Temporal and spatial relationships of diagenetic processes in the Upper Jurassic Morrison Formation, Colorado and New Mexico, and its implication to dinosaur fossils preservation

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TEMPORAL AND SPATIAL RELATIONSHIPS OF DIAGENETIC PROCESSES IN THE UPPER JURASSIC MORRISON FORMATION, COLORADO AND NEW MEXICO, AND ITS IMPLICATION TO DINOSAUR FOSSILS PRESERVATION

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Clay size fraction (< 2μm) of diagenetic mineral assemblages obtained from samples of the Morrison Formation in northwestern New Mexico and southern and western Colorado are dominantly smectitic ($\leq$ 5% illite layers) along the basin margin and illitic (30-90% illite layers) in the central part of the basin. Traces of kaolinite, chlorite, calcite, and quartz are also common.

K/Ar data on five illite/rich clays (30–90% illite) separated from regionally collected samples yielded an age range of 29.69 to 55.95 m.y. and are related to Laramide (Cretaceous-early Tertiary) tectonic deformation of the Morrison Formation in the San Juan basin. These data, coupled with the published minimum sedimentation age (131 $\pm$26 m.y.) obtained on smectite of an early diagenetic phase, suggest that there were at least two major diagenetic processes responsible for the formation of authigenic minerals in the Morrison Formation.

The minimum sedimentation age is also a minimum age for the dinosaur fossils found in the Brushy Basin Member of the Morrison Formation. Published vitrinite reflectance data and the prevalence of smectite in the fossil-bearing marginal sedimentary rock suggest that the fossil bones were subjected to low burial temperature ($\leq$ 60°C) and that Laramide-related tectonic deformation was minimal along the margin of the basin in this area.

INTRODUCTION

It has been suggested that soon after the deposition of the Morrison Formation in the Late Jurassic, pore fluids expelled during sediment compaction moved through porous rocks in the basin, initiating the formation of distinctive diagenetic mineral assemblages that were later affected by tectonically induced (Laramide Orogeny) fluid movement (Bell, 1987; Turner-Peterson and Fishman, 1987; Whitney, 1987). Diagenetic minerals associated with dinosaur fossil bones in the Upper Jurassic Morrison Formation, along the southeastern boundary of the San Juan basin about 50 km northwest of Albuquerque, New Mexico, (fig. 1) (Rigby, 1982; Gillette, 1986) shed important clues on burial history and on the conditions under which these minerals formed. Moreover, this information has direct implications for the nature and preservation of fossil bones in a sedimentary environment. Nine dinosaur bone sites have been identified and documented in the study area (Schwartz and Manley, 1989). Most of the dinosaur fossil bones occur in the Brushy Basin Member of the upper part of the Morrison Formation, although one lies in a zone of interfingering Brushy Basin and Westwater Canyon Members. The underlying Westwater Canyon Member is known to contain abundant fossil plants and dinosaur fossils as well (Lee and Brookins, 1978). The fossils in the study area occur in sandstone and claystone (mudstone) units.

The object of this study is to describe the diagenetic mineral assemblages in samples collected within, above, and below the fossil-bearing horizons and to compare these assemblages to diagenetic phases that occur regionally in samples from the Brushy Basin Member. In particular burial depths and temperatures during diagenesis of the Morrison Formation are sought. The K/Ar geochronologic method was used to constrain the time of diagenetic mineral formation, in particular the growth of potassium-rich clays (illite-rich clays). Unfortunately, the diagenetic mineral assemblages from the Morrison Formation at the dinosaur fossil sites are dominated by highly expandable (smectite) clays with traces of kaolinite, chlorite, illite/smectite ($\leq$ 5% illite layers), and microcrystalline silica. Brushy Basin Member samples containing potassium-rich clays (interstratified illite/smectite) were obtained from a drill hole (S6) in the Grants mineral belt northeast of Gallup (New Mexico) and from tuff bed outcrops in southern (Durango) and western (Grand Junction) Colorado (fig. 1). For the K/Ar geochronologic method, finer clay size fractions (<.25 μm) were mostly used in order to avoid detrital clay contamination.

