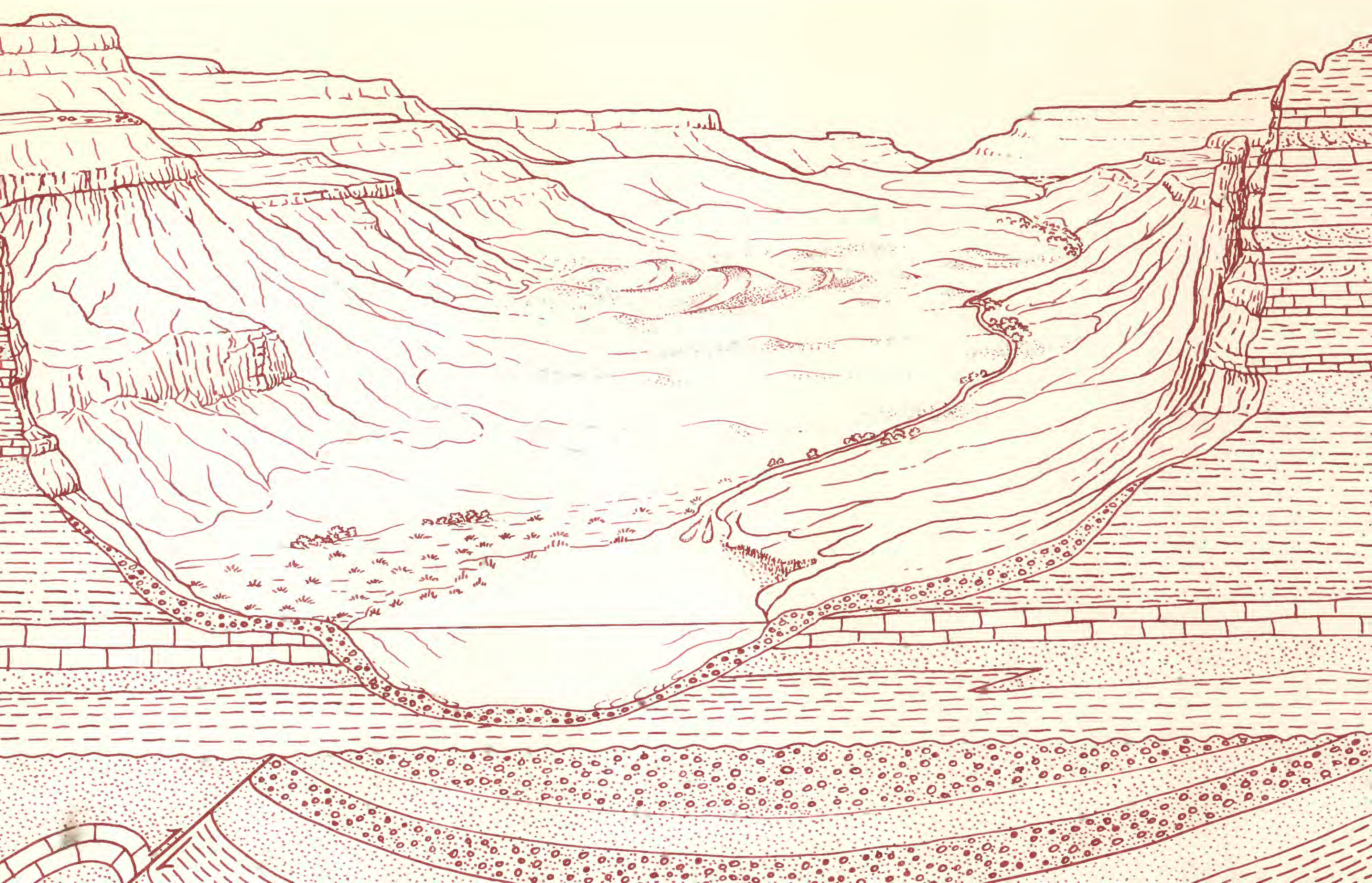
Regional Diagenesis of Sandstones in the Upper Jurassic Morrison Formation, San Juan Basin, New Mexico and Colorado: Geologic, Chemical, and Kinetic Constraints

U.S. GEOLOGICAL SURVEY BULLETIN 1808–H



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Chapter H

Regional Diagenesis of Sandstones in the Upper Jurassic Morrison Formation, San Juan Basin, New Mexico and Colorado: Geologic, Chemical, and Kinetic Constraints

By PAULA L. HANSLEY

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F–32)/1.8

Regional Diagenesis of Sandstones in the Upper Jurassic Morrison Formation, San Juan Basin, New Mexico and Colorado: Geologic, Chemical, and Kinetic Constraints

By Paula L. Hansley

Abstract

Early authigenic mineral assemblages (such as zeolite, silica, and feldspar cements) and vitroclastic textures are extraordinarily well preserved in upper sandstones of the Upper Jurassic Morrison Formation in the San Juan basin of New Mexico and Colorado. Early diagenetic reactions were driven by rapid dissolution of rhyolitic volcanic ash, which was incorporated into Morrison sediments at the time of deposition. The distributions of these authigenic minerals were controlled, in part, by chemical gradients in a large saline, alkaline lake (Lake T'oo'dichi') that existed in late Morrison time. Sandstones on lake margins were cemented by smectite and silica, whereas sandstones nearer the lake center, in which waters were most saline and alkaline, were cemented by zeolites. Diagenetic alterations in sandstones were promoted by alkaline interstitial waters that emanated from adjacent fine-grained, tuffaceous lake beds. Metastable phases that precipitated first were replaced relatively quickly by more stable, ordered phases in the geochemically favorable environment of the closed basin setting. Sandstones in the lower part of the Morrison Formation contained less ash at the time of deposition and thus have fewer diagenetic alterations. Diagenesis was dominated by precipitation of early pore-filling calcite cement and mixed-layer clay minerals. In the northern part of the basin, quartz is an abundant cement.

Vitrinite reflectance values for Cretaceous coals indicate that the Morrison Formation has remained relatively cool at basin margins throughout diagenesis. Elevation of temperatures above the geothermal gradient was provided by the influx of warm, deep-basin waters that locally modified early diagenetic assemblages during burial diagenesis. In organic- (and commonly also uranium ore-) bearing sandstones located primarily in the southern part of the basin, complex diagenetic assemblages resulted from water/rock reactions involving soluble organic complexes. Uplift of recharge areas promoted the downdip migration of meteoric waters through permeable sandstones of the Morrison in the Early Cretaceous and late Tertiary that caused widespread precipitation of kaolinite.

INTRODUCTION

The Upper Jurassic Morrison Formation is the major uranium- and vanadium-bearing unit on the Colorado Plateau and, as such, has been the focus of numerous sedimentologic, petrologic, and geochemical studies. (See Adams and Saucier, 1981, and Turner-Peterson and others, 1986, for bibliographies.) As a result, most research has concentrated on uranium ore-bearing strata; few studies have examined the regional petrology of the Morrison Formation. The major goal of the research discussed in this report was to extend a petrologic study of the Morrison Formation in eight U.S. Geological Survey (USGS) cores taken from drill holes in the Grants uranium region (fig. 1) in the southwestern part of the San Juan basin (Hansley, 1986a, b) to the rest of the basin in order to determine if observed diagenetic alteration patterns identified in the cores reflect basin-wide trends. A second objective was to use the mineralogy and paragenetic relationships of diagenetic assemblages to infer chemical processes responsible for observed postdepositional modifications of sandstones.

In order to accomplish these goals, sandstone samples were collected from 22 outcrops of the Morrison Formation and overlying Cretaceous sandstones around the margins of the basin (fig. 1). The Galisteo Dam

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section is 30 km northeast of Albuquerque, just east of the area shown in figure 1. In addition, sandstones from 15 cores in the southern part of the basin were examined to enlarge the core data set. New petrologic data were combined with previously published data to facilitate interpretations of basinwide patterns.

Virtually all outcrop localities were barren of uranium ore, with the exception of small uranium-vanadium claims in the Salt Wash Member of the Morrison near Oak Springs and in the Westwater Canyon Member of the Morrison at the Dennison-Bunn outcrop. Some uranium enrichment (discrete coffinite) was noted in the cores. A lack of ore-bearing samples was not a detriment to this study, however, because primary uranium mineralization in the Morrison Formation was a very early diagenetic process (Ludwig and others, 1984), and most diagenetic alterations discussed herein occurred subsequent to ore formation or formed in parts

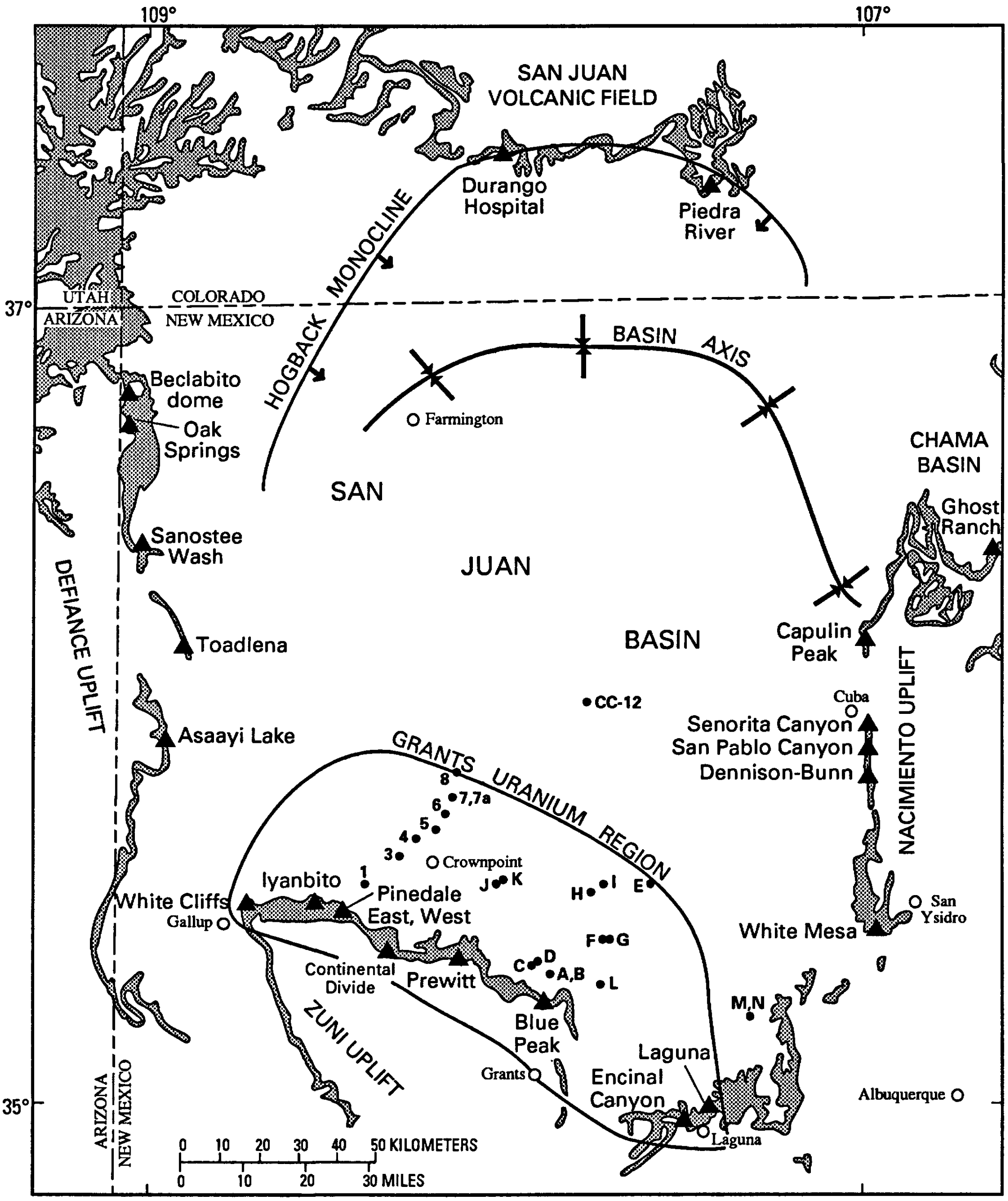


Figure 1. Major tectonic features and outcrop areas of rocks of Morrison Formation, San Juan basin. Location of sampled outcrops (triangles) and cores (solid circles) also shown. Numbers (1–8) indicate USGS core localities; letters (A–N) indicate other core localities (S.A. Adams, Colorado School of Mines). Tectonic features from Kelley and Clinton (1960); base map modified from Turner-Peterson (1986, fig. 1).

of the basin where the Morrison Formation is not known to contain ore. Furthermore, uranium enrichment in some of the cores and descriptions of uranium ore zones in previous studies provided a basis for comparing the petrology of barren sandstones to mineralized sandstones.

Acknowledgments.—I express appreciation to Isabelle Brownfield and Gary Skipp, USGS, for careful laboratory preparation of samples and for running heavy-mineral separations and clay-mineral diffraction patterns. In addition, I thank Neil Fishman and Christine Turner-Peterson, USGS, for furnishing some samples and thin sections from the northern and western parts of the basin.

