroan blocky calcite from dissolutional void in bioturbated mudstone; mudstone displays intense pseudomicrokarst	-12.61	-15.53
I70-64.2-B	weakly ferroan calcite from dissolutional void in skeletal wackestone	-9.71	-8.35
MFQ-23.9-F	ferroan equant drusy calcite from pseudomorph after evaporite (?)trona in micritic mudstone; minor late stage silicification in void	-9.83	-6.49
P2-1.25-D	weakly ferroan drusy calcite from pseudomorph after evaporites (?)trona; marly micritic mudstone	-12.58	-5.42
PCR-2.65-A	non-ferroan blocky calcite from vertical fracture in silicified (Magadi-type chert) microbial laminates	-11.41	-4.33
SD-18.15-A	coarse-crystalline ferroan blocky calcite from dissolutional porosity in skeletal wackestone	-10.92	-10.97
SD-18.35-A	ferroan blocky calcite from vertical fracture in skeletal wackestone	-11.92	-8.68
SD-18.5-B	ferroan blocky calcite from intragranular porosity (gastropod) in skeletal wackestone; contamination from micritic matrix possible	-11.28	-6.71
SDS-1.45-B	coarse-crystalline non-ferroan blocky calcite from void in skeletal wackestone; megaquartz cement also present; contamination from micritic matrix possible	-8.47	-3.07
Total (n): 13	Minimum:	-14.65	-15.53
	Maximum:	-8.05	-3.07
	Average:	-11.27	-7.23

Morrison Carbonate Stable Isotope Standards

#	Standard	Method	$\delta^{18}O$	$\delta^{13}C$	±1 σ $\delta^{18}O$	±1 σ $\delta^{13}C$
709	ANU M1	s	-6.105	1.485	0.006	0.004
928	ANU M1	s	-6.231	1.351	0.022	0.003
1359	ANU M1	c	-6.187	1.256	0.055	0.010
1360	ANU M1	c	-5.642	1.650	0.089	0.044
1486	ANU M1	c	-6.085	1.361	0.025	0.006
1487	ANU M1	c	-6.240	1.337	0.038	0.015
1488	ANU M1	c	-6.324	1.321	0.042	0.004
1489	ANU M1	c	-6.231	1.383	0.032	0.024
1501	ANU M1	c	-5.928	1.219	0.024	0.011
1506	ANU M1	c	-6.456	1.181	0.041	0.015
1510	ANU M1	c	-6.271	1.109	0.035	0.025
1521	ANU M1	c	-6.504	1.199	0.048	0.023
2849	ANU M1	c	-6.388	1.243	0.072	0.020
		average:	***-6.199***	***1.315***	***0.041***	***0.016***
		±1 σ:	***0.228***	***0.142***	***0.022***	***0.012***
1371	ANU M2	c	-6.295	3.258	0.115	0.060
1372	ANU M2	c	-6.272	3.337	0.115	0.052
1374	ANU M2	c	-6.439	3.204	0.081	0.047
1382	ANU M2	c	-6.940	3.005	0.124	0.064
1383	ANU M2	c	-7.368	2.807	0.055	0.033
1384	ANU M2	c	-7.224	2.889	0.044	0.036
2800	ANU M2	c	-8.258	2.138	0.028	0.019
2801	ANU M2	c	-7.663	2.424	0.024	0.018
2802	ANU M2	c	-7.546	2.487	0.024	0.032
2807	ANU M2	c	-7.498	2.246	0.036	0.025
2812	ANU M2	c	-6.988	2.863	0.027	0.020
2813	ANU M2	c	-7.091	2.873	0.036	0.028
2824	ANU M2	c	-7.367	2.442	0.023	0.025
2825	ANU M2	c	-7.086	2.472	0.022	0.025
2829	ANU M2	c	-7.154	2.543	0.026	0.024
		average:	***-7.146***	***2.733***	***0.052***	***0.034***
		±1 σ:	***0.532***	***0.372***	***0.038***	***0.015***