GEOLOGIC OVERVIEW

Current geologic data for the upper Jurassic Morrison Formation in northwestern New Mexico include detailed studies of depositional basin analysis, burial and diagenetic history, uranium mineralization, and other related topics (Brookins, 1980; Bell, 1987; Turner-Peterson and others, 1987; Whitney and Northrop, 1987). The Morrison Formation, with a Rb/Sr sedimentation age of 131 $\pm$26 m.y. is subdivided into the Recapture Member, Westwater Canyon Member, and the Brushy Basin Member, in ascending stratigraphic order (Lee and Brookins, 1980; Bell, 1987). The Recapture Member, the basal unit of the Morrison Formation, was deposited in a mixed eolian, fluvial, and lacustrine environment and consists of light-gray pebble conglomerate, quartz and feldspathic arenite, and various amounts of reddish brown sandstone (Bell, 1987; Turner-Peterson and Fishman, 1987). The overlying Westwater Canyon Member, which is fluvial in origin, is dominantly feldspathic arenite and mudchip conglomerate with interbeds of reddish-brown and greenish-gray mudstone that grade into the overlying Brushy Basin Member. The Brushy Basin Member exhibits major lateral facies changes from fluvial sandstone beds to low-energy lacustrine sediments characterized by thick intervals of volcanic tuffs, variegated silty and sandy mudstones, and well-sorted, strongly cemented sandstones deposited in alluvial plain, mudflat, and playa-lake environments (Bell, 1987). The dinosaur fossil sites in the Brushy Basin Member are exposed in broad and shallow canyons cut by ephemeral streams. The bone-bearing unit is about 80 m thick, consisting of ledge-forming sandstones alternating with variegated claystones and rare limestones; the units formed as channel and floodplain deposits (Schwartz and Manley, 1989).

Early diagenetic processes in the Morrison Formation were characterized by precipitation of authigenic minerals and by selective dissolution of both detrital and older authigenic phases (Turner-Peterson and Fishman, 1987).