GEOLOGIC SETTING

Regional Tectonic Setting and Climate

Although formation of the San Juan basin dates back to the Paleozoic, its present configuration reflects Laramide deformation (Kelley, 1951). In the Late Jurassic, the San Juan basin was bounded by the Zuni uplift to the south and the Defiance uplift to the west, and small positive areas also existed in southeastern Utah and southwestern Colorado (Santos and Turner-Peterson, 1986). Although the Defiance and Zuni uplifts may have been moderately active, furnishing local detritus to the basin during Morrison deposition (Santos and Turner-Peterson, 1986), major source areas for the Morrison were a magmatic arc west of the Colorado Plateau in present-day southeastern California, southwestern Arizona, and northwestern Sonora, Mexico (Hamilton, 1978; Dickinson, 1981), and the Mogollon uplift that extended from central Arizona into western New Mexico (Cooley and Davidson, 1963; Martinez, 1979; Lowy, 1982). In these source areas, volcanic, intrusive igneous, metamorphic, and minor sedimentary strata furnished detritus to northeastward- and eastward-flowing streams. Abundant rhyolitic to dacitic volcanic ash (Cadigan, 1967) that was blown eastward from volcanoes in the magmatic arc into the San Juan basin comprised a large part of the original matrix (now largely smectite) of Morrison sediments (Waters and Granger, 1953). Thick sequences (>100 m) comprised predominantly of altered ash beds as thick as a meter in lacustrine facies of the Brushy Basin Member attest to the enormous volumes of ash that were deposited (Turner-Peterson, 1987).

The climate during Morrison time was semiarid as evidenced by sedimentary structures, fluvial style (such as ephemeral, braided streams), the presence of eolian deposits in the lower part of the Morrison, and saline, alkaline lake deposits in the upper part of the Morrison (Bell, 1983, 1986; Turner-Peterson, 1987).

Stratigraphy

The Morrison Formation consists of five formal members in the basin (in ascending order): the Recapture, Westwater Canyon, Brushy Basin, Jackpile Sandstone, and Salt Wash. (The lowest of these, the Salt Wash Member, is only in the Four Corners region (Craig and others, 1955).) The contacts of members with each other are sharp to gradational and occasionally interfingering. The Morrison is overlain unconformably throughout most of the basin by the Upper Cretaceous Dakota Sandstone or by the Lower Cretaceous Burro Canyon Formation in the Chama basin and in the northern San Juan basin. The Jackpile is overlain by fluvial sandstones at the base of the Dakota Sandstone in the southeastern part of the basin (Aubrey, 1986). The Morrison is underlain by various formations of the Middle Jurassic San Rafael Group throughout the region (Turner-Peterson, 1986).

The average thickness of the Morrison Formation in the basin is 150 m (Turner-Peterson and Fishman, 1986). The Morrison thins erosionally and depositionally to the south where it is truncated by the Dakota Sandstone; hence, the Dakota rests on progressively older beds of the Morrison to the south. In the southwestern corner of the basin, the Brushy Basin has been eroded completely and the Dakota rests on the Westwater Canyon Member (Turner-Peterson, 1986).

The Salt Wash Member is present in the northwestern part of the basin where it reaches a thickness of 61 m (Condon and Peterson, 1986). It thins to the south and interfingers locally with the lower part of the Recapture Member. The Recapture Member is present throughout the basin, but it is not differentiated from the Beclabito Member of the underlying Middle Jurassic Wanakah Formation in the Cuba area (Condon and Peterson, 1986). The Recapture lies directly under the Brushy Basin Member in the Durango area (Turner-Peterson, 1987). The Recapture is as thick as 152 m on the west side of the basin. The Westwater Canyon Member thins to the south, north, and east; it pinches out depositionally south of the San Juan basin and north of the New Mexico-Colorado State line and is last recognized as far east as Galisteo Dam (Turner-Peterson, 1987). The Westwater Canyon Member is thickest (about 100 m) in outcrop along the western margin of the basin (Turner-Peterson, 1987, fig. 11) and is as thick as 135 m in the subsurface northeast of Gallup (Kirk and Condon, 1986). The Brushy Basin Member is thickest in the vicinity of Durango (fig. 1), where it is as thick as about 105 m (Turner-Peterson, 1987, fig. 32).

In the southeastern part of the basin, the Jackpile Sandstone Member lies above the Brushy Basin Member just under a regional Jurassic-Cretaceous unconformity. The type Jackpile is exposed in the Laguna area where it locally contains uranium ore and is as thick as 65 m (Owen and others, 1984). From Laguna, Owen and others extended the Jackpile north to Cuba and east to the Galisteo Dam area. The Jackpile was deposited along a syndepositional syncline (Hilpert and Moench, 1960), the trace of which trends to the northeast into the subsurface where a sandstone thought to be the Jackpile continues to appear at the top of the Morrison Formation (Flesch, 1975). This correlation has been extended to sandstones at the top of the Morrison Formation in surface exposures along the Nacimiento uplift (Ruetschilling, 1973; Woodward and Schumacher, 1973; Santos, 1975). Flesch (1975) mapped 7–30 m of Jackpile near San Ysidro, and Santos (1975) mapped 0–50 m of Jackpile in the San Ysidro area. Others, however, have questioned this identification because the Jackpile occupies the same stratigraphic position as the fluvial Burro Canyon Formation in the Chama basin (Aubrey, 1986). For example, Saucier (1974) extended the Jackpile northeastward from Laguna to the San Ysidro area, but, from San Ysidro along the Nacimiento uplift to the northeast toward the Chama basin, he replaced the Jackpile with the Burro Canyon Formation. Stratigraphic correlation is difficult because these two fluvial units are similar in composition except for a lack of conglomerate in the Jackpile (Flesch, 1975; Aubrey, 1986). The reason for this similarity is that the Burro Canyon consists mostly of reworked Morrison detritus (Santos, 1975).

Recently, the Encinal Canyon Member of the Dakota Sandstone, also a fluvial unit, was named formally in the southeastern San Juan basin (Aubrey, 1986). It locally cuts out the Jackpile in the southeastern part of the basin and includes parts of what have been called Burro Canyon Formation and Jackpile Sandstone Member along the Nacimiento uplift (Aubrey, 1986). In its type area, the Encinal Canyon Member includes part of the Jackpile as defined by Grant and Owen (1974). Where these fluvial units occur together, the sand-on-sand relationship is difficult to decipher because of the quartzose composition of all three units. The Jackpile is less conglomeratic and may contain more feldspar and volcanic-rock fragments than the Cretaceous units. The Burro Canyon Member is conglomeratic and contains abundant kaolinite, tripolitic chert (Santos, 1975), and oolitic, fossiliferous, silicified limestone pebbles (Ridgely, 1977). Generally, sandstones in the Encinal Canyon Member contain distinctive white, chalky chert pebbles (Aubrey, 1986). The uppermost Jurassic and Cretaceous stratigraphy used in this report follows that of Aubrey (1986, fig. 6) in the eastern part of the basin.

Depositional Environments and General Lithology

The Salt Wash Member was deposited by meandering and braided streams that originated in source areas to the west of the Colorado Plateau (Peterson, 1984). The Salt Wash consists of light-greenish-gray to light-brown, very fine to medium grained, moderately well sorted sandstone interbedded with greenish-gray to reddish-brown mudstone.

The Recapture Member was deposited in fluvial, lacustrine, and eolian environments (Condon and Peterson, 1986). Streams generally came into the basin from the southwest. The Recapture consists of very fine to fine grained (occasionally medium grained), light-gray to pale-reddish-brown sandstone beds interbedded with variegated red-brown to purplish silty mudstone and claystone beds.

The Westwater Canyon Member was deposited by braided streams that flowed northeastward to southeastward across the basin from distant source areas to the west and southwest of the Colorado Plateau (Turner-Peterson, 1986). Sandstones of the Westwater Canyon Member are poorly to well sorted, fine to medium grained, and locally conglomeratic. The Recapture and Westwater Canyon Members are reddish in outcrop owing to late Tertiary oxidation but are generally a drab gray in the subsurface (Turner-Peterson, 1986). Interbedded greenish-gray mudstones and claystones are bentonitic.

Sediments of the Brushy Basin Member were deposited in a classic saline, alkaline lake, Lake T'oo'dichi' (Turner-Peterson, 1987), in which mudflat facies around the margins grade into more saline, playa-lake facies toward the center of the basin (Bell, 1983, 1986; Turner-Peterson, 1987). Fluvial sandstones are light brown to gray and are similar in composition to sandstones of the Westwater Canyon Member. Sandstones are interbedded with thick sequences of bentonitic to zeolitic mudstone, claystone, altered tuff beds, and thin limestone units.

The Jackpile Sandstone Member was deposited by braided streams (Moench and Schlee, 1967) that flowed in a northeasterly direction at Laguna and in an easterly direction along the Nacimiento uplift (Flesch, 1975; Owen and others, 1984). Sandstone units are chalky gray, white to yellow, fine to medium grained, and locally conglomeratic and contain minor interbedded claystone. Silicified or coalified plant remains are locally present.

METHODS OF STUDY

Sandstone samples (217) were collected from 22 outcrops of the Morrison Formation on the margins of the San Juan basin. Some localities were sampled in detail, and others were sampled sparsely to check variations in petrology. Petrographic thin sections of outcrop samples were impregnated with blue-dyed epoxy and stained with sodium cobaltinitrate for potassium feldspar identification and with Alizarin Red-S for calcite identification. Point counts (300 points per section) were made of representative thin sections for sandstone classification. Additional petrographic thin sections (84) (donated by S.S. Adams, Colorado School of Mines) from 15 cores in the southern part of the basin were examined; point counts were not made of these thin sections.

Heavy-mineral separations of the <60>200 micron fraction of selected fine- to medium-grained samples were made in Bromoform (S.G. 2.87). The magnetic fraction was removed from the heavy fraction with a hand magnet, and the remaining nonmagnetic fraction (or a split thereof) was mounted with Canada balsam on a petrographic slide. Point counts of the heavy-mineral mounts were not conducted during this study. (See Hansley, 1986a, for point counts of samples from the USGS cores.)

Selected samples were examined with a Cambridge Stereoscan Mark 2 scanning electron microscope (SEM) with an attached Tracor Northern energy-dispersive system so that textural (paragenetic) relationships among authigenic minerals in sandstone pores could be described and the genetic nature (authigenic versus detrital) of clay minerals determined.

The <2-μm fraction of selected samples was analyzed by X-ray diffraction for determination of clay mineralogy. Three X-ray diffractograms were generated from each sample—air dried, glycolated, and 550 °C runs—in order to make clay-mineral identifications. The percentage of illite in interstratified illite/smectite (I/S) was determined by measuring the 001/002 and 002/003 peak positions (Reynolds, 1980); the notation of 0.7I means 70 percent illite in I/S. The presence of perfect ordering (ISIS, IIIS, and so forth) was evaluated by looking for a superlattice peak, noting positions of nonintegral peaks, and comparing the results to published (Reynolds, 1980) and unpublished (Maynard Slaughter, Colorado School of Mines, 1987) clay-mineral tables.

PETROLOGIC DATA

Heavy Minerals

Tourmaline, zircon, garnet, staurolite, apatite, and iron-titanium oxides comprise the bulk of heavy-mineral suites. Minor heavy-mineral species include epidote, rutile, hornblende, sphene, and monazite. The most notable change in composition among the members is the appearance of abundant staurolite in the Westwater Canyon and Brushy Basin Members, as compared to a lack of staurolite in the Salt Wash Member and a trace of staurolite in the Recapture Member. In general, staurolite is more abundant in the Westwater Canyon and Brushy Basin Members (including the Jackpile Sandstone Member) in the eastern part of the basin than in the rest of the basin, but it is notably absent at Galisteo Dam. Epidote is present in the Recapture and Westwater Canyon Members along the Nacimiento uplift and is most abundant in rocks at Senorita Canyon. Sphene was noted only at Galisteo Dam. Garnet is common throughout the Morrison except at the Durango Hospital section, where the Recapture and Brushy Basin Members contain no garnet. The Middle and Upper Jurassic Junction Creek Sandstone, which underlies the Recapture Member at Durango, does not contain garnet but does contain distinctive green hornblende not present in the overlying Morrison Formation.

Only a few Cretaceous samples were analyzed for heavy minerals. The marine Oak Canyon Member of the Dakota Sandstone is characterized by zircon and tourmaline; no garnet or apatite was observed. The underlying Encinal Canyon Member contains abundant zircon, tourmaline, and staurolite, but no garnet was noted in the samples analyzed.

Other Framework Minerals

The detrital mineralogy of sandstones in the Morrison Formation is also relatively consistent around the basin. Sandstones were classified according to Folk's scheme (1974). Classifications generally agree with those of previous workers (Cadigan, 1967; Schmitt, 1982; Steele, 1984a, b). Point counts of selected thin sections are shown in table 1.

Salt Wash Member

Sandstones of the Salt Wash Member are moderately well sorted, fine-grained subarkoses (fig. 2*A*) composed of quartz, microcline, orthoclase, sodic plagioclase, sanidine(?), and various rock fragments. The most common rock fragments are chert, limestone (micrite), silicified limestone, and fine-grained varieties such as siltstone and shale. Igneous (plutonic) and metamorphic (quartzite) lithic fragments are rare. Most plagioclase is untwinned; some displays albite twinning or zoning.

