Petrology of the Morrison Formation, Dinosaur Quarry Quadrangle, Utah

by

S. A. Bilbey, R. L. Kerns, Jr.,

and J. T. Bowman

UTAH GEOLOGICAL AND MINERAL SURVEY
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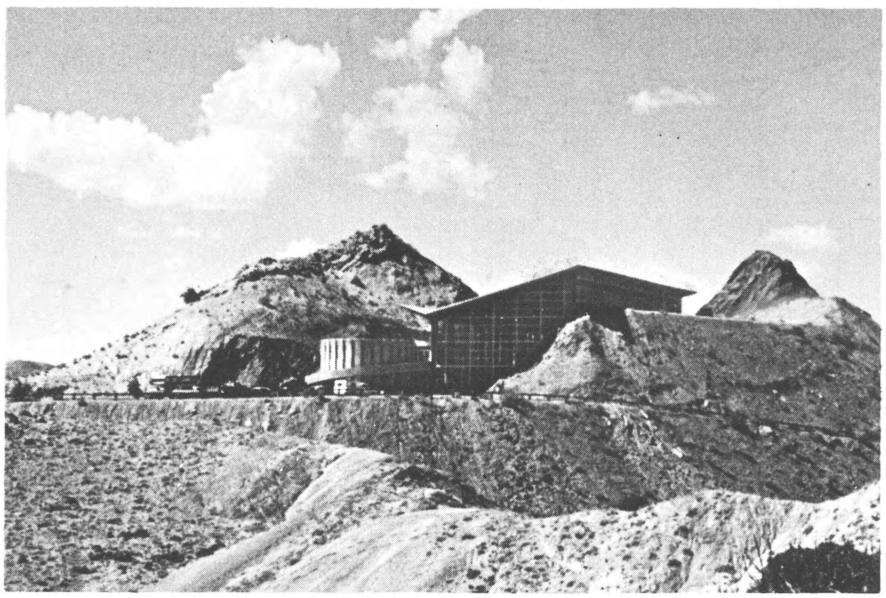

Dinosaur National Monument Quarry. Dinosaur National Monument, Utah. National Park Service, Department of the Interior.

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PETROLOGY OF THE MORRISON FORMATION, DINOSAUR QUARRY QUADRANGLE, UTAH

by Sue Ann Bilbey[1]*, Raymond L. Kerns, Jr.*[2]*, and James T. Bowman*[3]

ABSTRACT

Mineralogical and petrographic analyses of the Upper Jurassic-Lower Cretaceous units in the vicinity of the Dinosaur National Monument Quarry near Jensen, Utah, have clarified the units' characteristics and the locations of formational boundaries. The lower part of the Morrison Formation is distinguished by less illite and more kaolinite in contrast to the underlying Curtis Formation which contains approximately equal amounts of illite and kaolinite. The Salt Wash Member and the Brushy Basin Member of the Morrison are both lithologically and mineralogically identifiable in this area. Above the boundary between the two, kaolinite decreases and illite increases. In the strata above the Morrison, here recognized as an extension of the Cedar Mountain Formation, kaolinite is the dominant clay mineral, and illite is almost completely absent. The formations in the area represent differing depositional environments: the upper Curtis Formation is a near-shore marine deposit, the members of the Morrison Formation are fluvial and lacustrine and possible climatic or depositional changes during the depositional period are equated with the changes in the clay content, and the Lower Cretaceous sediments now comprising the Cedar Mountain Formation overlying the Morrison were formed in a transitional zone (fluvial to littoral) and were eventually covered by the Dakota Formation (littoral).

INTRODUCTION

The Morrison Formation, originally defined as the variegated shales and sandstones found in the eastern foothills of the Front Range of the Rocky Mountains near Morrison, Colorado, was named by Cross (1894). Eldridge first described and placed definite boundaries on an incomplete section near Morrison (Emmons and others, 1896). These boundaries were redefined by Lee (1920), but the type section was not completely described until 1944 (Waldschmidt and Leroy, 1944). The formation has since been recognized over an area of more than 600,000 square miles from southern Canada to central Arizona and New Mexico, and from southern Idaho and central Utah to Iowa and Kansas (Peterson, 1972). The strata later assigned to the Morrison Formation in Dinosaur National Monument were originally described as part of the Flaming Gorge Group (Powell, 1876), until the discovery of the dinosaur beds near Jensen, Utah, caused the strata to be formally recognized as the Morrison Formation (Gilmore, 1916).

Due to the lack of a diagnostic age indicator of the Morrison Formation, there has been considerable controversy over whether it is Jurassic, Cretaceous, or both. Eldridge (Emmons *et al.*, 1896) originally assigned the unit to the Jurassic period, but others (Lee, 1915; Osborn, 1915) claimed that it is of Cretaceous age. The consensus of more recent reports is that the Morrison Formation represents the Upper Jurassic from Kimmeridgian to early Portlandian (Simpson, 1926; Baker *et al.*, 1936; Imlay, 1952).

In the area of Dinosaur National Monument, the Morrison Formation rests on the Upper Jurassic Curtis Formation and underlies unnamed Lower Cretaceous rocks (Reeside, 1923; Untermann and Untermann, 1949; Bradley, 1952). Stokes (1952; 1955) identified the Cedar Mountain Formation as far north as the south flank of the Uinta Mountains and speculated on its correlation with the unnamed Lower Cretaceous rocks in Dinosaur National Monument. To facilitate the ensuing discussion, the unnamed unit above the Morrison and below the Dakota will be called the Cedar Mountain Formation.

The Morrison Formation has been divided into four members–the Salt Wash Member (Lupton, 1914; Gilluly and Reeside, 1928), the Brushy Basin Member, the Westwater Canyon Member, and the Recapture Member (Gregory, 1938). Of these four, only the Salt Wash and Brushy Basin Members extend into northeastern Utah (Craig *et al.*, 1955).

The Salt Wash Member is recognized as the oldest member of the Morrison Formation, correlative in part with the Recapture Member (Craig *et al.*, 1955), and is characterized by two lithologies–white to pale brown, massive, ridge-forming sandstones and greenish-gray to dark reddish-brown siltstones and mudstones. The siltstones and mudstones are poorly resistant and thick-bedded (Cadigan, 1967). The origin of these sediments was mainly a sedimentary rock source with some

[1] Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112.
[2] Assistant Professor of Geology, Utah State University, Logan, Utah 84322.
[3] Associate Professor of Biology, Utah State University, Logan, Utah 84322.

evidence for a minor volcanic source (Cadigan, 1967). The thickening of this deposit and the increase in grain size to the west and southwest and the thinning to the east and northeast indicate major source areas in Arizona, southern Nevada, and western Utah (Mook, 1915; Craig *et al.*, 1955; Cadigan, 1967).

The Brushy Basin Member is the younger of the two members present and is correlative with the Westwater Canyon Member in New Mexico (Cadigan, 1967). This is the more easily distinguished of the members due to its diagnostic variegated shales and mudstones. The beds vary in color from pale green to reddish-brown to purple. The lithology of this member is not restricted, however, to shales. Between some of these shales are thick-bedded, lenticular, conglomeratic sandstones containing the well-known fossil dinosaur fauna. The source area of the fine-grained sediments is the same as that of the Salt Wash, but with lower gradients, which account for the finer grain size (Craig *et al.*, 1955; Cadigan, 1967). The Brushy Basin also contains large quantities of volcanic tuff fragments, indicating a possible volcanic source area to the west (Hess, 1933; Stokes, 1944; Keller, 1953, 1962; Peterson, 1966; Cadigan, 1967; Suttner, 1968, 1969; Brady, 1969; Furer, 1970).