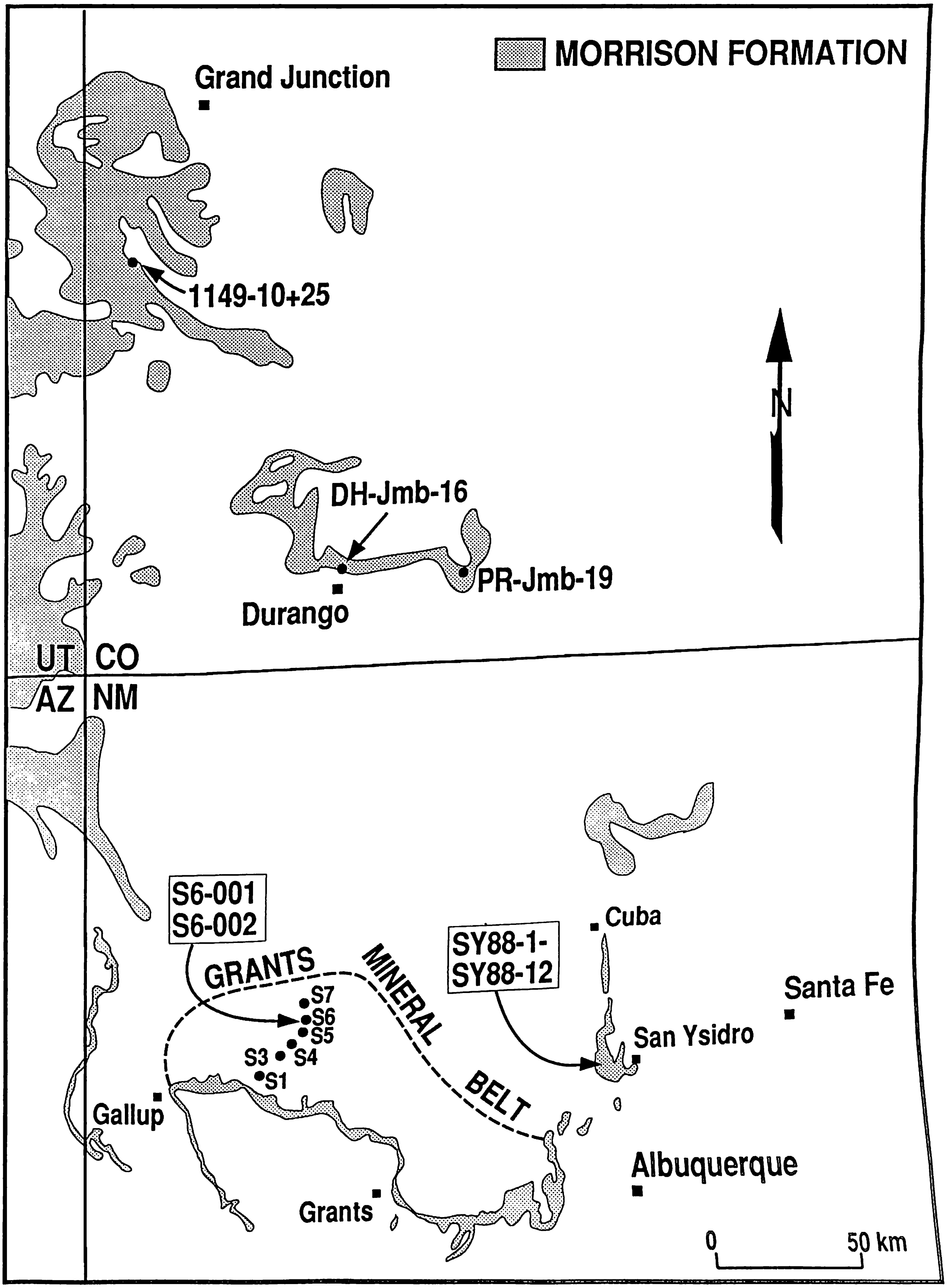

FIGURE 1. Regional distribution of the Morrison Formation in northwestern New Mexico and southwestern Colorado (after Turner-Peterson and Fishman, 1987; Whitney and Northrop, 1987). Sample locations indicated by dots and sample numbers.

According to Bell (1987), burial and diagenetic processes in mudstone and altered tuffs of the Brushy Basin Member and in upper parts of the Westwater Canyon Member were greatly influenced by fresh to hyper-saline and alkaline surface and groundwaters that resulted in distinct, zonally distributed authigenic mineral assemblages that vary from the margin to the center of the basin.

ANALYTICAL METHODS

Thin sections were prepared for some of the sandstone samples from the dinosaur fossil sites, while the rest of the specimens were processed for clay size separation (2 - 0.25 μm, 0.25 - 0.1 μm, and < 0.1 μm) in a DuPont Sorvall superspeed angle-rotor centrifuge alter thorough cleaning. Clay separates for K/Ar age determination were chemically treated to remove calcite, organic matter, and iron oxides using the procedures outlined in Jackson (1978). The chemical treatment was followed by a thorough dialyses of the clay fraction for four to five days in deionized water that was regularly changed. Effects of chemical treatment on clay mineralogy were monitored by XRD analyses before and after processing.

K/Ar age determinations were made on five illite/smectite clay fractions at the Case Western Reserve University K/Ar Laboratory in Cleveland, Ohio. Clay separates of 100-200 mg were used for Ar extraction in a multiload system and were analyzed with an MS-10 Mass spectrometer equipped with an on-line extraction system and a bulb-pipetted ^{38}Ar tracer calibrated by the LP-6 interlaboratory standard at 19.3 × 10^{-10} mol of radiogenic Ar (^{40}Ar*) per gram (Aronson and Burtner, 1983). Potassium was determined on duplicate samples with a flame photometer using acid solutions of sample beads fused in lithium metaborate.