Recapture Member

Sandstones of the Recapture Member are mainly subarkoses and lithic arkoses (fig. 2*B*) that have compositions similar to those of the Westwater Canyon

Table 1. Petrographic data derived from point counts of selected thin sections

[Data in volume percent; based on 300 points per thin section. Kdec, Encinal Canyon Member of Dakota Sandstone; Kbc, Burro Canyon Formation; Jmu, Morrison Formation (undifferentiated). Morrison Formation: Jmj, Jackpile Sandstone Member; Jmb, Brushy Basin Member; Jmw, Westwater Canyon Member; Jmr, Recapture Member; Jmsw, Salt Wash Member. Petrographic components: frag, fragments; Musc, muscovite; min, minerals; Anhy, anhydrite; Zeol, zeolites; ovgr, overgrowths; Chal, chalcedony]

Strat unit	Sample number	Qtz	Kspar	Plag	Rock frag	Biotite	Musc	Heavy min	Calcite	Anhy	Barite	Zeol	Qtz ovgr	Kspar ovgr	Albite ovgr	Chal	Clay	Hematite	Void
Senorita Canyon																			
Jmb	Sc-1	144	12	15	25	0	2	0	0	0	0	50	4	0	0	1	35	0	12
Jmb	Sc-2	121	6	15	56	0	0	0	0	0	0	21	33	0	0	1	37	0	10
Jmw	Sc-10	119	53	33	37	0	0	0	0	0	0	0	11	0	0	7	1	0	39
Jmw	Sc-11	134	19	10	29	0	0	0	106	0	0	0	0	0	0	2	0	0	0
Jmw	Sc-13	132	29	11	13	0	0	0	113	0	0	0	0	0	0	1	1	0	0
Capulin Peak																			
Kbc	Cp-1	209	3	0	23	0	0	0	0	0	0	0	2	0	0	0	7	0	56
Kbc	Cp-2	179	24	0	19	0	0	0	0	0	0	0	0	0	0	44	12	0	16
Jmw	Cp-8	140	51	3	19	0	0	0	50	0	0	0	0	0	0	1	27	0	9
Jmw	Cp-9	194	25	12	25	0	0	0	10	0	0	0	0	0	0	0	12	0	22
Jmw	Cp-10	127	28	11	23	0	0	0	107	0	0	0	0	0	0	0	0	0	0
Jmw	Cp-11	144	43	8	20	0	0	0	6	0	0	0	0	0	0	0	19	0	57
Jmw	Cp-14	141	42	5	16	0	0	0	89	0	0	0	0	0	0	0	5	0	2
San Pablo Canyon																			
Jmj	Sp-2	138	29	16	40	0	0	0	0	0	0	0	75	0	0	1	0	0	1
Jmw	Sp-5	138	22	21	40	0	0	0	0	0	0	4	54	3	0	2	9	0	7
Durango Hospital																			
Jmr	Dh-2	112	11	7	9	0	0	0	11	25	6	0	117	0	0	0	2	0	0
Jmr	Dh-3	136	25	7	9	0	0	0	20	0	0	0	66	0	0	0	37	0	0
Jmr	Dh-4	138	11	14	6	0	0	0	8	0	0	0	84	0	0	3	35	0	1
Jmr	Dh-5	162	12	12	8	0	0	0	70	0	0	0	29	0	0	0	2	0	0
Jmr	Dh-6	151	10	13	9	0	0	0	47	0	0	0	55	0	0	3	12	0	0
Jmb	Dh-8	153	9	18	11	0	0	0	3	0	0	0	25	0	20	0	22	0	39
Jmb	Dh-11	79	14	16	1	0	0	0	3	0	0	1	0	0	0	169	2	0	0
White Mesa																			
Jmj	Wm-1a	204	17	0	18	0	0	0	0	0	0	0	1	0	0	8	12	0	40
Jmj	Wm-1	145	30	23	35	0	0	0	0	0	0	0	10	1	0	56	0	0	0
Jmj	Wm-2	186	18	9	24	0	0	0	0	0	0	0	0	0	0	0	45	0	18
Jmb	Wm-3	112	25	17	48	0	0	0	76	0	0	0	0	0	0	0	20	1	1
Jmw	Wm-11	137	22	23	26	0	0	0	0	0	0	0	0	0	0	90	1	0	0
Jmw	Wm-12	103	25	33	37	0	0	0	0	0	0	99	0	0	0	0	0	1	0
Jmr	Wm-13	165	30	20	24	0	0	1	0	0	0	0	4	4	2	0	7	0	43
Laguna																			
Jmj	Lg-4	194	13	1	15	0	0	0	0	0	0	0	20	0	0	0	12	0	45
Jmj	Lg-5	160	26	5	23	0	0	0	0	0	0	0	0	0	0	0	28	4	54
Jmj	Lg-6	160	31	2	26	0	0	0	0	0	0	0	20	0	0	0	22	2	37
Jmb	Lg-7	185	18	11	18	0	0	0	0	0	0	0	17	0	0	0	25	0	26
Jmb	Lg-8	149	19	14	23	0	0	0	0	0	0	0	34	2	4	0	15	0	40
Jmw	Lg-9	151	16	6	21	0	0	1	36	0	0	57	6	0	0	0	4	0	2
Jmw	Lg-10	140	3	4	58	0	0	0	93	0	0	0	0	1	0	0	0	0	2
Jmw	Lg-11	143	11	1	19	0	0	0	126	0	0	0	0	0	0	0	0	0	0
Jmr	Lg-13	178	15	5	17	0	0	0	85	0	0	0	0	0	0	0	0	0	0
Encinal Canyon																			
Kdec	Ec-1	172	12	0	21	0	0	0	38	0	0	10	29	0	0	0	0	0	28
Kdec	Ec-2	177	18	0	38	0	0	0	1	0	0	0	19	0	0	0	26	0	21
Kdec	Ec-3	177	21	0	17	0	0	0	0	0	0	0	43	0	0	1	25	0	16
Kdec	Ec-4	207	18	0	19	0	0	0	0	0	0	0	4	0	0	0	49	0	3
Galisteo Dam																			
Kbc	Gd-1	207	0	0	30	0	0	0	0	0	0	0	0	0	0	0	43	0	3
Jmb	Gd-5	98	56	0	19	0	0	0	5	0	0	0	0	0	0	110	12	0	0
Jmu	Gd-6a	134	22	27	19	0	0	0	87	0	0	0	8	0	0	0	3	0	0
Jmu	Gd-8	153	18	10	15	0	0	0	0	0	0	0	59	0	0	0	11	22	12

Table 1. Continued

Strat unit	Sample number	Qtz	Kspar	Plag	Rock frag	Biotite	Musc	Heavy min	Calcite	Anhy	Barite	Zeol	Qtz ovgr	Kspar ovgr	Albite ovgr	Chal	Clay	Hematite	Void
Ghost Ranch																			
Kdec	Gr-1	207	1	0	8	0	0	0	0	0	0	0	38	0	0	15	6	1	24
Kbc	Gr-4	158	8	1	31	0	0	0	11	0	0	0	2	0	0	73	6	7	3
Jmb	Gr-5	150	28	1	18	1	0	0	0	0	0	0	0	0	0	0	90	0	10
Dennison-Bunn																			
Kdoc	Db-Kd	211	14	0	6	0	0	0	0	0	0	0	19	0	0	0	27	0	23
Jmj	Db-1	187	19	0	20	0	0	0	0	0	0	0	48	2	0	0	7	0	17
Jmj	Db-2	238	13	0	6	0	0	0	0	0	0	0	0	0	0	0	1	1	41
Jmb	Db-5	174	32	0	26	0	0	0	0	0	0	0	0	0	0	0	24	0	44
Jmb	Db-6	182	20	1	4	0	0	0	0	0	0	0	1	12	0	0	21	1	56
Jmw	Db-8	191	20	4	18	0	0	0	0	0	0	0	24	11	0	0	7	0	25
Jmw	Db-9	190	16	1	16	0	0	0	0	0	0	0	15	13	0	0	28	0	21
Jmw	Db-10	147	36	2	40	0	0	0	0	0	0	0	15	10	0	1	19	0	30
Jmw	Db-11	160	33	9	25	1	1	1	13	0	0	0	5	5	0	0	18	2	25
Jmr	Db-12	127	27	6	35	0	0	3	97	0	0	0	0	0	0	0	5	0	0
Jmr	Db-14	163	38	6	15	1	0	0	1	0	1	0	0	0	0	0	12	1	62
Beclabito dome																			
Jmsw	Bd-4	207	12	3	13	0	0	1	24	2	1	0	16	0	0	0	7	0	13
Jmsw	Bd-5	125	9	1	14	0	0	0	29	0	0	0	27	0	0	0	3	0	22
Jmsw	Bd-6	181	10	10	17	0	0	0	17	0	0	0	20	0	0	0	3	0	42
Jmw	Bd-8	167	12	15	20	0	0	0	1	0	0	0	47	1	9	0	23	0	5
Jmw	Bd-11	206	13	18	15	0	0	0	0	0	0	6	3	0	2	0	11	0	26
Jmw	Bd-13	187	17	14	10	0	1	0	6	0	0	6	14	0	0	0	25	0	20
Jmb	Bd-18	113	3	11	12	0	0	0	1	0	0	58	8	0	0	88	0	0	0
Jmb	Bd-22	158	2	8	23	0	0	0	2	0	0	1	0	0	1	0	3	0	1
Oak Springs																			
Jmsw	Os-17	173	21	4	10	0	0	2	39	1	0	25	0	0	0	0	0	0	25
Jmsw	Os-20	185	26	7	22	0	0	1	2	0	0	0	1	0	0	0	19	0	37
Jmsw	Os-22	176	25	14	22	0	0	0	6	0	0	0	12	0	0	0	0	0	45
Jmr	Os-25	169	29	13	6	0	0	3	0	0	0	0	0	0	0	0	3	0	77
Jmr	Os-26	174	26	14	13	0	0	1	0	0	0	0	1	0	0	0	6	0	56
Jmr	Os-30	137	29	15	23	0	1	1	74	0	0	0	0	0	0	0	11	1	8
Jmw	Os-32	186	19	9	29	0	0	0	11	0	0	0	0	0	0	0	13	0	33
Jmw	Os-34	218	15	4	18	0	0	0	2	0	0	0	12	0	0	0	4	0	27
Jmw	Os-38	207	23	4	23	0	0	0	2	0	0	0	4	0	0	0	18	0	19
Jmw	Os-42	194	12	7	15	0	0	0	0	0	0	0	26	2	0	0	6	0	30
Jmb	Os-43	136	15	9	32	0	0	0	57	0	1	3	29	2	0	0	11	4	0
Jmb	Os-50	152	13	12	29	1	0	0	0	0	0	0	0	0	1	79	13	0	0

Member. Micritic fragments were noted at the Dennison-Bunn and Oak Springs sections, and micritic oolites occur at Laguna. Most rock fragments are chert, other fine-grained sedimentary rocks such as shale and siltstone, volcanic (felsite), and metamorphic (stretched polycrystalline quartz, chlorite) types. The most notable aspect of framework mineralogy is the (rare) appearance of detrital plagioclase grains rimmed with potassium feldspar (anti-rapakivi texture) near the top of the Recapture Member. (See discussion on Westwater Canyon Member in next section.) Some plagioclase is untwinned; twinned varieties are dominantly albite and minor pericline and carlsbad. Low angles between twin planes and cleavage traces and the thinness of twin laminae suggest that plagioclase compositions range from albite to andesine.

Westwater Canyon Member

Sandstones of the Westwater Canyon Member are principally subarkoses and lithic arkoses (fig. 2*C*) characterized by large amounts of volcanic material including sanidine and volcanic rock fragments. The dominant fragments are fine-grained felsic volcanic rocks containing rare quartz or feldspar phenocrysts (fig. 3). Other rock fragments are (in decreasing order) polycrystalline quartz (metamorphic and plutonic igneous), chert, and chlorite. Rare plutonic fragments are very fine grained and have a "granitic" composition. Relict shard textures that were preserved by early smectite, calcite, or zeolite cements (fig. 4) indicate that volcanic ash composed much of the original matrix of these sandstones.