According to Mook (1916), the deposition of the Morrison Formation took place on a peneplain fed by several major streams and by many minor intermittent ones in which sediments accumulated in lakes and floodplain marshes. Mook also postulated that, as on any flat plain near sea level, there was much shifting of channels and reworking of sediments to form the greatly variable lithology, both laterally and vertically. The climatic conditions at the time of deposition of the Morrison Formation were compared to those of the modern Yangtze and Hwang-Ho river plains. Mook considered the fossil flora and the semi-aquatic fauna to be indicative of a wet, hot climate.

Stokes (1944), on the other hand, argued that a wet climate is not indicated. He found no strong evidence for great river systems, *i. e.* no great increase in clastic sediments to the west, and very few plant fossils suggesting the existence of ephemeral lakes and intermittent streams which provided enough water and vegetation for the dinosaurs.

A third environment was proposed by Moberly (1960) who suggested a savannah-like climate with alternate seasons of wetness and dryness. His postulated paleogeography allows radical seasonal changes comparable to the monsoon season in Southeast Asia, and accounts of the presence both of trees 50 feet tall and of salt precipitates.

The presence of dinosaur bones and uranium has stimulated extensive petrologic and petrographic work on the Morrison. Mook's (1916) discussion of descriptive petrography and petrology laid the foundation for many of the studies which followed. Interest in radioactive minerals has prompted several mineralogical analyses of the clay minerals in the formation (Weeks, 1953; Keller, 1953, 1959, 1962); other such studies have been directed toward clarifying the depositional environment and source areas (Tank, 1956; Brady, 1969; Ballard, 1966; Cadigan, 1967; Suttner, 1968; Furer, 1970). Wahlstrom (1966) included some geochemical data on the Morrison, and many workers have investigated the ore deposits (see Brown, 1961, for a comprehensive bibliography).

The Cedar Mountain Formation was originally defined on the southwestern flank of Cedar Mountain, Emery County, Utah, by Stokes (1944), as part of the Cedar Mountain Group which included both the Cedar Mountain Formation and the Buckhorn Conglomerate. Stokes (1952) combined the two units. These Lower Cretaceous rocks are found above the Morrison Formation in the Colorado Plateau area. Stokes (1952) measured many sections of the Morrison Formation and the strata above the Morrison along the south flank of the Uinta Mountains. He found the same lithologies and the same stratigraphic relationships as in the San Rafael Swell, where the formation was first identified.

According to Stokes (1944), the Buckhorn Member of the Cedar Mountain Formation is a massive conglomerate with chert pebbles 1.25 inch in diameter and smaller, gradually changing to a thin-bedded, coarse-grained sandstone along the northern edge of the member. The shales and sandstones of the Cedar Mountain Formation above the Buckhorn Member are similar to those of the Morrison Formation, however, the colors in the shales are less variable and more subdued. The lower shales are pale red to light purple, grading upward to dull gray and white. There are numerous lenticular sandstones which appear to be channel deposits. In northeastern Utah, this formation is overlain by the Dakota Formation.

The present study was undertaken to complement existing stratigraphic and paleontologic data in order to generate a more complete data base for interpreting the phenomena in Dinosaur National Monument.

ACKNOWLEDGEMENTS

The authors sincerely appreciate the critical reading of the manuscript by Dr. W. L. Stokes. The National Park Service expedited the project by granting permission for the field work to be conducted on

Dinosaur National Monument lands and the cooperation of the Monument personnel was invaluable. The work was completed while Sue Ann Bilbey was a graduate student in geology at Utah State University.

GENERAL GEOLOGY

Dinosaur National Monument is located at the eastern end of the Uinta Mountains in northeastern Utah and northwestern Colorado (figure 1). The Dinosaur Quarry is in the western portion of the monument, seven miles north of Jensen, Utah, in the Dinosaur Quarry Quadrangle (USGS map, 7½-minute survey series). Within the quadrangle are the three stratigraphic sections discussed here. The geology of the monument area was studied extensively by Untermann and Untermann (1949), and their work is the basis for the following general description.

The geologic structures of the Monument area include minor flank folds and faults of the Uinta Mountain system. One of the larger folds is Split Mountain anticline in which the strata dip slightly at the crest and plunge steeply (maximum dip 67°) on the flanks. Erosion of these strata has exposed the Morrison Formation almost continuously around the periphery of Split Mountain. Differential weathering and erosion of the formations form hogbacks, cuestas, and valleys, all of which are essentially free of vegetation due to the semi-arid climate.

The stratigraphic sequence exposed within Dinosaur National Monument includes the Uinta Mountain Group (Precambrian) through the Browns Park Formation (Pliocene) with the exception of rocks representing the Ordovician through the Devonian periods. The Split Mountain anticline exposes rocks from the Madison Formation (Mississippian) through the Mancos Formation (Upper Cretaceous) in a sedimentary sequence of limestones, dolomites, sandstones, shales, and mudstones. The Jurassic strata containing the Morrison Formation in which the Dinosaur National Monument Quarry is located are exposed on the south flank of the Split Mountain anticline.

METHODS

Three sections 0.3 to 0.5 mile apart were stratigraphically measured and sampled. The Dinosaur Quarry is located between sections 1 and 2 and section 3 is east of section 2 (figure 1). The measured sections included the upper part of the Curtis Formation, the Morrison and Cedar Mountain Formations, and the lower part of the Dakota Formation. Samples were taken every 10 lineal feet and obvious lithologic changes were sampled even though they did not occur at the regular 10-foot intervals.

Section 2 was chosen as the representative section because it is between the other two, contains some facies of both, and is closest to the Dinosaur Quarry. Precise correlation of the three sections is possible for only a few beds, the most prominent being the quarry layer because the Morrison Formation is a continental deposit. All three stratigraphic sections are illustrated (figure 2), but only the representative section has been studied in detail.

Powder preparations ($\leqslant 3.0\ \phi$) of all samples from the middle section were analysed by X-ray diffraction to determine the relative abundances of quartz, dolomite, and calcite and other minor mineral constituents, except the clay fraction. The relative quantities of illite, montmorillonite, and kaolinite were measured by analyzing scans of sedimented preparations of particulate material $\leqslant 2\ \mu$, both before and after being solvated with ethylene glycol.

The samples chosen for petrographic analysis were selected from among the consolidated sandstones, conglomerates, limestones, and dolomites of section 2. A total of forty-eight samples were categorized according to lithology, mineralogy, and grain size and fifteen representative slides were selected for more extensive analyses; each slide was point-counted to determine the approximate percentages of the different minerals in the sample, the mineral grains were classified according to roundness (Powers, 1953), grain size, and sorting, and the entire slide was described according to the procedures outlined by Folk (1968). From this information, petrologic inferences on the source area, depositional area, and diagenetic changes were made.