SAMPLE DESCRIPTIONS AND CLAY MINERALOGY

The main dinosaur bone excavation is of the remains of a *Seismosaurus* (Gillette, 1986); the excavation site is about 15 km west of San Ysidro along the southern edge of a low-lying mesa capped by a strongly cemented and well sorted sandstone (sample SY88-4). The section at this site is about 40 m high and consists of several alternating beds of sandstone and variegated claystones of variable thicknesses. In thin section the basal sandstone (SY88-1) is moderately cemented and sorted with subrounded to rounded quartz grains having secondary silica overgrowth around the rims of individual grains. The matrix consists of calcite and minor clayey material. A few fairly altered plagioclase, biotite, hornblende and granitic rock fragments were also recognized. The next sample (SY88-2) was obtained about 1.5 m above SY88-l. The sample is similar to the previous one; however, it contains more calcite cement. Few altered plagioclase, biotite, and rock fragments are associated with this moderately sorted and cemented sandstone. Smectite and kaolinite clays dominate the matrix of a sandstone sample collected about 1.5 m above SY88-2. This sample contains no calcite and has a few zircon grains. The next unit (SY88-5), unlike the previous ones, has abundant rock fragments in addition to subrounded to rounded quartz grains with minor biotite and feldspar; smectite fills the interstices. The *Seismosaurus* fossil-bearing arkosic sandstone (SY88-6B) is coarse-grained, moderately indurated and buff to grey in color. Vertical joints in the arkosic arenite are filled with calcite and the quartz grains along the joint surfaces are extremely fractured, suggesting movement along joint planes. Petrographic examination indicates that the smectite, kaolinite and secondary silica are confined to grain boundaries and pore spaces.

The clay-size fractions (< 2 μm) separated from four sandstone beds contain abundant smectite, kaolinite, chlorite, calcite, quartz, and traces of interstratified illite/smectite (≤ 5%, R=0) (table 1). The friable and moderately sorted *Seismosaurus* fossil-bearing arkosic arenite (SY88-6B) is dominated by smectite with minor chlorite and kaolinite. The proportion of illite in illite/smectite and range of order (Reichweite or R) were obtained by calculating a series of patterns (Reynolds, 1980) for which R and percent illite were adjusted by matching calculated patterns with the XRD data.

At the Martini site, about 1.4 km east of the main excavation, fragmentary dinosaur bones occur in the interfingering zone of the Brushy Basin and Westwater Canyon Members (Schwartz and Manley, 1989). The two sandstone units (SY88-7 and SY88-8) collected below and above the fossil horizon are moderately sorted and light

TABLE 1. Mineralogy of diagenetic clay size mineral assemblages (< 2, 0.25-2, and < 0.25 μm) in the Brushy Basin and Westwater Canyon Members of the Morrison Formation.

Sample No.	Location	Host Rock	Lithologic Unit	Clay Mineral Assemblages	% Illite	R
SY88-2	SS1	Sandstone	Brushy Basin	S, K, Q	—	—
SY88-3	SS1	Sandstone	Brushy Basin	S, K, Q	—	—
SY88-5	SS1	Sandstone	Brushy Basin	I/S, Ch, Q	≤ 5	0
SY88-6A	SS1	Sandstone	Brushy Basin	Calcite, Q	—	—
SY88-6B	SS1	Sandstone	Brushy Basin	S, Ch, Q	—	—
SY88-7	MT1	Sandstone	Brushy Basin/Westwater Canyon	I/S, Ch	≤ 5	0
SY88-8	MTl	Sandstone	Brushy Basin/Westwater Canyon	I/S, Ch	≤ 5	0
SY88-10	MCl	Sandstone	Brushy Basin/Westwater Canyon	K, S, Q	—	—
SY88-11	MCl	Volcanic ash	Jack Pile Sandstone	S, K, Q	—	—
SY88-12	MCl	Volcanic ash	Jack Pile Sandstone	I/S	≤ 5	0
S6-001	GMb	Claystone	Dakota Sandstone			
S6-002	GMb	Tuff	Brushy Basin	I/S, Ch	≤ 30	0
DH Jmb-16	Durango	Tuff	Brushy Basin	I/S, Ch	≤ 50	0.5
PR Jmb-19	Durango	Tuff	Brushy Basin	I/S	≥ 90	3
1149-10+25	Grand Junction	Tuff	Brushy Basin	I/S, Ch	≥ 90	3

SS1 = Seismosaurus site, MT1 = Martini site, MC1 = McConnell site, GMB = Grants mineral belt, S = Smectite, K = Kaolinite, Q = Quartz, I/S = Illite-smectite, Ch = Chlorite, and R = Reichweite.

TABLE 2. K/Ar age data of clay fractions (> 2μm) from the Brushy Basin Member of the Morrison Formation in southern (Durango) and western (Grand Junction) Colorado and in northwestern (Grants mineral belt) New Mexico.