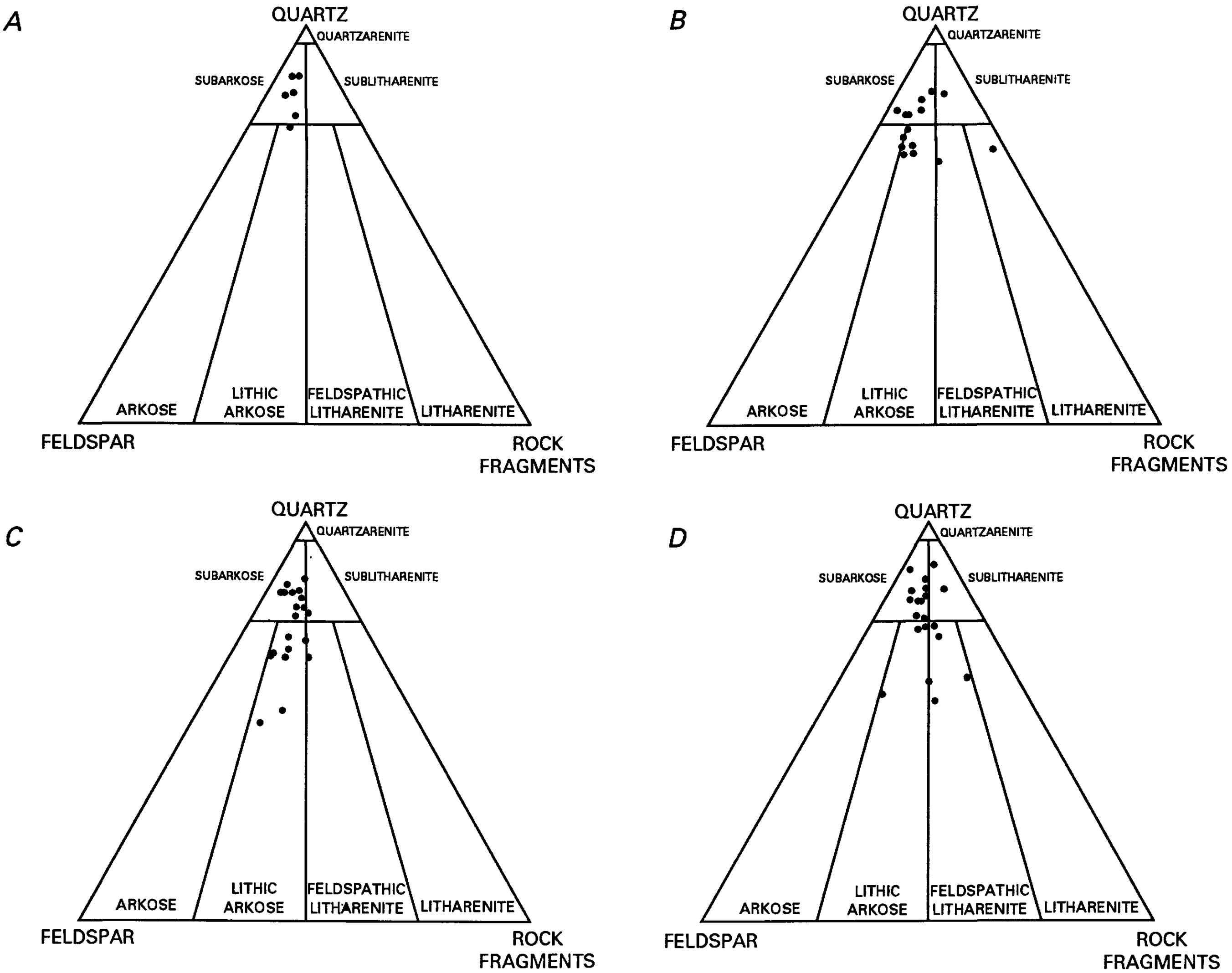


Figure 2. Classification of sandstones in the Morrison Formation. *A*, Salt Wash Member; *B*, Recapture Member; *C*, Westwater Canyon Member; *D*, Brushy Basin Member. Classification scheme after Folk (1974).

Plagioclase grains having potassium feldspar rims (for example, anti-rapakivi texture) occur throughout the Westwater Canyon Member (fig. 5*A*) but are most common in medium-grained sandstones of the middle to upper part of the Westwater Canyon Member. The only place that these grains do not occur is in the Morrison Formation at Durango, where most feldspars have been completely albitized. Locally, the plagioclase core has been partly to totally dissolved such that only a rim of potassium feldspar enclosing a void remains (fig. 5*B*). Although some potassium feldspar-rimmed grains display overgrowths (fig. 5*C*), most potassium feldspar extends inward from the rims of plagioclase-cored grains without overgrowth development. Remnants of plagioclase cores are commonly albitized as indicated by high birefringence (fig. 5*D*) and electron microprobe analyses showing 99 mole percent albite (Hansley, 1986b). Associated mixed-layer I/S may or may not be illitized.

In the Grants uranium region, the presence of hollow potassic sanidine rims without plagioclase cores led Austin (1963, 1980) to conclude that these distinctive potassium feldspar rims were skeletal detrital sanidine grains. Subsequently, these rims were reinterpreted to be metasomatic replacement of plagioclase by potassium feldspar and (or) authigenic potassium feldspar overgrowths that had precipitated on detrital plagioclase grains; rims became hollow when the plagioclase dissolved (Hansley, 1986b). This conclusion was based on detailed quantitative electron microprobe analyses, observations that the potassium feldspar rim was composed of many euhedral, micron-size authigenic potassium feldspar crystals having different optical orientations, and the presence in the sample suite of the total spectrum from a detrital plagioclase having a potassium feldspar rim to a potassium feldspar rim enclosing a void (Hansley, 1986b). The potassium feld-

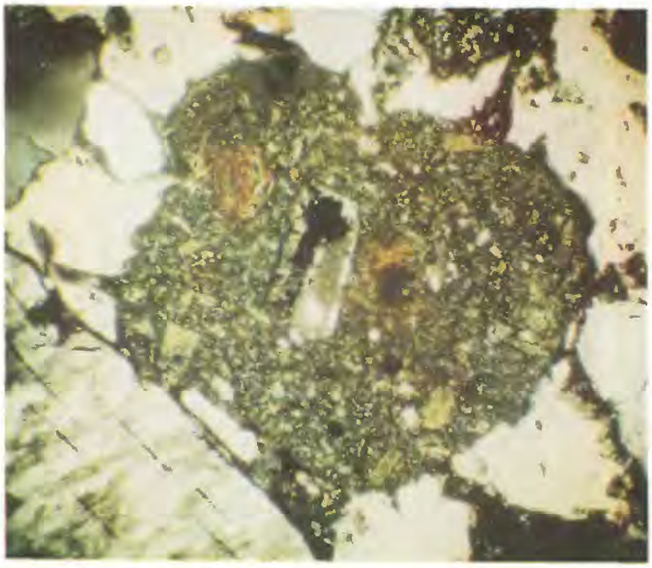


Figure 3. Photomicrograph showing felsic volcanic rock fragment in the Westwater Canyon Member at Oak Springs. Plane-polarized light; length of field, 0.2 mm.

spar rims did not exhibit cathodoluminescence and are almost pure potassic sanidine containing 16.27 percent K_2O, 0.15 percent Na_2O, and 0.003 percent CaO (Hansley, 1986b); thus, they formed at low temperatures (Kastner, 1971). What was not considered in either Hansley's or Kastner's study was the possibility that the potassium feldspar rims are in part detrital.

Petrographic observations made during the present study suggest that plagioclase grains having anti-rapakivi textures were inherited from the source area: (1) development of potassium feldspar rims even at grain contacts, (2) potassium feldspar-rimmed plagioclase in sandstones cemented by early quartz and zeolite cements, and (3) lack of potassium feldspar overgrowth development on adjacent detrital potassium feldspars. The abrupt appearance of these distinctive grains in the upper part of the Recapture Member suggests that intermediate volcanic rocks were unroofed in the source area or, alternatively, that a new source area began to feed sediments into the San Juan basin. The appearance of these grains coincides with the appearance of other types of volcanic material such as sanidine and euhedral zircons. Thick sequences of Mesozoic rhyolitic and dacitic volcanic rocks in southern Arizona (Cooley and Davidson, 1963) were potential sources for these grains as well as for the potassic volcanic rock fragments. An orogenic belt to the west of the Colorado Plateau may have been another source of andesitic material. Plagioclase grains having anti-rapakivi textures are common in dacites and andesites (Williams and others, 1954).

Brushy Basin and Jackpile Sandstone Members

Most fluvial sandstones of the Brushy Basin and Jackpile Sandstone Members are subarkoses (fig. 2*D*) having compositions very similar to those of sandstones in the Westwater Canyon Member. Moench and Schlee (1961) reported 80–95 percent quartz and 1–19 percent feldspar in sandstones of the Jackpile, but Adams and others (1978) reported only 60–79 percent quartz and 13 percent feldspar. Sandstones of the Brushy Basin and Jackpile Sandstone Members contain fewer rock fragments owing to their generally smaller grain size. In some Brushy Basin samples, early silica and zeolite cements apparently protected feldspars from dissolution resulting in a higher feldspar content than in other sandstones of the Morrison Formation. Potassium feldspar-rimmed plagioclases were noted only in coarser sandstones of the lower part of the Brushy Basin Member.

Cretaceous sandstones

Most sandstones of the Encinal Canyon Member of the Dakota Sandstone are sublitharenites; sandstones containing more feldspar are subarkoses. Major constituents are quartz, potassium feldspar, and silicic rock fragments such as chert and quartzite. Unlike sandstones of the Jackpile, sandstones of the Encinal Canyon contain no plagioclase. This absence may be the result of diagenesis, or it may reflect an original lack of plagioclase; too few samples were examined to be able to determine the reason for this absence.

DIAGENESIS

Heavy Minerals

The results of previous studies (Hansley, 1986a) and of the present study indicate that of the common heavy-mineral species in the Morrison, staurolite and garnet were the most affected by intrastratal solution, and zircon, tourmaline, and apatite show virtually no effects of diagenetic alteration. In the USGS cores, staurolite and garnet were deeply etched and possibly totally dissolved locally by diagenetic processes (Hansley, 1986a). In the outcrop samples of this study, however, both are preserved (not etched). Deeply etched garnets (fig. 6) texturally similar to those in the USGS cores (Hansley, 1986a, 1987) were found only in the Salt Wash Member in the northwestern part of the basin (fig. 7) in sandstones stratigraphically equivalent to ore-bearing sandstones. At Durango Hospital, the lack of garnets may be due to intrastratal dissolution. In other outcrop sections, many garnets display minor surface etching, but

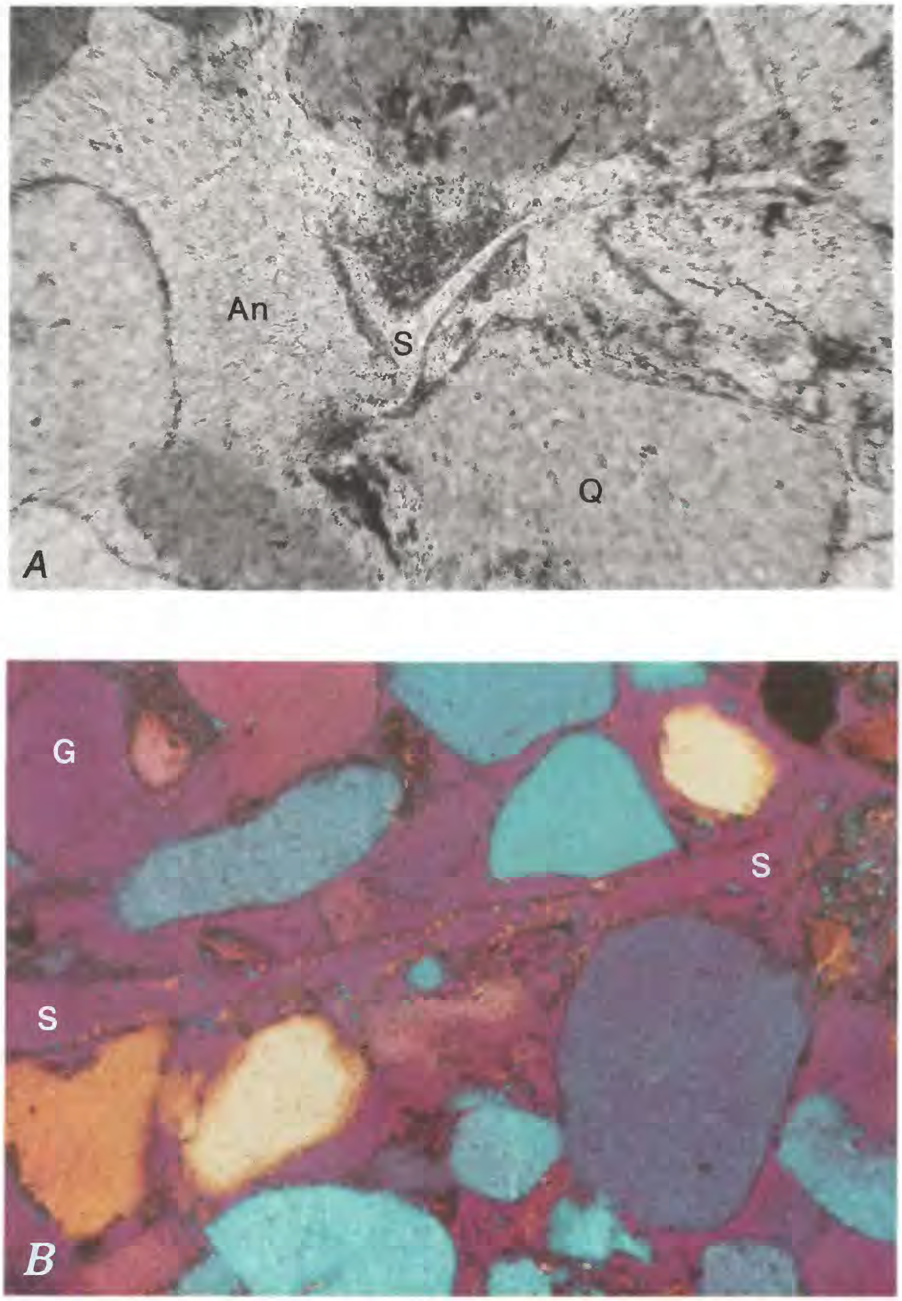


Figure 4. Photomicrographs showing vitric textures preserved in analcime-cemented sandstone of the Brushy Basin Member from Senorita Canyon (plane-polarized light). *A*, Clinoptilolite- and smectite-rimmed shard (S) infilled with analcime (An). Analcime also fills voids. Q, detrital quartz grain. Length of field, 0.6 mm. *B*, Shard (S) infilled by analcime (S's are at each end of the shard); shard is outlined by micron-size yellow clinoptilolite grains. Analcime-filled pores are reddish purple due to insertion of gypsum plate. Note grain (G) that has been replaced entirely by analcime and preponderance of floating grains. Length of field, 0.8 mm.

most are unetched. The Encinal Canyon Member does not contain any garnets, probably as a result of attrition during transport or during the reworking of older sediments. Unfortunately, the sample number (13) is not large enough to ascertain whether this is truly a major distinction between sandstones of the Encinal Canyon and the Jackpile, which are otherwise very similar in composition.