STRATIGRAPHY

The Morrison Formation in Dinosaur National Monument is characterized by light gray to yellowish-gray sandstones and conglomerates below variegated shales and mudstones, and by lenticular, light gray limestones. The sandstones are massive with lenticular, channelled conglomerates and thin shales separating the major layers. The shales and mudstones above are thick units recognizable in the weathered valleys between resistant lenticular limestones and conglomerates. A detailed stratigraphic description of the representative section (section 2) is shown on page 6.

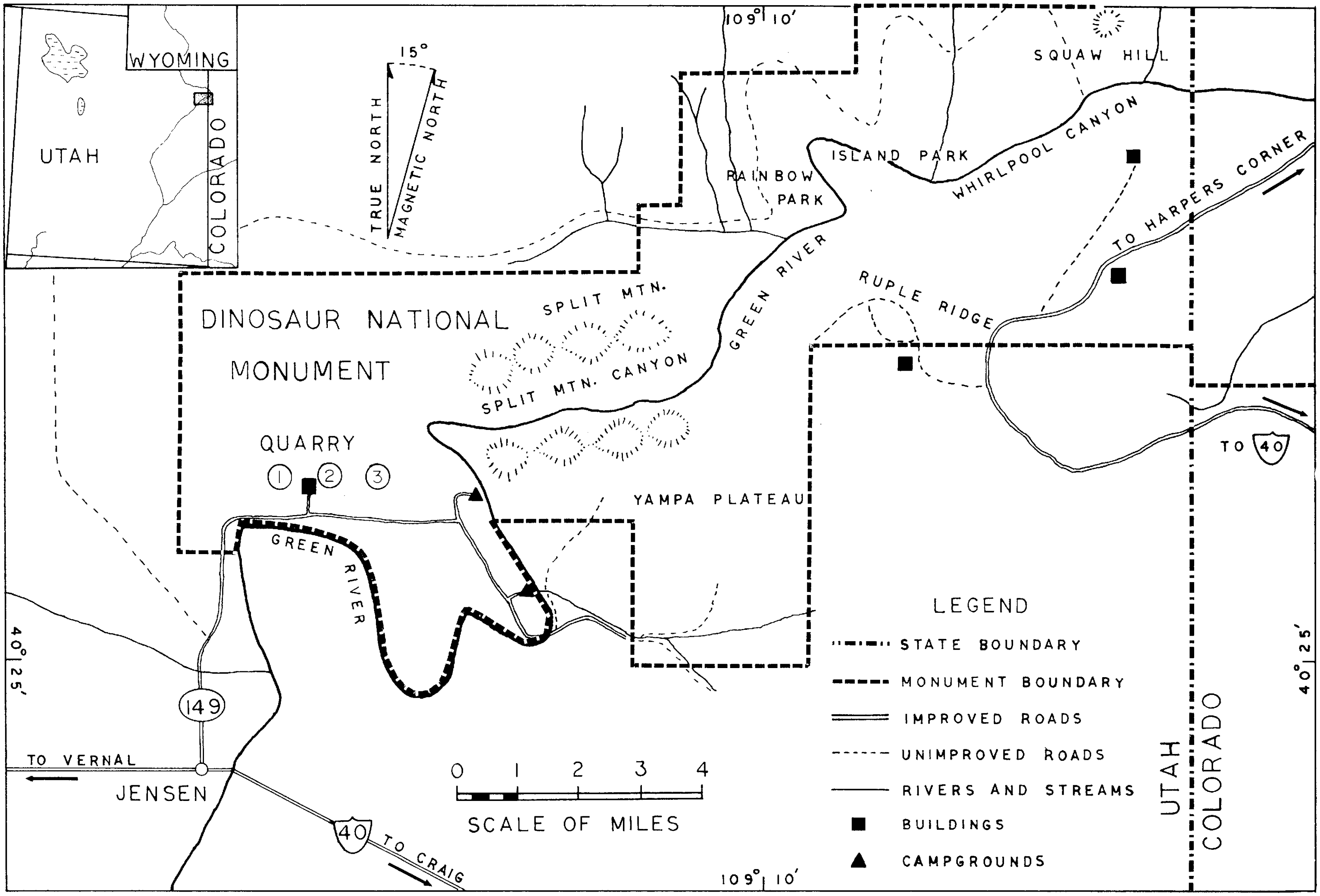

Figure 1. Index map of the western portion of Dinosaur National Monument.

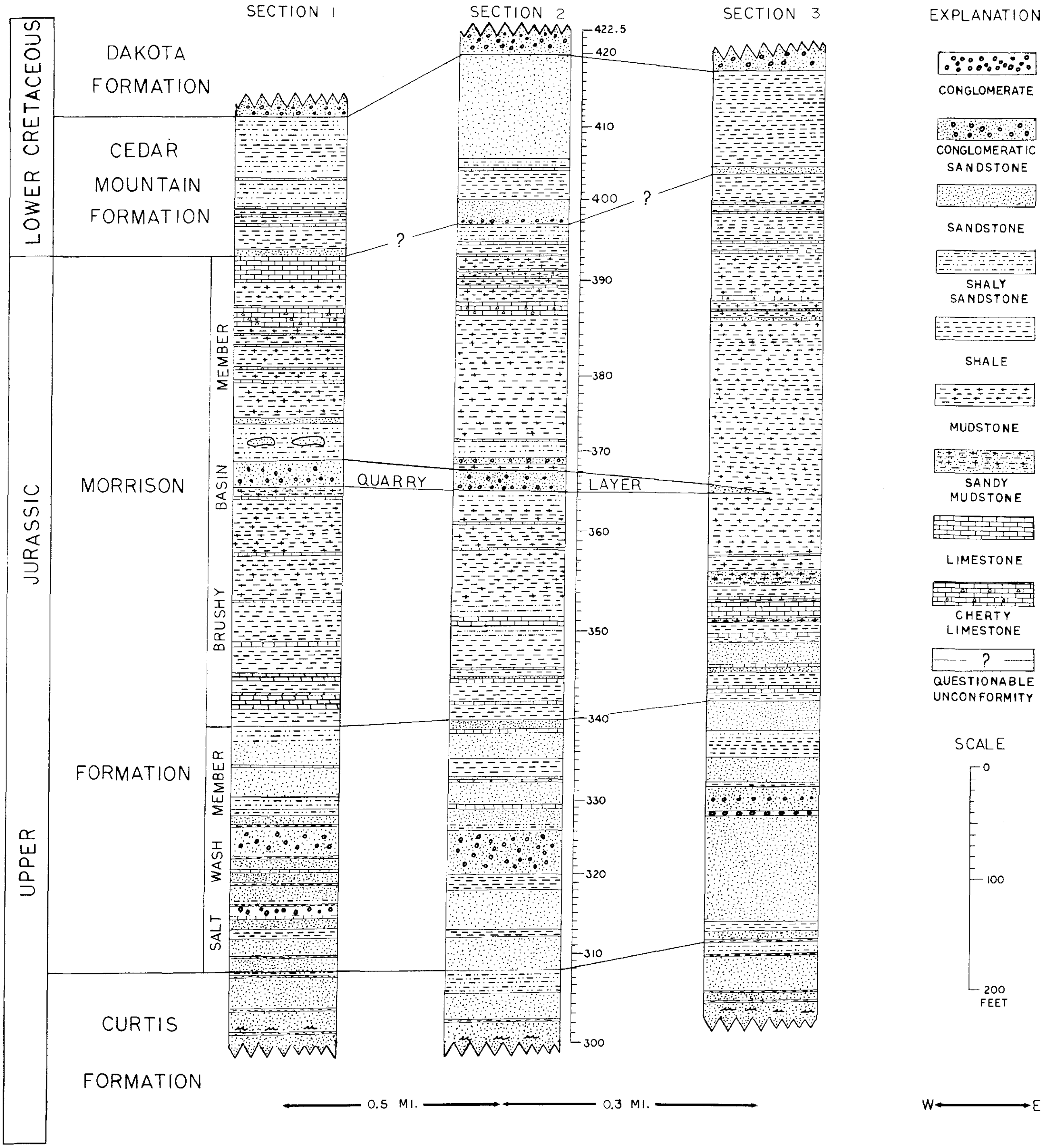

Figure 2. Stratigraphic columns of measured sections in Dinosaur National Monument including Upper Jurassic through Lower Cretaceous Formations.