Sample No.	Location	Weight(g)	Particle Size (μm)	K_2O (%)	$^{40}Ar^*$ (10^{-10}mol/g)	$^{40}Ar^*$ (%)	Age** (m.y.)
1149-10	70 km south of Grand Junction	0.1476	<0.25	5.975	4.685	66	53.68±0.97
DH-jmb-16	vicinity Durango	0.1789	<0.25	7.258	5.936	76	55.95±0.99
PR-jmb-19	vicinity Durango	0.1846	<0.25	6.880	5.579	78	55.48±0.99
S6-001	S6 drill hole, Grants mineral belt	0.1770	<0.25	1.761	0.759	24	29.69±0.56
S6-002	S6 drill hole, Grants mineral belt	0.1907	0.25-2	4.172	2.048	43	33.79±0.60

*Radiogenic
**Determined from decay constants and isotopic abundance of ^{40}K according to Steiger and Jager (1977).

grey to olive grey in color. The fossiliferous horizon is part of a channel-point bar facies (Schwartz and Manley, 1989). The clay size fractions from these samples consist of interstratified illite/smectite (< 5% illite, R=0) and traces of chlorite (SY88-7).

At the McConnell site, about 2.8 km southeast of the *Seismosaurus* fossil site, several disarticulated skeletal fragments were recognized in silty olive claystone that is part of a thick floodplain-lake margin sequence (Schwartz and Manley, 1989). Three samples were collected from the walls of this narrow valley. The north side of the valley is capped by the Jackpile Sandstone (SY88-10) which is fine-grained, friable, and white in color. The base of the valley consists of the dinosaur fossil-bearing claystone bed (SY88-l2). Across the valley from the claystone, a thin layer (~30 cm thick) of altered volcanic ash (SY88-11) occurs at the base of the 94±15 m.y. old Dakota Sandstone (Della Valle, 1980; Schwartz, personal comm.). The volcanic ash is totally altered and contains a few minute grains of sanidine. The three samples from this site consist of smectite, kaolinite, traces of interstratified illite/smectite (55% illite, R=0), and microcrystalline silica in the fine clay fraction (SY88-12).

Five Brushy Basin Member samples were obtained from areas outside the dinosaur fossil sites in the San Ysidro area of northwestern New Mexico (fig. 1). Two of these samples come from a drill hole (S6) in the Grants mineral belt from a depth of 761 m (S6-001) and 762.2 m (S6-002). Sample S6-001 is a reworked tuffaceous sandstone bed with a fine-grained altered glassy matrix. It is moderately cemented and poorly sorted. Sample S6-002, which is about a meter below S6-001, is a very fine-grained altered and partly limonitized vitric tuff. It is whitish in color and moderately cemented. Three other Brushy Basin Member tuff beds from the central part of the San Juan Basin in southern and western Colorado were also analyzed. The two samples (DH-Jmb-16 and PR-Jmb-19) from the Durango area (southern Colorado) are very similar and about 60 km apart. Both samples are very fine grained, well cemented, and moderately recrystallized. They are medium grey in color. The third sample, which is light green in color comes from western Colorado about 70 km south of Grand Junction. This sample (1149-10+25) was obtained about 150 km north-northwest of the Durango area samples. It is very fine-grained, finely recrystallized, and strongly cemented.

The five samples described above consist of dominantly interstratified illite/smectite with varying proportions of illite (30-90%) and range of order (R=0, R=0.5, and R=3). The illite/smectite in two clay size fractions (2-0.25 μm and <0.25 μm) of sample S6-001 from a depth of 761 m contains about 30% illite (R=0), whereas sample S6-002 from a depth of 762.2 m contains more illite layers (≥50%, R=0.5) and minor amounts of chlorite. The three samples obtained from tuff beds in southern and western Colorado are illite-rich (≥90%, R=3) with two of the samples (119-10+25 and PR Jmb 19) containing minor chlorite. The clay mineralogy data indicate an increase in illite proportions from the Grants mineral belt northeast toward the center of the basin and correlate with the diagenetic mineral distribution of the playa-lake deposit mentioned in the introduction (Bell, 1987).

K/Ar DATA

Illitic clay is a good K/Ar clock; the K/Ar technique can be used to date diagenetic events in a variety of geologic settings (Aronson and Burtner, 1983; Aronson and Lee, 1986; Glasmann, 1987; Glasmann and others, 1987). The K/Ar data from such samples, when viewed in the context of basin development and diagenetic processes, provide information on fluid migration, burial temperature, and the timing of illitization.