Several varieties of authigenic heavy minerals including leucoxene, anatase, and pyrite are common in

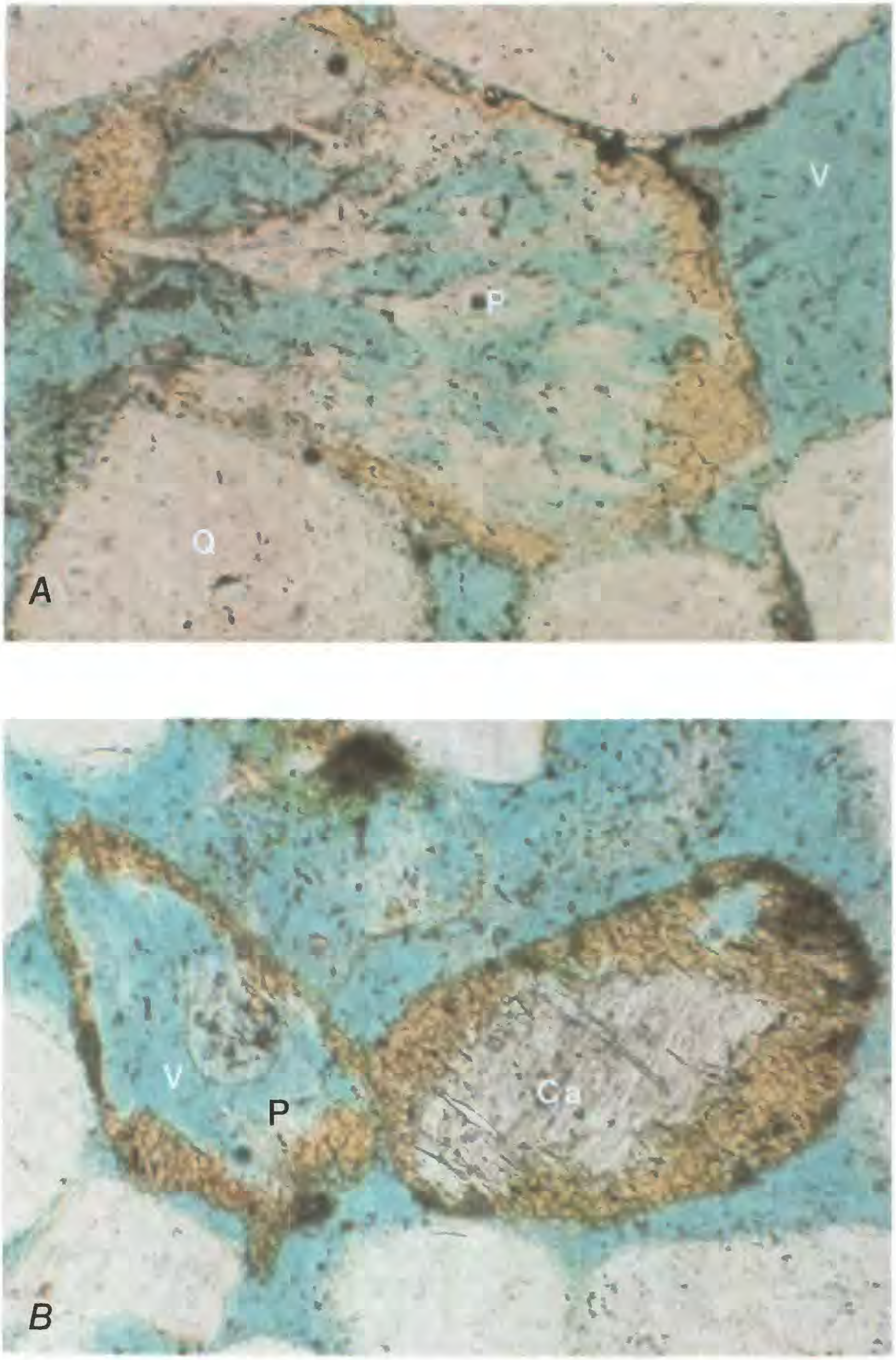
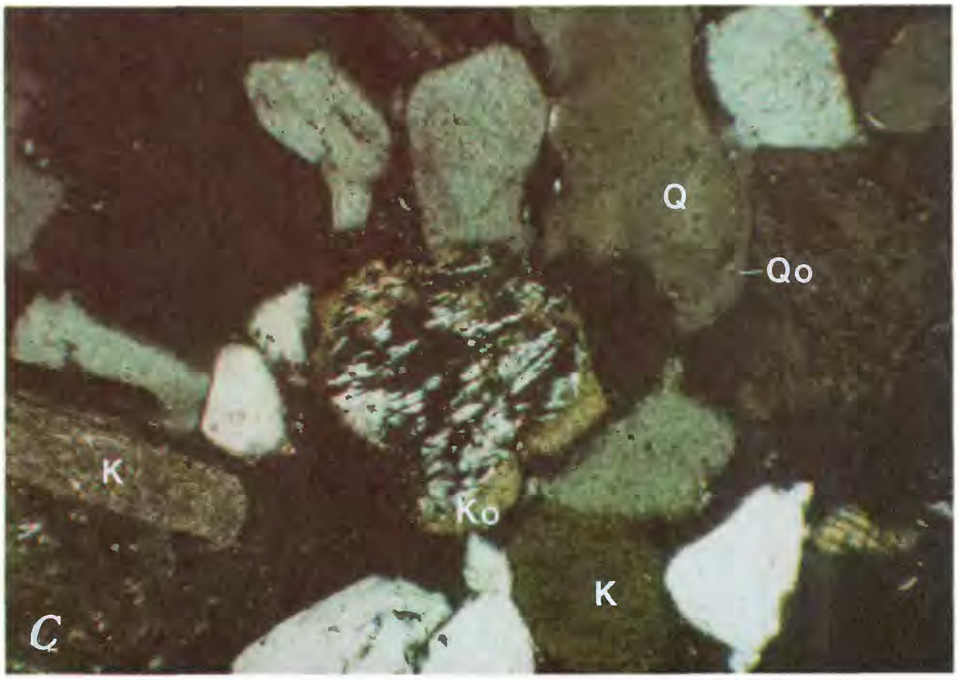


Figure 5 (above and following page). Photomicrographs showing anti-rapakivi textures of detrital plagioclase grains. Note inward extension of potassium feldspar from detrital rims. Plagioclase grains are in sandstone of the Westwater Canyon Member at Beclabito dome. *A*, Partly dissolved plagioclase grain (P) rimmed by potassium feldspar overgrowth (stained yellow green by potassium cobaltinitrate). V, void (blue); Q, quartz. Plane-polarized light; length of field, 0.4 mm. *B*, Two potassium feldspar overgrowth rims (yellow) that remain after dissolution of plagioclase cores: one rim contains plagioclase remnants (P) in the dissolution void (V); the other is filled in with calcite (Ca). Plane-polarized light; length of field, 0.7 mm. *C*, Partly dissolved, albitized detrital plagioclase grain with potassium feldspar rim (Ko, stained greenish yellow) near detrital potassium feldspar grains (K) that do not have overgrowths. Note quartz overgrowth (Qo) on detrital quartz grain (Q). Crossed polars; length of field, 0.8 mm.



the Morrison Formation. Pyrite is locally abundant as a cement and as euhedral grains in the Westwater Canyon Member associated with organic matter and uranium enrichment in cores; it is rare in outcrop sections. Euhedral titanium dioxide minerals such as anatase are present in most heavy-mineral grain mounts and are thought to be alteration products of detrital iron-titanium oxide minerals. Comprehensive studies of iron-titanium oxide minerals and their alteration products in the Morrison Formation in the San Juan basin were conducted by Adams and others (1974) and Reynolds and others (1986).

General Sandstone Diagenesis

The distributions of authigenic minerals in all members reveal distinct trends across the basin highlighted by an increase in the complexity of alterations to the north. The regional distributions of major authigenic clay minerals in sandstones of the Recapture, Westwater Canyon, and Brushy Basin Members are shown in figure 8. Scanning electron microscope observations of (delicate) textures and of trends in expandability of mixed-layer clay minerals in the Morrison Formation indicate that these clays are authigenic. (See table 2 for point counts of authigenic phases in thin section.) Diagenesis has severely altered framework-mineral assemblages around the basin, and the inferred paragenesis of major postdepositional alterations is shown in figure 9.

Salt Wash Member

Lower sandstones of the Salt Wash Member are sporadically well cemented with quartz overgrowths and calcite. Upper sandstones are characterized by dissolution as evidenced by skeletal plagioclase, corroded quartz grains, moderately etched garnets, and remnant calcite cement. Small uranium-vanadium claims occur in the upper part of the Salt Wash near Oak Springs.

The clay mineralogy of the Salt Wash Member was determined only at Beclabito dome where the dominant authigenic clay mineral is chlorite. The 002 and 004 peaks do not have an appreciably greater intensity than

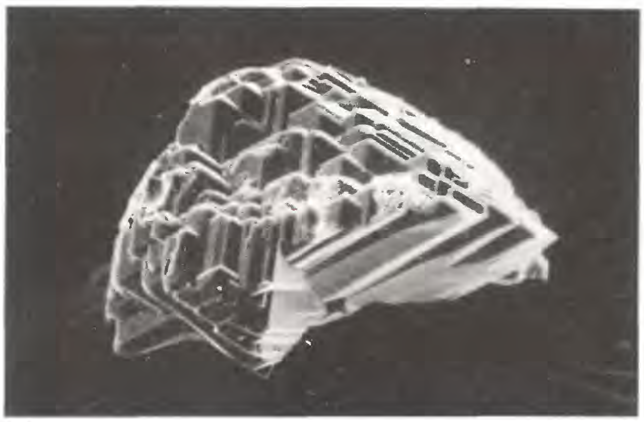


Figure 6. Scanning electron micrograph showing deeply etched garnet from the Morrison Formation. Length of field, 0.30 mm. Sample is from USGS core 7.

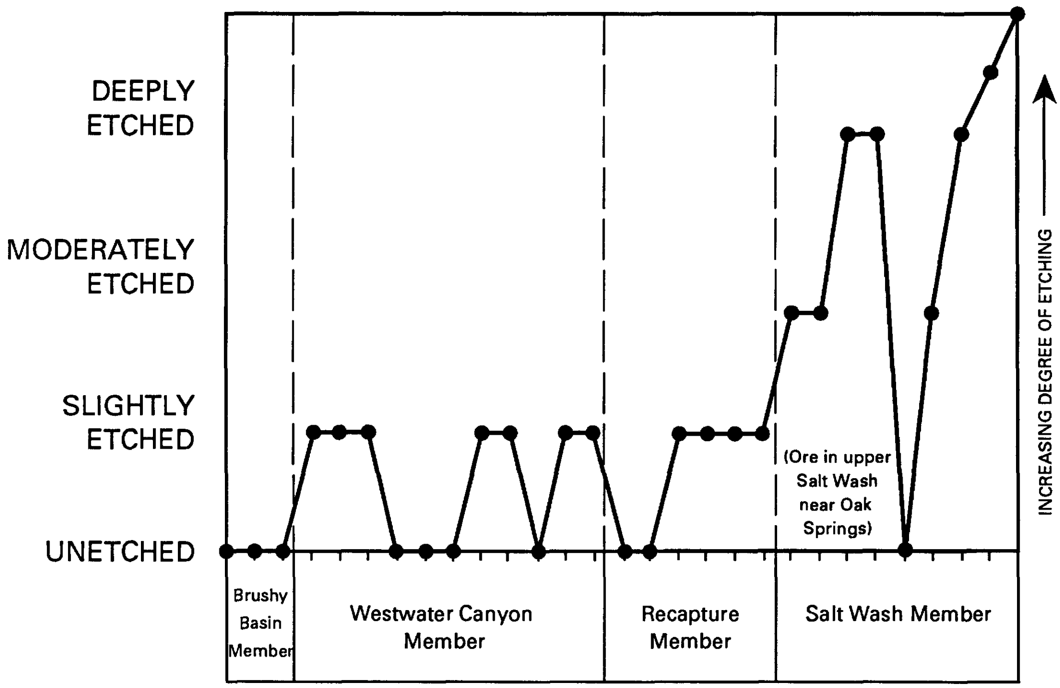


Figure 7. Occurrence of garnet textures in the Morrison Formation at Oak Springs. Note correlation between deeply etched garnets and uranium ore. One sandstone in the middle part of the Salt Wash Member containing unetched garnets is fine grained; the other sandstones are medium grained.

than the 001 and 003 peaks (fig. 10), indicating that the chlorite is not ferroan (Brown and Brindley, 1980). Both minor ordered I/S having 70–90 percent illite layers (0.7–0.9I) and kaolinite are present in most samples.