Section 2: representative section.

Location: Dinosaur National Monument; nearly N-S line 0.2 mile east of Dinosaur Quarry; S ½ central portion Sec. 26, T. 4 S., R. 23 E., Uintah County, Utah.

Thickness, in feet

Dakota Formation

1. Conglomeratic sandstone; yellowish-gray; weathers very pale orange; poorly-sorted; fine- to coarse-grained; torrential cross-strata; ridge former.

Sharp contact between conglomerate and poorly resistant sandstone.

Cedar Mountain Formation

3. Sandstone; yellowish-gray to grayish-orange; weathers light brown; well-sorted; fine- to medium-grained; partially covered intervals with resistant ridges between; parallel bedding with minor low-angle cross-strata 90
2. Shale with one bed of recrystallized dolomite: yellowish-gray to brownish-gray; silt near the top; dolomite: very pale orange; very fine-grained; 2 ft thick 27
1. Sandstone; light gray to yellowish-gray; weathers grayish-orange; moderately- to well-sorted; fine-grained with a pebbly base; low-angle cross-strata; ridge former 23

Total Cedar Mountain Formation 140

Sharp contact of pebbly sandstone with Morrison shales.

Section offset 0.1 mile to the west following the sandstone ridge.

Morrison Formation
Brushy Basin Member

18. Shale; pale red to greenish-gray; silty; up to 10 ft beds; separated by lenticular dolomite beds: yellowish-gray; weathers light brownish-gray; 2 ft beds 57
17. Covered interval; talus of light gray limestone with chert; pits reveal yellowish-gray weathered mudstone 14
16. Limestone with chert pebbles and veins; light gray to yellowish-gray; 3 to 4 ft beds; ridge formers; probably source of limestone talus above and below 19
15. Covered interval; talus of light gray limestone; pits reveal weathered mudstone; light gray to brownish-gray 71
14. Mudstone; very light gray to greenish-gray with 1 ft beds of reddish-brown; one limestone bed 1 ft thick near the base 50
13. Covered interval; talus of yellowish-gray conglomeratic sandstone; pits reveal calcareous shaly sandstones; pale brown 15
12. Conglomeratic sandstone; yellowish-gray; poorly-sorted; coarse-grained; scours; mostly chert pebbles; calcareous cement. 4
11. Mudstone; grayish-red 2
10. Conglomeratic sandstone; yellowish-gray; poorly-sorted; fine- to coarse-grained; chert pebbles and quartz grains; chalcedony cement; "quarry layer"; dinosaur bones; fresh water clams (*Unio*); ridge former 19
9. Covered interval; pits reveal weathered shaly sandstone grading into mudstone; pale olive gray to greenish-gray; bentonitic with thin lenticular limestones; light yellowish-gray; weathers pale yellowish-brown; 2 ft beds 60
8. Mudstone grading into shale; greenish-gray; bentonitic; lenticular limestone; pale yellowish-brown; resistant beds 124

Section offset 0.1 mile to the east returning to original transit.

7. Shale; light olive gray to dark greenish-gray; weathered on the surface; bentonitic 22

Total Brushy Basin Member 435

Sharp contact between shale and conglomerate.

Salt Wash Member

6. Conglomeratic sandstone; yellowish-gray to very pale orange; fine- to coarse-grained; poorly-sorted; low-angle scours; dinosaur bone fragments; one lenticular sandy limestone; yellowish-gray 27
5. Shale; light olive gray to pale yellowish-brown; calcareous 18
4. Sandstone; yellowish-gray to greenish-gray; fine- to medium-grained; shaly sandstone at the base; one lenticular limestone; greenish-gray; marly; 3 ft thick 51
3. Conglomeratic sandstone to sandstone; yellowish-gray to grayish-orange; moderately well-sorted; fine- to medium-grained; cross-strata; slightly calcareous 47
2. Shale; light olive gray to greenish-gray 19
1. Sandstone; yellowish-gray to very pale orange; poorly- to moderately-sorted; fine- to medium-grained; thin laminae; scours; petrified wood; with shale interbedded; light olive gray with reddish-brown mottled; 8 ft bed; slightly calcareous 72

Total Salt Wash Member 234

Total Morrison Formation 669

Contact not distinct in the field, base of sandstone in contact with covered interval, pits reveal lithologic change from sandstone to shaly sandstone.

Curtis Formation

1. Covered interval; pits reveal sandstone grading into shaly sandstone; pale olive green to yellowish-gray; poor- to moderate-sorting.

The formation immediately below the Morrison Formation is the Upper Jurassic, marine Curtis Formation, containing dull gray shales and light colored, thin-bedded, friable sandstones. The origin is deduced from the presence of fossils of belemnites, oysters, and other marine invertebrates. The predominant sandstone is a medium-grained ridge-former near the upper contact and includes ripple marks, channel scours, and worm burrows. In the shaly sandstones immediately above the predominant sandstone there were no fossils identified. Just below the contact with the Morrison, the lithologies are characterized by easily-weathered, light olive to yellowish-gray, shaly sandstones.

The basal unit of the Morrison Formation is a moderately well-sorted, cross-bedded sandstone member, the Salt Wash, which is yellowish-gray, of variable thickness, and contains some petrified wood. Higher in the member, in a similar type of sandstone, poorly preserved fossil dinosaur bones are found but no other fossils were noted.

Intercalated with the sandstones of the Salt Wash are a few thin layers of shale varying in color from light reddish-brown to greenish-gray, usually averaging only a few feet in thickness with rare exceptions ranging to 30 feet. The lower shales are characterized by mottled red and green colors, though neither color dominates and they may be a result of present weathering.

Lenticular conglomerates are closely interbedded with sandstones in the upper part of the Salt Wash Member. These conglomerates occur as cross-cut channel deposits within the sandstones and contain pebbles greater than 2 cm in diameter set in a matrix of smaller pebbles, sand, silt, and clay. Most of the pebbles are sub-rounded chert fragments. The enclosing sandstone contains both quartz and chert grains.

The upper Brushy Basin Member includes a large amount of variegated shales and mudstones. These rocks, which are best recognized by the well-segregated color variations and sharp boundaries between beds, range from grayish-red to light gray to greenish-gray to pale reddish-purple. The grayish-green mudstones are bentonitic, showing typical "pop-corn" texture.