Five illite-rich samples (30-90% illite) from the Brushy Basin Member dated by the K/Ar method are Eocene to Oligocene in age (29.69-55.95 m.y., N=5) (table 2). The two core samples from the Grants mineral belt located within the smectite-dominated diagenetic facies yielded younger ages of 29.69 and 33.79 m.y. Sample S6-001 (<0.25 μm) from a depth of 761 m and having about 30% illite represents the youngest age (29.69±0.56 m.y.), whereas S6-002 about a meter below it in the same drill hole contains more than 50% illite and gave an age of 33.79±0.60 m.y. The three illite-rich (90% illite layer) tuff beds of the Brushy Basin Member in Colorado are concordant in age. A sample (1149-10 + 25) from the analcime-potassium feldspar facies in the vicinity of Grand Junction in western Colorado is 53.68±0.97 m.y. old. The two other samples (DH-Jmb-16 and Pr-Jmb-19) from the albite facies at the center of the playa-lake deposit in the Durango area of southern Colorado are 55.95±0.99 and 55.48 0.99 m.y. old. The two age groups are consistent with the Cretaceous-early Tertiary Laramide structural deformation that resulted in the burial of the Morrison Formation to depths in excess of 2,000 m in the deepest part of the basin (Bell, 1987), thereby initiating fluid migration and reaction of the early diagenetic phases to form new minerals including illite-rich clays at elevated burial temperatures.

DISCUSSION

As briefly outlined in the introduction, the Brushy Basin Member in the San Juan Basin is characterized by four concentric diagenetic facies formed in variable salinity (fresh to hyper-saline and alkaline) and temperature (<60°C to 100°C) gradients (Bell, 1987; Turner-Peterson and Fishman, 1987). At least two major diagenetic facies are recognized in the Morrison Formation. The first is related to fluid movements generated by sediment lithification that initiated the earliest phase of authigenic mineralization. The second phase occurred during Laramide time about 75 m.y. later. The early diagenetic mineral assemblages along the southeastern periphery of the San Juan Basin are dominated by smectite from the alteration of volcanic tuffs. Kaolinite and traces of illite/smectite (≤5% illite layer) are also associated with the smectite. According to Bell (1987), the altered volcanic tuff beds (bentonites) in the San Ysidro area are in the outermost smectite facies and have probably never been heated to temperatures in excess of 60°-100°C, based on vitrinite reflectance data (60°C) and the fact that smectite-rich bentonite beds heated to 100°C react to form ordered illite/smectite (≥65% illite layers) clays (Hoffman and Hower, 1979).

Diagenetic mineral assemblages in the five tuff bed samples from the Grants mineral belt and Colorado are different from those found at the dinosaur site west of San Ysidro. The percent illite and range of order in the interstratified illite/smectite clays increase from about 30% illite (R=0) along the basin margin to about 90% illite (R=3) in the center of the basin, consistent with increase in depth of burial and in temperature, alkalinity, and salinity basinward. In fact, samples S6-001 and S6-002 obtained from the subsurface (761-762.2 m) lie within the smectite facies; however, they contain about 30% and ≥50% illite, unlike those diagenetic minerals obtained from the surface in the vicinity of San Ysidro. Illite contents in the tuff bed samples obtained from Colorado are similar although they come from adjacent diagenetic facies. The finer clay size fractions (2-0.25 and <0.25 μm) in a sample (1149-10+25) from the analcime-potassium feldspar facies is mineralogically and temporally similar to those from the albite facies in the center of the basin.

It has been suggested that the basinward systematic change from authigenic smectite to zeolites and to feldspars along with increased pore water alkalinity and salinity was responsible for the near-surface, low temperature (>90°C) origin of illite-rich clays in the Brushy Basin Member during early diagenetic alteration (Turner-Peterson and others, 1987b; 1988). However, during the Cretaceous-early Tertiary Laramide Orogeny, deformation and burial of the Morrison Formation (Brushy Basin and Westwater Canyon Members) initiated fluid circulations at elevated temperatures that reacted and converted early diagenetic phases to a new authigenic mineral assemblage of quartz, feldspars, chlorite, and interstratified illite/smectite (Bell, 1987; Whitney, 1987; Whitney and Northrop, 1987). As a result, the Westwater Canyon and the Brushy Basin Members are more illitic near the center of the basin and become less illitic toward the basin margin, an effect attributed to migrating warm (>100°C) potassium- and aluminum-rich fluids that moved updip from the center to the margin of the basin. This suggestion implies that temperature and fluid chemistry played a major role in the illitization process (Bell, 1987; Whitney, 1987; Whitney and Northrop, 1987).