Recapture Member

In general, sandstones in the Recapture Member are characterized by abundant (early) calcite cement, which commonly fills as much as 30 percent of the primary pores; little additional alteration is present except for minor anhydrite and barite cement. Where dissolution of calcite has taken place, skeletal plagioclase is present.

Diagenesis is most advanced in the eastern part of the study area at Galisteo Dam where the Recapture equivalent is present and at the Durango Hospital section. At Galisteo Dam, the lower sandstones in the Morrison (Recapture equivalent?) contain abundant quartz overgrowths and (or) minor albite overgrowths. Hematite cement coats the overgrowths. In the northernmost part of the study area at the Durango Hospital section, the Recapture, which lies directly under the Brushy Basin, contains abundant quartz and albite overgrowths (for example, even on detrital potassium feldspar) and calcite, and locally anhydrite, barite, and hematite cements. Intermittent sericitization of plagioclase grains suggests that sericitization occurred before deposition.

Clay-mineral trends in the Recapture parallel the trends of other authigenic minerals in that more advanced diagenetic phases occur in the northern part of the basin. At Beclabito dome, chlorite and ordered I/S (>0.75I) are dominant, and kaolinite is a minor phase. At the northernmost section of this study, Durango Hospital, the Recapture contains major I/S (>0.9I) and minor kaolinite. In contrast, along the eastern side of the basin from Capulin Peak south to White Mesa, clays are dominantly kaolinite and expandable I/S (<0.1I). In the USGS cores from the southern part of the basin, authigenic clays in the Recapture are also dominantly smectite (Whitney, 1986).

Westwater Canyon Member

Diagenesis in sandstones of the Westwater Canyon Member is characterized by a general upward increase in amount of diagenetic alteration in outcrops and in cores and by an increase in intensity of alteration to the north.

In the northwestern part of the basin at Beclabito dome, sandstones of the Westwater Canyon Member contain abundant quartz and albite overgrowths and minor potassium feldspar overgrowths. Tabular clinoptilolite crystals (>50 μm) partly fill pores (fig. 11) and may be intergrown with authigenic quartz (fig. 12) in upper sandstones. Analcime occurs locally as a cement or as an infilling in skeletal plagioclase grains (fig. 13*A*), and

Table 2. Results of X-ray diffraction analyses of the <2-µm fraction of selected sandstones
[+++, 3,000 counts; ++, >2,000 counts; + >500<2,000 counts; Trace, <500 counts; leaders (---) indicate none detected. <0.1I indicates <10 percent illite in illite/smectite]

Stratigraphic unit	Sample No.	Chlorite	Illite/smectite	Kaolinite
		Beclabito Dome		
Burro Canyon Formation	81-Bd-37	---	+++ (<0.3I)	+
Dakota Sandstone	---	---	---	++
Brushy Basin[1]	81-Bd-36	---	Trace (0.8I, >0.9I)	+
Do.	81-Bd-35	Trace	Trace (0.8I, 0.65I)	Trace
Do.	81-Bd-34	Trace	Trace	Trace
Do.	81-Bd-33	+	Trace (0.75I, 0.5I)	+
	81-Bd-32	+	Trace (0.5I 0.8I)	+
Westwater Canyon[1]	81-Bd-31	Trace	Trace (0.7I, <0.6I)	Trace
Do.	81-Bd-30	---	Trace (2 phases)	Trace
Do.	81-Bd-29	Trace	+ (0.7I)	+
Do.	81-Bd-28	+	Trace	+
Do.	81-Bd-26	Trace	Trace	Trace
Do.	81-Bd-25	Trace	Trace	Trace
Recapture[1]	81-Bd-24	+	+ (>0.6I)	Trace
Do.	81-Bd-23	++	Trace (>0.6I)	+
Do.	81-Bd-22	+	Trace (0.7I)	Trace
Do.	81-Bd-21	++	+ (0.7I)	Trace
Do.	81-Bd-20	Trace	Trace	Trace
Salt Wash[1]	81-Bd-19	+++	Trace (0.6I, 0.7I)	---
Do.	81-Bd-18	+	+ (>0.9I)	+
Do.	81-Bd-16	+++	Trace (>0.9I)	---
Do.	81-Bd-15	+	+ (>0.8I)	---
Do.	81-Bd-17	+++	Trace (>0.9I)	---
Do.	81-Bd-14	++	+ (>0.8I)	---
		Sanostee Wash		
Brushy Basin[1]	85-Sw-13	---	+ (<0.1I)	+++
Do.	85-Sw-12	---	++ (<0.1I)	+
Do.	85-Sw-11	---	++ (<0.1I)	Trace
Westwater Canyon[1]	83-Sw-10	---	+ (<0.1I)	Trace
Do.	83-Sw-7	---	++ (<0.1I)	Trace
Do.	83-Sw-5	+	++ (<0.2I)	+
Do.	83-Sw-2	+	+ (<0.2I)	+
Do.	83-Sw-1	+	+ (<0.2I)	+
		Asaayi Lake		
Westwater Canyon[1]	83-Al-12	Trace	Trace	++
Do.	83-Al-10	Trace	Trace	+++
Do.	83-Al-9	+	+ (<0.1I)	++
Do.	83-Al-7	Trace	+ (<0.1I)	++
Do.	83-Al-3	+	---	+
Do.	83-Al-2	+	+ (<0.1I)	++
		Toadlena		
Westwater Canyon[1]	83-Td-10	+	++ (smectite)	++
Do.	83-Td-8	+	Trace (smectite)	+++
Do.	83-Td-7	Trace	Trace(smectite)	+++
Do.	83-Td-3	++	(smectite)	+++
Do.	83-Td-1	+	Trace (smectite)	+++
		Ghost Ranch		
Encinal Canyon[2]	86-Gr-1	---	---	+++
Morrison Formation	86-Gr-6	---	+++ (<0.1I)	Trace
Do.	86-Gr-3	---	++ (>0.9I)	++
		Laguna		
Jackpile Sandstone[1]	86-Lg-6	Trace	Trace (>0.9I)	+++
Do.	86-Lg-4	---	(<0.1I)	+++
Do.	86-Lg-5	---	++(<0.1I)	+++

Table 2. Continued

Stratigraphic unit	Sample No.	Chlorite	Illite/smectite	Kaolinite
		San Pablo Canyon		
Westwater Canyon[1]	85-Sp-5	---	---	+
		White Mesa		
Jackpile Sandstone[1]	85-Wm-13	+	++ (<0.1I)	+
Do.	85-Wm-2	+	++ (<0.1I)	
Do.	85-Wm-1	---	+ (<0.1I)	---
		Encinal Canyon		
Encinal Canyon[2]	86-Ec-4	Trace	Trace	+++
Do.	86-Ec-3	Trace	Trace	+++
Do.	86-Ec-2	Trace	Trace (0.8I ordered)	+++
Do.	86-Ec-1	---	++ (0.6I ordered)	Trace
		Galisteo Dam		
Burro Canyon Formation	86-Gd-1	---	+++ (>0.9I)	---
Brushy Basin[1]	86-Gd-2	---	+++ (>0.9I)	---
Morrison Formation	86-Gd-6	---	Trace	+
Do.	86-Gd-4	---	+ (>0.75I)	++
Do.	86-Gd-3	---	+++ (>0.9I)	---
Recapture[1]	86-Gd-7	---	Trace	+
		Senorita Canyon		
Brushy Basin[1]	85-Sc-1	---	+++ (<0.1I)	Trace
Westwater Canyon[1]	85-Sc-7	---	Trace	---
Do.	85-Sc-6	---	++ (<0.1I)	---
		Capulin Peak		
Brushy Basin[1]	85-Cp-6	---	+++ (<0.1I)	++
Do.	85-Cp-4	---	+	++
Westwater Canyon[1]	85-Cp-10	---	+++ (<0.1I)	++
Do.	85-Cp-9	---	+++ (<0.1I)	++
Do.	85-Cp-8	---	+++ (<0.1I)	++
Recapture[1]	85-Cp-14	---	++ (<0.1I)	+++
Do.	85-Cp-13	---	+++ (<0.1I)	+++
Do.	85-Cp-12	---	+++ (<0.1I)	+++
Do.	85-Cp-11	---	+++ (<0.1I)	+
		Durango Hospital		
Recapture[1]	85-Dh-6	---	+ (>0.9I)	---
Do.	85-Dh-4	---	+ (>0.9I)	---
Do.	85-Dh-3	---	+ (>0.9I)	---
		Dennison-Bunn		
Burro Canyon Formation	85-Db-2	---	Trace	---
Do.	85-Db-1	---	Trace	---
Brushy Basin[1]	85-Db-6	+	+++ (<0.1I)	---
Westwater Canyon[1]	85-Db-11	---	+++ (<0.1I)	---
Do.	85-Db-10	---	+ (<0.1I)	+
Do.	85-Db-9	---	Trace	+++
Do.	85-Db-8	---	++ (<0.1I)	++
Recapture[1]	85-Db-16	Trace	+++ (<0.1I)	+
Do.	85-Db-15	---	+++ (<0.1I)	Trace
Do.	85-Db-14	---	+++ (<0.1I)	Trace

[1]Member of Morrison Formation.

[2]Member of Dakota Sandstone.

analcime-cemented sandstones are adjacent to analcimized tuff beds (fig. 13*B*). Potassium feldspar grains are albitized, and complete albitization has formed "chessboard albite" grains (fig. 14) that look identical to those reported by Walker (1984); however, electron microprobe analyses were not made of the grains to check for potassium feldspar remnants such as Walker found. Just to the south of Beclabito dome, at Oak Springs, sandstones contain abundant potassium feldspar overgrowths but fewer albite overgrowths than at Beclabito dome. Farther south, diagenetic alterations are less complex, except in the upper part of the Westwater