Within these shales and mudstones are lenticular, thin-bedded, yellowish-gray to light gray limestones. They are very fine-grained, with an occasional ostracod-like structure noted in the field, but no fossils appeared in thin sections. Abundant secondary calcite and chalcedony fill fissures and partially replace the limestone.

The lenticular conglomerates and sandstones of the Brushy Basin Member forming ridges are relatively scarce in this area with one important exception, the quarry layer. This cross-bedded conglomeratic sandstone contains the fossil remains of at least fourteen species of dinosaurs, three species of turtles, and two species of crocodiles (White, 1968). The bones have been replaced with SiO_2 and the unit containing the quarry conglomerate has a SiO_2 (chalcedony) cement which is different from many of the other sandstones and conglomerates in the section having a $CaCO_3$ cement. Casts of *Unio* and carbon traces of *Equisetum* are also preserved (White, 1968). The major fossil-bearing layer is found from 100 to more than 200 feet below the upper contact of the Morrison.

More lenticular limestones and massive sections of shales are found above the quarry layer. Scattered on the surface of the shales are pieces of limestone and well-polished chert pebbles known as "gastroliths". The source of these pebbles, which are probably wind polished, is not known, but they are thought to have been originated higher in the section and were carried down the weathered shale slopes. None have been found in association with the fossil dinosaur bones at the quarry.

The upper contact is not always easily located. In the area studied, a ridge-forming conglomeratic sandstone grading into a fine-grained sandstone was selected as the lowermost part of the Cedar Mountain Formation because it overlies the typical greenish-gray and pale red shales diagnostic of the Morrison. Although this sandstone appears to be lenticular, it has moderate lateral extent, and its mineralogy is more similar to the thickly-bedded sandstones above than to those of the Morrison. This Cedar Mountain basal unit may correlate with the Buckhorn Member of Stokes (1944, 1952). Bradley (1952) correlated the shales and sandstones above the contact with the Cedar Mountain Formation, and Stokes (1952) speculated that these beds are, indeed, an extension of the Cedar Mountain Formation.

MINERALOGY

The X-ray diffraction scans of the samples from section 2 showed differences in the mineralogies of the Curtis Formation and the Morrison Formation, of the members of the Morrison Formation, and of the Morrison and the beds above it. Scans of the powdered samples revealed varying amounts of quartz, feldspar, calcite, dolomite, and barite throughout the section (table 1). Unfortunately, no direct correlation could be made from these data in identifying boundaries.

The lithologic changes at the contacts between the units are reflected in the corresponding clay-mineral suites (figure 3). Near the top of the Curtis Formation, in a mixture of sandstones, shales and shaly sandstones, the relative abundances of illite, montmorillonite and kaolinite are variable but approximately equal. Just above the contact between the Curtis and the Morrison Formation (Salt Wash Member), illite disappears almost entirely from the

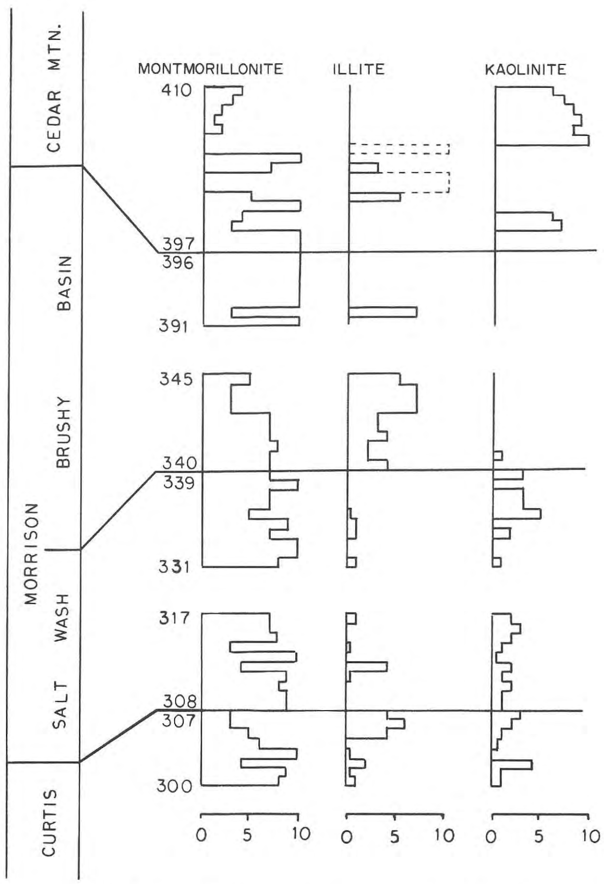

Figure 3. Relative abundances of montmorillonite, illite, and kaolinite above and below unit boundaries in section 2.

sandstones. The relative abundance of kaolinite decreases above the contact of the Salt Wash, with the Brushy Basin paralleling the change of sandstone to shales and mudstones which contain appreciable quantities of illite. Near the top of the Brushy Basin, illite gradually disappears from all lithologies, but is not accompanied by a reappearance of kaolinite. Above the contact between the Morrison and the Cedar Mountain Formation, an increase in kaolinite is correlated with the return of sandstone.

Montmorillonite is present, with few exceptions, as the dominant clay mineral throughout the entire section. Its abundance shows no marked change from below the lower contact of the Morrison through the contact between the members of the Morrison, though in some parts of the Brushy Basin Member, especially the middle and upper portion, it is the only clay present in measurable quantities. There is, however, a marked relative decrease in total montmorillonite content near the upper Morrison contact and through the beds above.

Apart from the three major clays, only two other types appear in the scans. One is chlorite, which was found in only two samples in the entire section, both near the bottom: one in the Curtis and the other in the lower part of the Morrison. The other clay is a mixed-layer illite-montmorillonite. It appears four times, once in the Salt Wash Member and three times in the Cedar Mountain Formation above the Morrison. The mixed-layer clays may actually be more prevalent than indicated by the scans, since solvating the clay may have resulted in preferential identification of montmorillonite.

Dolomite was rare in the scans of powdered samples except near the lower and upper boundaries of the Morrison. The microcrystalline carbonate rocks which appear throughout the upper member are, for the most part, limestones. Even where dolomite is abundant, near the top, some calcite is also present.

Table 1. Distribution of minerals in the Curtis, Morrison (Salt Wash and Brushy Basin Members), Cedar Mountain, and Dakota Formations as determined by X-ray diffractometry. Entries are number of samples and, in parentheses, percentage of samples which contained detectable quantities of each mineral.

Minerals	Curtis	Salt Wash	Brushy Basin	Cedar Mountain	Dakota
Quartz	8 (100%)	38 (100%)	73 (100%)	29 (100%)	1 (100%)
Feldspar	7 (88%)	26 (68%)	48 (66%)	16 (55%)	0
Calcite	7 (88%)	33 (92%)[1]	37 (51%)[2]	9 (35%)	0
Dolomite[3]	4 (50%)	6 (16%)	5 (7%)	6 (23%)	0
Barite	1 (25%)	17 (45%)	24 (33%)	23 (79%)	1 (100%)
Montmorillonite	8 (100%)	38 (100%)	72 (100%)[4]	29 (100%)	1 (100%)
Illite[5]	7 (88%)	17 (45%)	41 (56%)[6]	5 (19%)	0
Kaolinite[7]	7 (88%)	35 (92%)	8 (11%)	19 (66%)	1 (100%)
Chlorite	1 (12%)	1 (3%)	0	0	0

[1] Very low relative abundance in 31 of the 33 samples.
[2] Includes 11 limestones.
[3] As dolomite in upper Brushy Basin and lower Cedar Mountain.
[4] Predominant clay in upper half.
[5] Very low relative abundance in sandstones and conglomerates.
[6] Absent at top.
[7] Very low relative abundance in shales and mudstones.