#	Standard	Method	$\delta^{18}O$	$\delta^{13}C$	±1 σ $\delta^{18}O$	±1 σ $\delta^{13}C$
919	ANU PRM-2	s	-17.333	0.880	0.018	0.011
927	ANU PRM-2	s	-17.296	0.920	0.040	0.014
929	ANU PRM-2	s	-17.345	0.873	0.013	0.009
		average:	***-17.325***	***0.891***	***0.024***	***0.011***
		±1 σ:	***0.026***	***0.025***	***0.014***	***0.002***
657	CHCC	s	-9.277	-10.540	0.014	0.011
672	CHCC	s	-11.386	-11.680	0.065	0.022
674	CHCC	s	-9.553	-10.614	0.044	0.018
717	CHCC	s	-8.340	-10.419	0.045	0.048
		average:	***-9.639***	***-10.814***	***0.042***	***0.025***
		±1 σ:	***1.275***	***0.583***	***0.021***	***0.016***
1492	NBS 18	c	-22.811	-4.827	0.052	0.018
1497	NBS 18	c	-22.693	-4.974	0.031	0.022
1505	NBS 18	c	-22.964	-4.995	0.019	0.009
1516	NBS 18	c	-22.800	-5.081	0.054	0.021
1531	NBS 18	c	-22.719	-4.919	0.047	0.015
2797	NBS 18	c	-22.238	-4.986	0.038	0.025
2798	NBS 18	c	-22.673	-4.914	0.022	0.016
2799	NBS 18	c	-22.321	-4.969	0.024	0.020
2818	NBS 18	c	-22.596	-5.021	0.037	0.014
2834	NBS 18	c	-22.533	-5.028	0.038	0.023
2835	NBS 18	c	-22.781	-5.139	0.038	0.019
2836	NBS 18	c	-22.071	-4.556	0.086	0.609
2837	NBS 18	c	-21.944	-4.712	0.050	0.018
2842	NBS 18	c	-22.156	-4.720	0.026	0.037
2843	NBS 18	c	-22.016	-4.758	0.271	0.197
2847	NBS 18	c	-23.328	-4.755	0.008	0.016
2850	NBS 18	c	-23.239	-4.989	0.040	0.029
2855	NBS 18	c	-22.276	-4.806	0.035	0.011
2860	NBS 18	c	-21.549	-4.763	0.028	0.014
2861	NBS 18	c	-22.304	-4.843	0.069	0.049
2867	NBS 18	c	-22.104	-4.622	0.025	0.007
2872	NBS 18	c	-22.712	-4.854	0.048	0.007
		average:	***-22.492***	***-4.874***	***0.049***	***0.054***
		±1 σ:	***0.435***	***0.152***	***0.052***	***0.130***

#	Standard	Method	$\delta^{18}O$	$\delta^{13}C$	±1 σ $\delta^{18}O$	±1 σ $\delta^{13}C$
937	NBS 20	s	-4.249	-1.042	0.016	0.013
				final average standard deviation (all data):	*0.039*	*0.081*

Notes:
1) # - refers to the assigned internal laboratory analysis number
2) Methods -
   s = single sample, vacuum off-line
   c = Carbo-Flo ™

Carbonate Stable Isotope Standards:

University of Tennessee
Stable Isotope Lab average values:

Standard	$\delta^{18}O$	σ	$\delta^{13}C$	σ
ANU M1	-6.07	0.12	1.27	0.06
ANU M2	-7.22	0.08	2.76	0.05
ANU PRM-2	-17.18	0.14	0.74	0.07
CHCC	-9.28	0.07	-10.68	0.06
NBS 18	-22.87	0.08	-5.11	0.05
NBS 20	-4.08	0.11	-1.08	0.11

Expected values
(all laboratories reporting):

Standard	$\delta^{18}O$	$\delta^{13}C$
ANU M1	-6.16	1.35
ANU M2	-7.35	2.81
ANU PRM-2	-17.41	0.72
CHCC	-9.23	-10.66
NBS 18	-23.00	-5.00
NBS 20	-4.14	-1.06

VITA

Stan Porter Dunagan was born in Columbia, Missouri, on July 19, 1970, to two wonderful parents. After short stints in Jefferson City, Missouri, and Fort Knox, Kentucky, Stan, at the tender age of two, and his family settled down in Martin, Tennessee. For the next 21 years, Stan would live, play, and go to school in Martin. In 1988, Stan graduated with an Honors Diploma from Westview High School in Martin and prepared to attend the University of Tennessee at Martin in August of 1988. After majoring in aerospace engineering and then history, Stan took an introductory geology class as a pre-law major and eventually changed majors for the last time to geology. Stan graduated from the University of Tennessee at Martin with highest honors in May of 1993 and in August left for "Big Orange" country and graduate school with the Department of Geological Sciences at the University of Tennessee. While in graduate school, Stan married Stephanie Carter – whom he had met as an undergraduate at Martin. Stan and Stephanie bounced around Greeneville and Johnson City, Tennessee as they tried to balance graduate school with the demands of medical school. After making good friends and having many good times in East Tennessee, Stan and Stephanie returned to Martin in December of 1997 for Stan to teach as an Adjunct Instructor at the University of Tennessee at Martin. In August 1998, Stan Porter Dunagan received his doctorate degree in geology from the University of Tennessee.