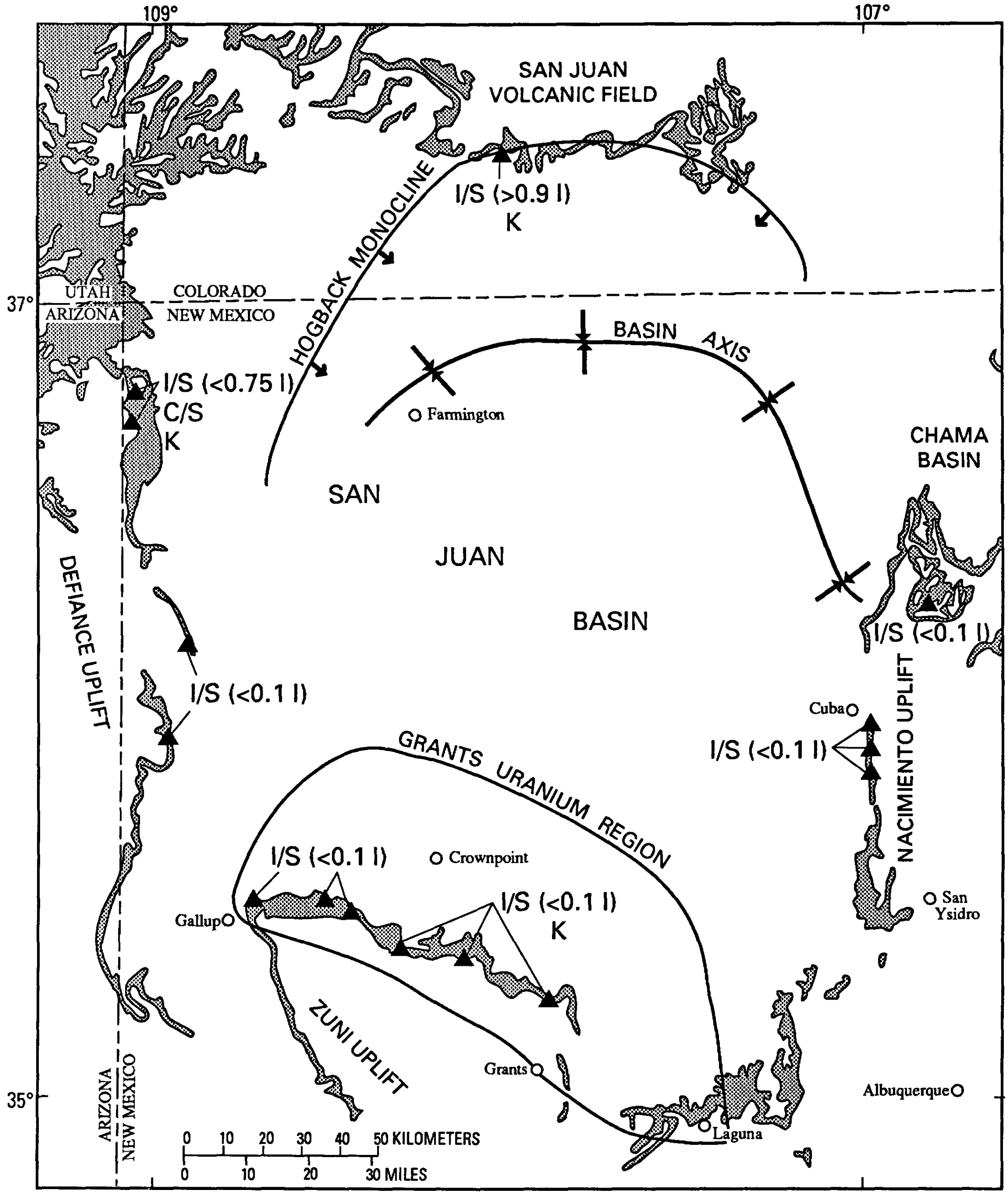
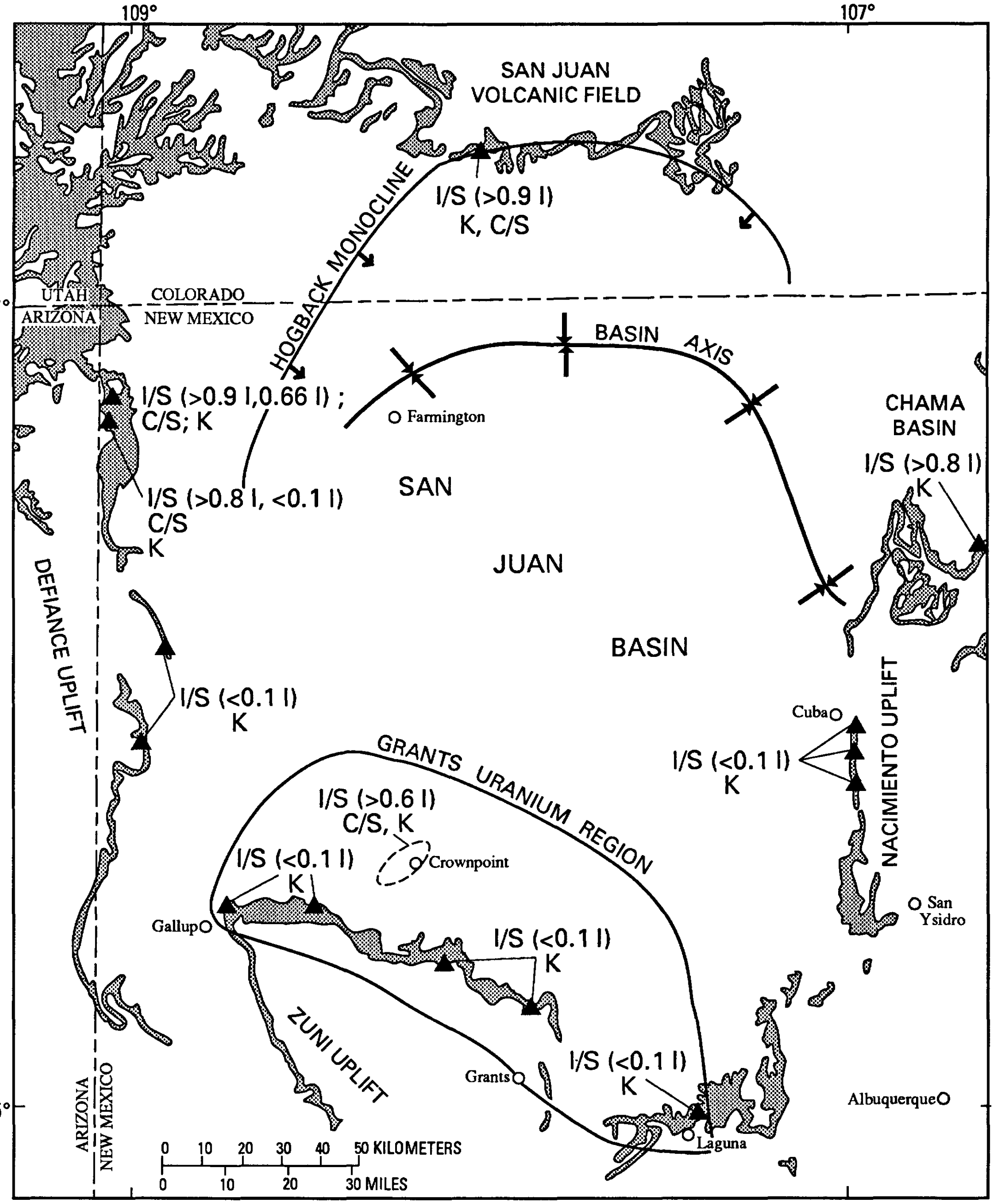


Figure 8 (above, facing, and following page). Regional distribution of major authigenic clay minerals in the Morrison Formation (pattern), San Juan basin. Sample localities indicated by triangles. K, kaolinite; I/S, illite/smectite, 0.7I means 70 percent illite in I/S; C/S, chlorite/smectite (>0.9C). *A*, Recapture Member; *B*, Westwater Canyon Member; *C*, Brushy Basin Member.

Canyon Member where quartz overgrowths, but no detrital plagioclase, are present. The lack of plagioclase is due to dissolution because, proceeding downward, skeletal plagioclase grains appear and finally near the base of the member entire grains are preserved. Kaolinite (as an alteration of plagioclase?) is a common pore-filling cement. Along the southern margin of the basin, sandstone grains commonly are coated with thick hematite rims, which in turn are overlain by chlorite, quartz overgrowths, kaolinite, and calcite cement.

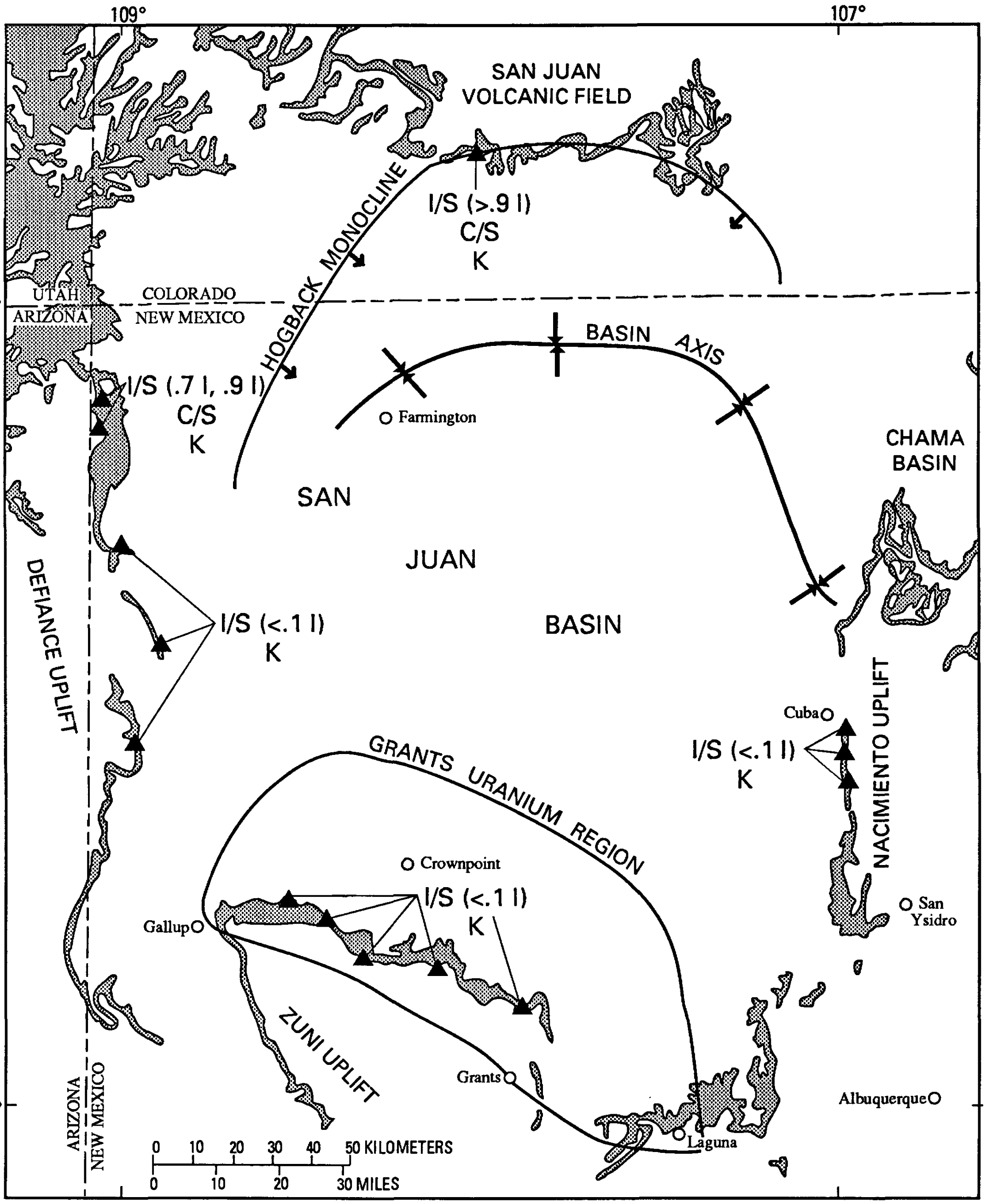
Additional potassium metasomatism of plagioclase grains having anti-rapakivi textures and formation of potassium feldspar overgrowths were caused by fluids that escaped into the sandstones from associated saline, alkaline beds. (See, for example, Oak Springs and Dennison-Bunn sections.) The precipitation during early



diagenesis of potassium feldspar overgrowths is suggested by the occurrence of these overgrowths under poikilotopic calcite cement in which framework grains float (fig. 15*A*). Potassium feldspar overgrowths are coated with early hematite cement in sandstones at the Dennison-Bunn section (fig. 15*B*). Potassium-metasomatized plagioclase has also been found in Cenozoic saline, alkaline lake deposits (Hay, 1966).

Not all development of authigenic potassium feldspar was caused by fluids from the Brushy Basin Member because these distinctive grains occur throughout the basin in all depositional facies, not just in sandstones adjacent to or in the saline, alkaline lake facies. Abundant authigenic potassium feldspar also occurs in and adjacent to ore zones. Where the paragenetic sequence could be determined in ore zones, a major episode of potassium metasomatism and overgrowth formation could be seen to have occurred after chlorite rim precipitation.

Trends in the distributions of authigenic clay minerals exhibit similar patterns. For instance, at Beclabito dome authigenic I/S ranges from 0.5I to 0.9I, and near the top of the section rectorite (a perfectly ordered ISIS mixture) is indicated by the presence of a superlattice peak (fig. 16). Chlorite is the most abundant clay mineral at the top of the Westwater Canyon Member; it



overgrows expandable I/S and is intergrown with illitic I/S (X-ray diffractograms indicate the presence of two I/S phases). Similar authigenic clay mineralogy is present in the Chaco Canyon cores (fig. 17). Variable amounts of kaolinite and chlorite occur in most samples. Directly to the south of Beclabito dome, at Oak Springs, I/S (0.3–0.6I) is dominant and is accompanied by major chlorite, minor kaolinite, and illitic I/S (>0.8I). Proceeding farther southward along the western side of the basin, expandable I/S (< 0.1–0.5I) occurs at Sanostee Wash and more expandable I/S (< 0.1I) at Asaayi Lake and Toadlena. Kaolinite is dominant at all three localities but is more abundant to the south, whereas chlorite becomes less abundant southward.

On the eastern side of the basin, authigenic clay-mineral trends are also evident. At the easternmost locality, Galisteo Dam, clay minerals are mainly kaolinite and ordered I/S (0.66I), whereas along the Nacimiento uplift authigenic clays are more expandable(< 0.1I). Major kaolinite occurs with minor expandable I/S (< 0.1I) at Capulin Peak, and just to the south at San Pablo Canyon clays are predominantly kaolinite. In the southeastern part of the basin, at Laguna, I/S (< 0.1I) is also expandable.

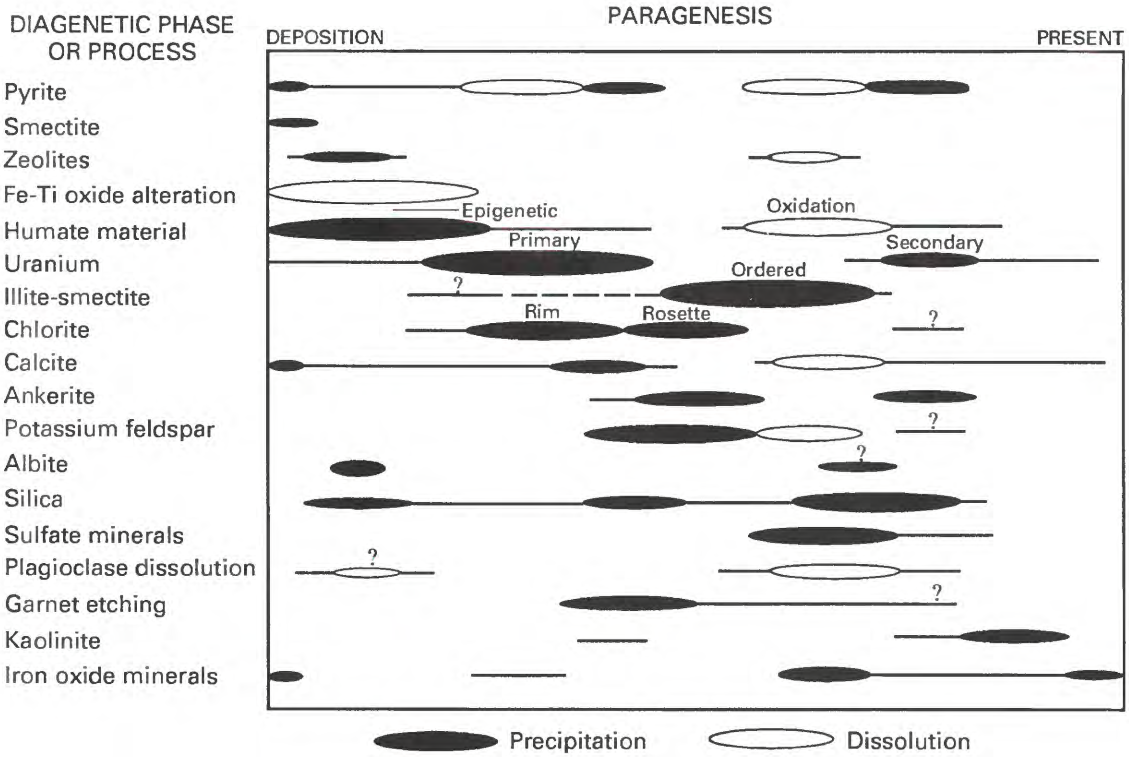


Figure 9. Paragenesis of major authigenic phases and diagenetic events in the Morrison Formation.