This situation holds through the upper contact and into the beds above.

PETROGRAPHY

Detailed data from the petrographic analyses are recorded in tables 2 and 3 which should be consulted in connection with the following descriptions. The classifications of the sandstones and conglomerates are taken from Folk (1968). The limestones and dolomites are classified by the scheme used by Bissell and Chilinger (1967).

The sample (300) selected for petrographic study of the upper portion of the Curtis Formation is a well-sorted, silty, very fine sand: calcitic, submature, subchertarenite. Its main terrigenous constituents are quartz and chert; other minerals and rock fragments are minor. The bonding agent is sparry calcite cement which fills all the spaces between the grains, making the porosity of the rock very low. In the field, cross-bedding and ripple marks are present in this unit. No fossils were found in the sampled stratum although gastropods and belemnites were observed lower in the formation.

The lower Salt Wash Member of the Morrison Formation is divisible into several lithologies, primarily sandstone and conglomerate, with minor limestone and shale. One sample of each of these except the shale was chosen for detailed petrographic analysis. The sandstone (313) is classified as a moderately well-sorted, medium sandstone: calcitic, submature, subchertarenite. The detrital sediments include quartz, chert, and chalcedony, with minor quantities of feldspar and volcanic rock fragments with clay in the matrix. Sparry calcite cement fills the pore spaces within the rock.

The conglomerate (324) is classified as a moderately-sorted conglomeratic sandstone: calcitic and chalcedonic, submature, tuffaceous chert-arenite. The detrital grains include quartz, chert, and devitrified tuff fragments. The chert and tuff fragments are morphologically similar except that the tuff fragments have shard remnants in the recrystallized material. This conglomeratic sandstone is a cross-bedded, channel deposit.

The limestones (332) found in the lower member are classified as detrital micritic varieties. A cryptocrystalline calcite matrix constitutes most of the rock; fissures are filled with sparry calcite cement. The silt-sized to very fine sand-sized quartz, chert, and feldspar are trapped in the matrix of the limestone.

Most of the rocks of the upper Brushy Basin Member of the Morrison are shales and mudstones. Within these layers are lenticular limestones, dolomites, and conglomerates. Each of these was sampled, and representative examples were described petrographically.

Detrital micritic limestones represented in tables 2 and 3 by sample 360B, consist predominantly of cryptocrystalline calcite matrix in the lower and middle portions of the upper member, with calcite spar filling the fissures within the matrix. Fine-grained detrital quartz is present in very minor quantities. No fossils were seen in the thin sections, although a few ostracod-like structures were seen in the field.

In tables 2 and 3, sample 389 is listed as representative of the crypotocrystalline micritic dolomite observed in the upper portion of the upper member. It has the same texture and appearance as the calcite in the limestones except for more extensive brecciation

Table 2. Physical properties as determined by petrographic analyses of selected samples from section 2.

Sample number	Grains counted	Percent grains	Grain size			Sorting (in ϕ)	Skewness	Percent		
			Range(mm)	Median(mm)	Mean(mm)			Gravel	Sand	Silt
				Curtis Formation						
300	93	60	0.05-0.33	0.11	0.11	0.5	+0.30	0	74	26
				Salt Wash Member of the Morrison Formation						
313	101	76	0.07-0.90	0.26	0.31	0.6	+0.10	0	100	0
324	97	71	0.05-2.25	0.65	1.00	0.8	+0.04	5	94	1
332	21	15	0.02-0.10	0.03	0.04	NA	NA	0	29	71
				Brushy Basin Member of the Morrison Formation						
360B	16	13	0.02-0.11	0.05	0.07	NA	NA	0	50	50
363.5	77	55	0.13-2.25	1.00	1.10	1.0	+0.14	13	87	0
389	7	5	0.03-0.14	0.05	0.06	NA	NA	0	43	57
				Cedar Mountain Formation						
397.1	94	68	0.05-0.52	0.13	0.16	0.8	-0.40	0	97	3
404B	0	0								

Table 3. Mineralogical properties as determined by petrographic analyses of selected samples from section 2.

Sample number	Minerals[1]	RA	QET[2]	RA	Grain size(mm) Range	Median	Roundness[3] SA	SR	O	Bonding agent[4]	RA	Remarks
						Curtis Formation						
300	Q	85	U	17	0.05-0.26	0.10	31	69	0	C. cem.	100	bubble inclusions and rutile needles in quartz grains
			N	83	0.02-0.28	0.10	29	71	0			
	C	3			0.05-0.20	0.10	100	0	0			
	Ch	3			0.05-0.20	0.10	33	67	0			
	TF	2			0.05-0.10	0.07	50	50	0			
	M	3			0.05-0.26	0.11	50	50	0			etched feldspar
	P	2			0.05-0.10	0.08	100	0	0			
	B	1			0.10		0	100	0			
	T	1			0.05-0.10	0.06	100	0	0			
						Salt Wash Member						
313	Q	69	U	86	0.15-0.33	0.20	67	33	0	Cal. cem.	86	bubble inclusions and rutile needles in quartz grains
			N	9	0.07-0.52	0.26	35	63	0	Cl. mat.	14	
			P	5	0.13-0.52	0.20	70	30	0			
	C	6			0.15-0.90	0.26	67	33	0			
	Ch	6			0.19-0.52	0.33	67	33	0			
	TF	4			0.15-0.90	0.35	0	100	0			devitrified tuff with shards
	M	2			0.13-0.52	0.20	50	50	0			
	S	6			0.13-0.52	0.20	80	20	0			
	P	2			0.14		50	50	0			etched
	RF	5			0.20-0.60	0.39	0	100	0			sedimentary rock fragments
324	Q	32	U	9	0.39-1.00	0.46	33	67	0	Cal. cem.	41	bubble inclusions in quartz
			N	91	0.04-1.00	0.52	25	71	4	Fe stain	36	
	C	5			0.52-1.00	0.75	40	60	0	C. cem.	23	
	Ch	32			0.33-2.00	0.75	42	58	0			
	TF	25			0.26-2.25	1.25	29	71	0			devitrified tuff with shards
	S	6			0.46-0.75	0.65	17	83	0			etched
332	Q	86	N	100	0.02-0.10	0.03	50	50	0	Cal. cem.	14	
	Ch	9			0.03		100	0	0	Cal. mat.	81	
	S	5			0.10		100	0	0	Cl. mat.	5	
						Brushy Basin Member						
360B	Q	81	N	100	0.02-0.11	0.06	91	9	0	Cal. cem.	3	
	Cl	19			0.05-0.08	0.06	100	0	0	Cal. mat.	91	
363.5	Q	11	N	100	0.13-0.46	0.26	0	100	0	Cal. cem.	4	
	Ch	51			0.20-2.50	1.25	23	77	0	C. cem.	88	
	TF	35			0.26-2.30	1.30	8	92	0	Cl. mat.	8	devitrified tuff with shards
	M	1			0.33		0	100	0			
389	Q	72	N	100	0.03-0.44	0.06	40	60	0	Cal. cem.	18	iron staining
	Ch	14			0.05		100	0	0	C. cem.	5	
	H	14			0.03		100	0	0	Cal. mat.	76	
										Cl. mat.	1	
						Cedar Mountain Formation						
397.1	Q	82	U	6	0.11-0.33	0.16	40	60	0	Cal. cem.	42	iron staining
			N	94	0.03-0.52	0.14	19	81	0	Qtz. ogr.	38	
	Ch	13			0.08-0.33	0.20	67	33	0	C. cem.	13	
	P	3			0.10-0.12	0.12	100	0	0	Cl. mat.	7	
	TF	2			0.16		0	100	0			devitrified tuff
404B										Dolo. mat.	92	dolomite rhombs
										Fe stain	8	