The K/Ar data (29-55 m.y., table 2) on interstratified illite/smectite clays (30-90% illite layers) separated from regionally collected tuff beds (fig. 1) are consistent with the suggestion that fluid movement responsible for illitization in the Morrison Formation occurred subsequent to the basin formation during Laramide time. Geohistory models constrained by measured vitrinite reflectance and potassium bentonite K/Ar data from the San Juan Basin suggest thermal maturation during the early to mid-Eocene (55-45 m.y.) coinciding with high paleotemperature gradients (Glasmann and others, 1987) probably related to the Cretaceous-early Tertiary Laramide tectonic process. Rb/Sr isochron ages (44±7 and 41±9 m.y.) obtained on illite/smectite from redistributed uranium deposit in the Westwater Canyon Member in the Grants area (Della Valle, 1980; Brookins and Della Valle, 1989) are within the age range of the K/Ar data. The Eocene-Oligocene ages (29.68-55.95 m.y.) obtained on illite/smectite clays from the San Juan Basin are also consistent with the mean age of illitization measured on Cretaceous bentonites regionally selected from drill core samples in the Denver Basin and from outcrops along the Front Range, the western margin of the basin. K/Ar ages of 42-49 m.y. (20-40% illite layers) and 54-59 m.y. (50-60% illite layers) were reported from shallow and deep levels of drill holes, respectively (Elliott and others, 1986). It is further suggested that samples from areas of high geothermal gradient within the Denver Basin (Denver Hot Spot) are highly illitized (55-75% illite layers) with an illitization age of 60-61 m.y. The correlation between percent illite, K/Ar age of illite/smectite, and depth in the Denver Basin were also recognized in the San Juan Basin to the southwest. Differences in K/Ar age and illite content with depth was shown by samples S6-001 (~30% illite, 29.68±0.56 m.y.) and S6-002 (≥50% illite, 33-79±0.60 m.y.) from drill hole S6 located in the Grants mineral belt. Moreover, the variation in percent illite from the margin (0-5% illite layer) to the center of the basin (≥90% illite) in the San Juan Basin provides more evidence regarding the relationships among age, percent illite, and depth of illitization.

The K/Ar and Rb/Sr ages on interstratified illite/smectite presented above are much younger than the Rb/Sr sedimentation age of the Brushy Basin Member (124±28 m.y., Della Valle, 1980) and the Westwater Canyon Member (131±26 m.y., Lee and Brookins, 1980) obtained from diagenetic smectite. The diagenetic smectite is considered to have formed soon after the deposition of the Morrison Formation (Bell, 1987; Turner-Peterson and Fishman, 1987) and represents the age of early diagenesis due to compaction and dewatering of sediments during the deposition of the Morrison Formation. This also provides a minimum age of sedimentation, and of the dinosaur fossils contained in these sediments. On the other hand, the Tertiary diagenetic mineral ages reflect recent tectonic deformation associated with the Laramide Orogeny.

CONCLUSION

Clay mineralogy studies of authigenic minerals from the Brushy Basin and the Westwater Canyon Members of the Morrison Formation indicate a basinward enrichment in illite contents (5-90% illite layers). Low illite content in diagenetic mineral phases along the basin margin suggests shallow burial, minimum structural deformation of the fossil-bearing rocks, and the preservation of original organic materials in the fossils. K/Ar data on illitic clays (30-90%) also increase basinward suggesting that illitization processes started earlier in the central and deepest part of the San Juan basin. A published Rb/Sr isochron age on smectite from the basin margin is much older (131±26 m.y.) and represents a minimum sedimentation age. The geochronologic data demonstrate that at least two major diagenetic processes are recorded in the Morrison Formation.

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