[1] C = Chalcedony; Ch = Chert; Cl = Clay; H = Hematite; M = Microcline; P = Plagioclase; Q = Quartz; RF = Rock fragments; S = Sanidine; T = Tourmaline; TF = Tuff fragments.
[2] U = Undulatory; N = Non-undulatory; P = Polycrystalline.
[3] SA = Subangular; SR = Subrounded; O = Other; R = Rounded.
[4] C. cem. = Chalcedony cement; Cal. cem. = Calcite cement; Cal. mat. = Calcite matrix; Cl. mat. = Clay matrix; Dolo. mat. = Dolomite matrix; Fe stain = Iron stain; Qtz. ogr. = Quartz overgrowth.

within the rock itself. Dolomite in the thin sections was identified by X-ray diffraction analysis of the entire rock which also revealed the presence of quartz in minor amounts, whereas only rare detrital quartz grains and undeterminable carbonates appeared in petrographic preparations.

Usually the conglomerates are rare lenses within the mudstones; the predominant one at the Dinosaur quarry (363.5) is classified as a poorly sorted, conglomeratic sandstone: chalcedonic, submature, tuffaceous, chert-arenite composed mainly of chert and devitrified tuff fragments. In this lens are the silicified bones of dinosaurs, turtles, and crocodiles.

The beds of the Cedar Mountain Formation above the upper Morrison contact are typified by moderately well-sorted sandstones, shales, and finely-crystalline dolomites. The shales were not studied petrographically.

The sandstones represented in the tables by sample 397.1 grade from moderately well-sorted, fine sandstone: dolomitic and calcitic, submature, subchertarenite to well-sorted, fine sandstone: chalcedonic, mature, sublitharenite. All contain large quantities of chert and feldspar. The differences are minor: the chalcedonic cement replaces the calcite and dolomite cements, and the rounding and sorting improves toward the top of the section.

The dolomite (404B) in the Cedar Mountain Formation is finely-crystalline. Dolomite rhombs are seen through the microscope, though in hand specimen the rock appears the same as any of the other carbonates. No detrital grains were seen, but X-ray diffraction revealed a minor amount of quartz.

STRATIGRAPHIC CORRELATIONS

The Morrison Formation and the beds overlying it have been discussed at length in the literature. Although the Morrison in Dinosaur National Monument has been described stratigraphically in detail, the Salt Wash and Brushy Basin Members have not been identified specifically nor has the boundary between the Morrison and the overlying beds of the Cedar Mountain Formation, been set.

North of Vernal, Utah, near Steinaker Reservoir, Craig *et al.* (1955) identified 285 feet of Salt Wash and 600 feet of Brushy Basin. The data of the present study show that these members extend into the monument area where they are approximately 230 feet and 450 feet thick, respectively. Their lithologic properties are consistent with those descriptions given by Cadigan (1967) in his survey of the Morrison Formation in the Colorado Plateau.

By comparison with the descriptions by Stokes (1944, 1952), the strata above the Morrison correspond stratigraphically and lithologically to the Lower Cretaceous Cedar Mountain Formation. The lower member of the Cedar Mountain, the Buckhorn Conglomerate, is apparently absent; the only layer which might be considered temporarily correlative to it is the lowermost sandstone of the formation. This sandstone has a pebbly base which might represent the Buckhorn. Without further investigations, however, the validity of this suggestion can not be confirmed.

DEPOSITIONAL ENVIRONMENTS

Models of Clay Formation

The physico-chemical and geological conditions for the formation of montmorillonite are discussed at length by Millot (1970). The association of montmorillonite and volcanic tuff fragments suggests that the former may have arisen from the latter since volcanic tuff fragments, when deeply buried, may change diagenetically to montmorillonite. Another alternative gives the same result: if the tuff should fall into a sedimentary basin which has moderate drainage and an alkaline environment, it could crystallize into montmorillonite. Such an alkaline environment may result either from semi-arid climatic conditions or from lacustrine or marine conditions. A third explanation for the formation of montmorillonite is based on lateritic soil. According to this model, abundant rain water percolates through the soil and dissolves metal ions causing the solution to become increasingly more alkaline. If the water is restricted to an area with poor drainage, the metal ions combine with silicate anions to form montmorillonite and other clays.

Although illite formation, as described by Millot (1970), can occur in a variety of depositional regimes, the process is restricted to alkaline environments, where it forms most readily under marine conditions by the combination of potassium cations with silicate anions. In a wet, hydrologically well-circulated, terrestrial regime, detrital illite will alter to kaolinite, but if the ground water becomes sufficiently enriched in metal cations the process will reverse. Illite also forms in lacustrine (in which the pH is 7.5 to 8.5) and in semi-arid and arid terrestrial environments where the water sequestered in basins is alkaline. Under these conditions illite from older sedimentary source rocks is not altered since not enough water circulates through the system to carry away the metal ions.

The formation of kaolinite, according to Millot (1970), is restricted to acidic environments such as streams, which are generally slightly acidic. In this process some detrital illite is altered to kaolinite which is relatively stable, even though its long-term stability depends on hydrologic circulation to maintain the level of dissolved metal cations below that required for conversion back to illite.

Source Area

The petrographic data suggest the sediments which formed the Curtis, Morrison, and Cedar Mountain Formations in the Dinosaur National Monument area were derived from either a single large or several smaller source areas which were quite similar. The sandstones and conglomerates contain minor amounts of chert, chalcedony, and other sedimentary rock fragments and the quartz grains present are subangular to subrounded and equant, which indicates reworking of quartz from sedimentary rocks. Potassium and sodium feldspars are present in minor quantities (0-5%), as shown by point-counting grains in thin sections and by X-ray diffraction data, and heavy minerals are essentially absent. Tuff fragments were consistently found, however, these may have originated near the depositional site and later have been carried by streams or by the wind into the basin of deposition.

Curtis Formation

The rocks determined to be part of the Curtis Formation in the field have fossil and clay-mineral assemblages indicative of a near-shore marine deposit. The presence of moderately well-sorted sandstones containing both illite and kaolinite is consistent with the model proposed by Smoot (1960; Millot, 1970) describing a sedimentary source area of weathered clay minerals which recrystallize to illite in the sea. Kaolinite is deposited with the sands in an acidic, fresh-water, environment. At the interface of the two depositional environments, (stream mouths) mixing occurs by wave and current action, preserving the kaolinite by rapid burial. Such a phenomenon may account for the mixed illite and kaolinite found in the upper part of the Curtis Formation.

Morrison Formation, Salt Wash Member

As the Curtis sea withdrew, rivers and streams carried continental deposits into a basin of deposition, the Morrison plain, covering the marine sediments. Heavy rainfall, with consequent vigorous streams, or a close source area could account for the moderately- to poorly-sorted sandstones and conglomerates in the Salt Wash Member of the Morrison. Thin limestone beds within the sandstones indicate an entrapment of surface water where the pH increased and carbonate precipitated as a very fine micritic mud. The very fine detrital sand found in the limestones was probably of aeolian origin.

A change from marine to fluvial deposits near the boundary between the Curtis Formation and the Salt Wash Member of the Morrison Formation is indicated by the presence of fossil marine fauna in the former and fossils of a terrestrial fauna in the latter. The sandstones and shales of the Curtis are moderately well-sorted, whereas those of the Salt Wash are variable. The relative abundances of illite and calcite decrease and kaolinite is present in greater relative abundance in the Salt Wash sandstones and conglomerates, but small amounts of calcite and illite are found in almost all the samples. These data present a problem: the three minerals present are not all stable under the same conditions. Considering the models of clay formation discussed above, it appears that the kaolinite is primary, having been formed in a regime characterized by efficient water circulation, and the illite and calcite are probably secondary, having been formed in an alkaline ground-water regime. This interpretation is supported by the observation that the calcite fills the pore spaces between the grains as a coarsely crystalline spar. The higher relative abundance of the illite and calcite in the fine-grained sediments is probably due to deposition in an area of restricted drainage, *e.g.* a lake, or a semi-arid to arid climate. Since these types of environments are alkaline, illite would persist, calcite would form, and kaolinite would alter to illite. The montmorillonite in the system probably formed from volcanic tuff, based on observations of tuff fragments in petrographic thin sections. Devitrification of the tuff could have occurred in each of the three ways previously discussed.

Morrison Formation, Brushy Basin Member

At the boundary between the Salt Wash Member and the Brushy Basin Member of the Morrison, the lithology changes from a dominantly sandstone unit to a dominantly shale unit. This lithologic change is accompanied by a reversal of the relative abundance of kaolinite and illite indicating an abrupt change from an acid to an alkaline environment. The disappearance of kaolinite and the increase in relative abundance of illite and the carbonates emphasize this change (Keller, 1956; Millot, 1970). This point, of course, assumes no compositional change of the source area.

Kaolinite, which was the dominant clay in the sandstones of the Salt Wash, decreases appreciably in the shales and mudstones of the Brushy Basin; illite increases proportionally. One possible explanation is that the climate changed from humid to semi-arid and the mudstones may have been deposited on a flood-plain where reduced circulation of water enhanced the stability of illite and montmorillonite. The thinly-bedded limestones, containing fossil ostracods and algal mounds, were most likely formed in persistent lakes.

The conglomerates may have been formed by flash floods carrying heavy loads of sediment. Another possible explanation is that at least some of the mudstones and shales formed in a lacustrine environment. Under lacustrine conditions illite is stable, montmorillonite may form from volcanic ash, and calcite precipitates, but the dominance of these minerals in the Brushy Basin does not necessarily indicate a lacustrine environment since they can be formed under other conditions. Among the criteria listed by Picard (1957) for distinguishing lacustrine deposits, is the presence of mudstones which are brown, gray, or green; indurated; subwaxy and resinous; include iron sulfides, chert, and saline minerals; cemented with calcite, dolomite or silica; varved and shaly; and associated with extensive and varied limestones and dolomites. Fluvial mudstones, on the other hand, are red or green; friable; earthy; cemented by calcite; poorly-bedded; and are associated with thin, spotty limestones. Since mudstones satisfying both of these sets of criteria are found in the Brushy Basin, it is quite possible that each of the two types of environment occurred at different times during deposition.

An increase of dolomite in the upper portion of the Morrison suggests a period of aridity. The dolomites resemble the limestones morphologically, but do show an increase in shrinkage brecciation. With increased aridity, illite decreases in abundance and grades into montmorillonite (Millot, 1970), consistent with the upper strata of the Brushy Basin.

Cedar Mountain Formation

A pronounced lithologic change takes place above the boundary between the Morrison and the Cedar Mountain Formations. Paralleling an increase in sandstone, kaolinite reappears sporadically near the base of the unit and the carbonate minerals decrease appreciably, leaving only quartz, kaolinite, and minor quantities of montmorillonite. This profile of mineralogical and physical characteristics indicates a depositional environment resembling that of the Salt Wash. Higher in the section, the sorting improves in the sandstones, and the Cedar Mountain grades into a littoral deposit, the Dakota Formation, retaining the same clay-mineral assemblage.

CONCLUSION

The area studied in this work is in Dinosaur National Monument, at the Dinosaur Quarry, near Jensen, Utah. The sections in the Morrison Formation chosen for study flank the quarry on the east and west. These were measured stratigraphically and sampled at regular intervals. The samples were analyzed by X-ray diffraction and petrographic techniques. Data collected by X-ray diffractometry indicate a different clay-mineral assemblage for each unit correlating with the corresponding lithologies. The boundary between the marine Curtis Formation and the fluvial Salt Wash Member of the Morrison Formation is denoted by a change from a marine sandstone and shale with a montmorillonite, illite, and kaolinite suite to fluvial sandstones characterized by montmorillonite and kaolinite. A reversal from the presence of kaolinite and lack of illite to the lack of kaolinite in the shales of the Brushy Basin Member reinforces the placement of the boundary between these members. Another change is noted in the clay minerals as the lithologies change at the boundary of the Morrison and the Cedar Mountain Formations where illite, which is found in very small quantities through the shales in the upper portion of the Brushy Basin, completely disappears in the sandstones of the Cedar Mountain and kaolinite becomes the diagnostic clay mineral.

The clay-mineral suites are good indicators of changes in the depositional environments. The illite-kaolinite suite in the upper Curtis Formation indicates an interface between marine and fresh-water environments with rapid deposition. The presence of kaolinite and reduced abundance of illite in the fluvial sandstones in the Salt Wash Member of the Morrison indicate an acidic environment, *i. e.*, a wet climate with enough water to carry heavy sediment loads in the streams and to dissolve the carbonates and illite which interfere with the formation of kaolinite. The Brushy Basin Member is typified by mudstone, lenticular limestomes, conglomerates, and a clay suite including montmorillonite and illite, which indicates an alkaline environment, possibly either a variable semi-arid climate or a lacustrine environment. The Cedar Mountain Formation, like the Salt Wash Member of the Morrison, contains an appreciable amount of kaolinite in the sandstones, which again suggests a humid climate. Also, the change in the sorting of the sandstones indicates a progression from fluvial deposits to the littoral deposits of the Dakota Formation.

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UTAH GEOLOGICAL AND MINERAL SURVEY

103 Utah Geological Survey Building
University of Utah
Salt Lake City, Utah 84112

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