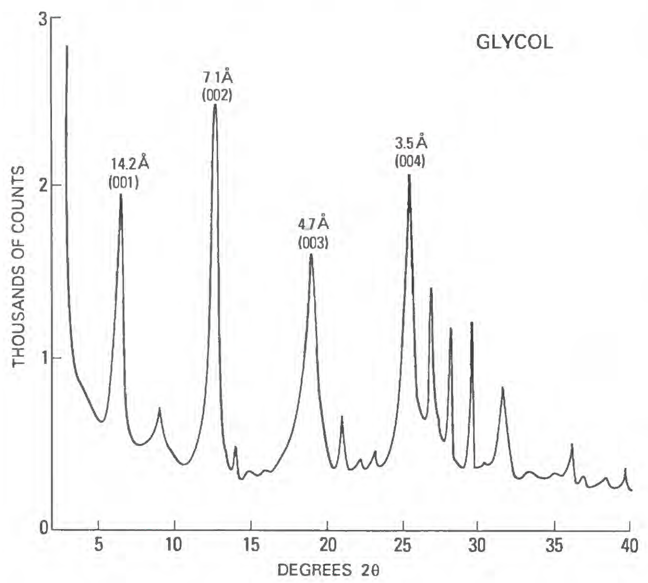


Figure 10. X-ray diffractogram of authigenic nonferroan chlorite in sandstone of the Westwater Canyon Member at Beclabito dome.

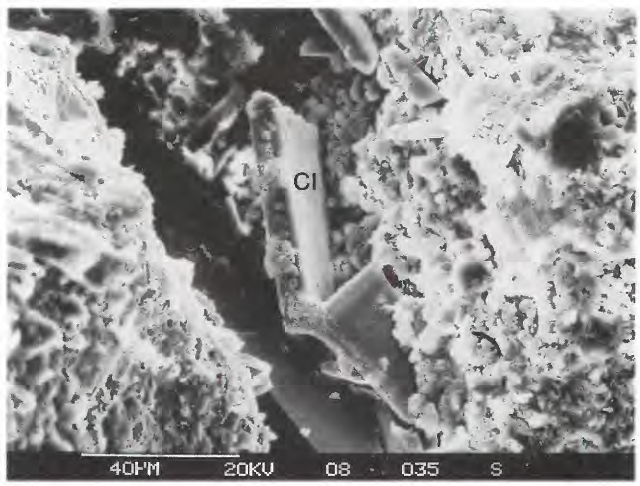


Figure 11. Scanning electron micrograph showing clinoptilolite crystals (Cl) in a sandstone pore of the Westwater Canyon Member at Beclabito dome. Length of field, 0.16 mm.

In the cores, diagenetic alterations also increase both vertically and to the north. In the northernmost and deepest core (Chaco Canyon core), analcime has replaced some plagioclase grains (also noted in other Chaco Canyon cores by Hicks, 1981); however, most plagioclase is albitized. Chlorite rosettes occur commonly in pores. Two stages of quartz overgrowths are present, and in the lower part of the Westwater Canyon Member anhydrite fills pores rimmed by quartz overgrowths. Hollow albite rims that look identical to hollow potassium feldspar rims occur in the cores farthest to the northeast. Associated plagioclase grains are albitized, and rare chlorite rims are under albite overgrowths.

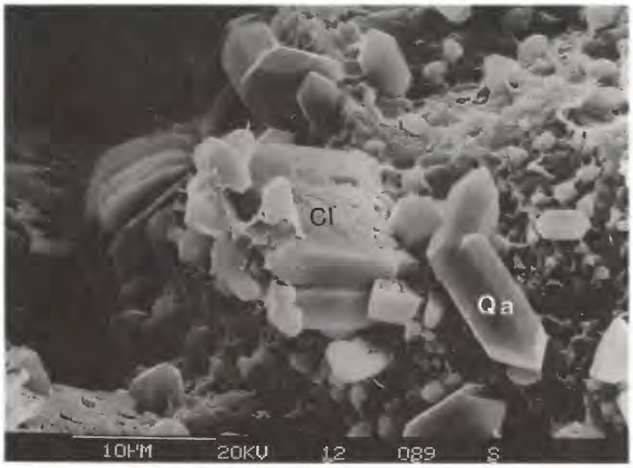


Figure 12. Scanning electron micrograph showing clinoptilolite (Cl) intergrown with authigenic idiomorphic quartz (Qa) in sandstone pore of the upper part of the Westwater Canyon Member at Beclabito dome. Length of field, 45 μm.

In the other cores, authigenic chalcedony cement, quartz overgrowths, and skeletal plagioclase grains are most common in the upper part of the Westwater Canyon Member.

Many diagenetic alterations are best developed in and adjacent to uranium-bearing sandstones; such is the case in the USGS cores (Hansley, 1986b). For example, in and adjacent to coffinite-bearing sandstone in core H–26–22, grains are cemented with pyrite, large quartz overgrowths, and potassium feldspar overgrowths. Abundant early authigenic potassium feldspar and hollow potassium feldspar rims are notable among alterations associated with uranium enrichment. As noted previously, the high amount of primary porosity (filled with calcite) in these sandstones provides evidence that potassium feldspar overgrowths formed early. A similar association of uranium enrichment and authigenic silica has been noted in the Morrison Formation in other areas of the Colorado Plateau (Goldhaber and others, 1987).

Brushy Basin Member

Regional diagenetic alteration patterns are well established in sandstones of the Brushy Basin Member. As in the other members, diagenetic alterations are more advanced from south to north; however, the severity of diagenesis varies widely from sandstone to sandstone within one outcrop. The Brushy Basin Member is characterized throughout the basin by mixed-layer clays, silica, and zeolite cements. As many as four distinct generations of chalcedony cement may be present (fig. 18), and the minimal diagenetic alteration of framework grains in these silica-cemented samples indicates that the silica cements were precipitated during early diagenesis.

In the northern part of the basin at the Durango Hospital and Piedra River outcrops, porosity is close to zero because the sandstones are cemented with quartz and albite overgrowths (fig. 19) and later formed pore-filling chalcedony and calcite (fig. 20). Small potassium feldspar overgrowths are on some detrital potassium feldspar grains at Durango, but just to the east, at Piedra River, most potassium feldspar has been completely albitized. Most plagioclase grains are albitized, and those at the top of the member commonly are replaced by analcime. At both sections, hematite, dolomite, and anhydrite cements locally replaced earlier diagenetic minerals.

On the other hand, in the southeastern part of the basin at Laguna, plagioclase grains are skeletalized and albitized and large areas of framework grains are cemented by kaolinite (fig. 21). Remnants of calcite cement occur in pores, and albite and quartz overgrowths are abundant. To the east, at Galisteo Dam, chert and chalcedony cement are major diagenetic alterations, and micron-size, authigenic, twinned and doubly terminated albite crystals occur in pores.

On the eastern side of the basin, along the Nacimiento uplift, diagenetic alterations decrease from north to south. Sandstone grains are intensely zeolitized at Senorita Canyon: analcime has replaced feldspar and molds of shards are infilled with analcime. Grain-rimming chert or smectite is superceded by pore-filling chalcedony or analcime. Plagioclase exhibits minor dissolution textures. On the other hand, sections to the south contain few zeolites. Sandstone matrix at San Pablo Canyon, just to the south of Senorita Canyon, is mostly smectitic and contains few zeolitized or albitized plagioclase grains and minor zeolite cement. Farther to the south, at White Mesa, sandstones are characterized by abundant smectite and by silica cement that has been superceded locally by calcite.

In the northwestern corner of the basin, at Beclabito dome and Oak Springs, some sandstone beds have a matrix comprised of authigenic smectite; other beds contain a wide variety of zeolites, authigenic feldspars, and illitic I/S. Many sandstone grains are coated with low-birefringent smectite rims surrounding voids filled with analcime, calcite, or chalcedony. Shardlike molds are filled with microcrystalline silica and rimmed by albite(?). Albitization of potassium feldspar has produced grains that appear to be "chessboard albite", and untwinned plagioclase locally is skeletalized and albitized. Albite overgrowths are more abundant at Beclabito dome than at Oak Springs, and potassium feldspar overgrowths were not noted at either section. At both sections, sandstones near the base of the member contain oxidized pyrite, barite cement, and small potassium feldspar overgrowths. An inverse correlation exists between the abundance of analcime and albite:

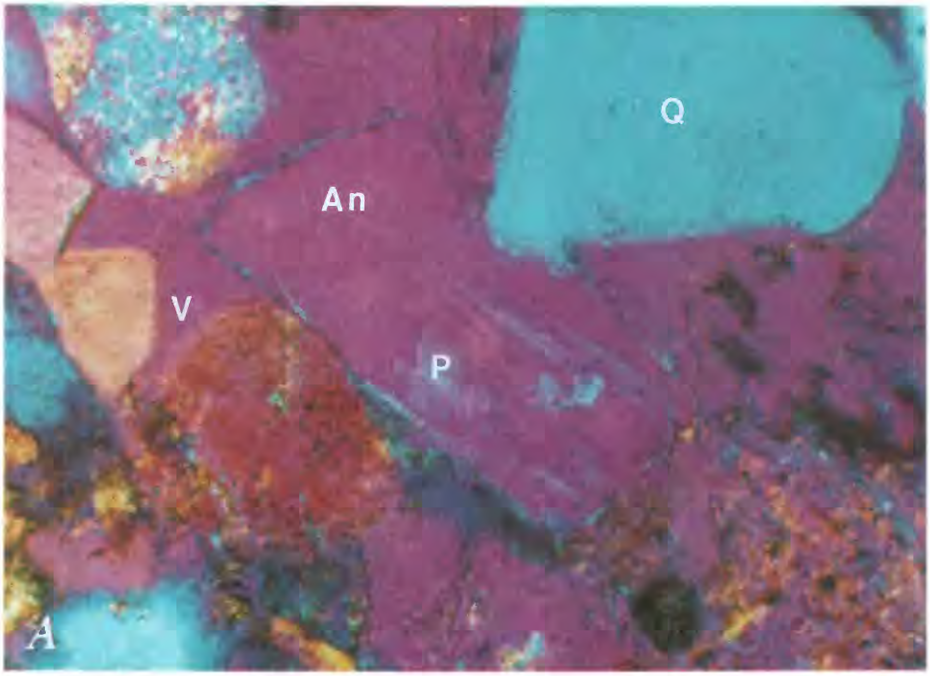


Figure 13. Photomicrographs showing analcime-cemented sandstones in the Morrison Formation. *A*, Detrital plagioclase (P) replaced partly by analcime (An) in sandstone of the Westwater Canyon Member at Senorita Canyon. Note ghosts of twin lamellae. Rim on plagioclase is chert, which precipitated before analcime cement. Q, detrital quartz grain; V, void. Plane-polarized light; length of field, 0.7 mm. *B*, Analcime-cemented sandstone adjacent to analcimized tuff in outcrop at Beclabito dome.

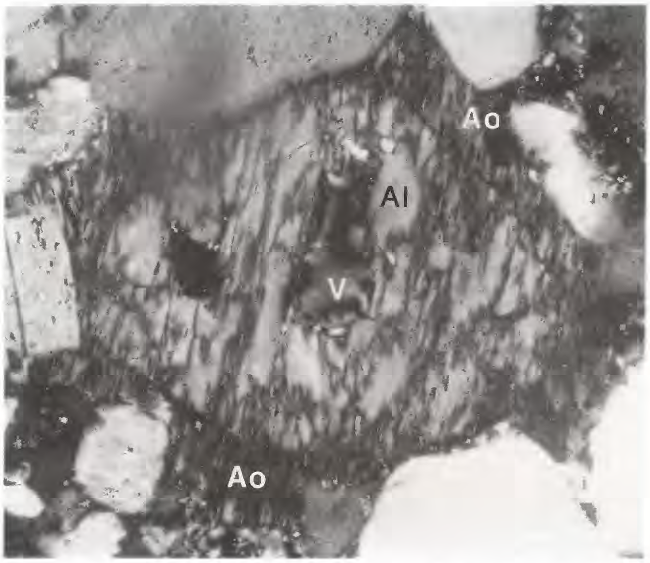


Figure 14. Photomicrograph showing "chessboard albite" grain (Al) in sandstone of the upper part of the Westwater Canyon Member at Beclabito dome. Note albite overgrowths (Ao) on grain; V, void. Crossed polars; length of field, 0.5 mm.

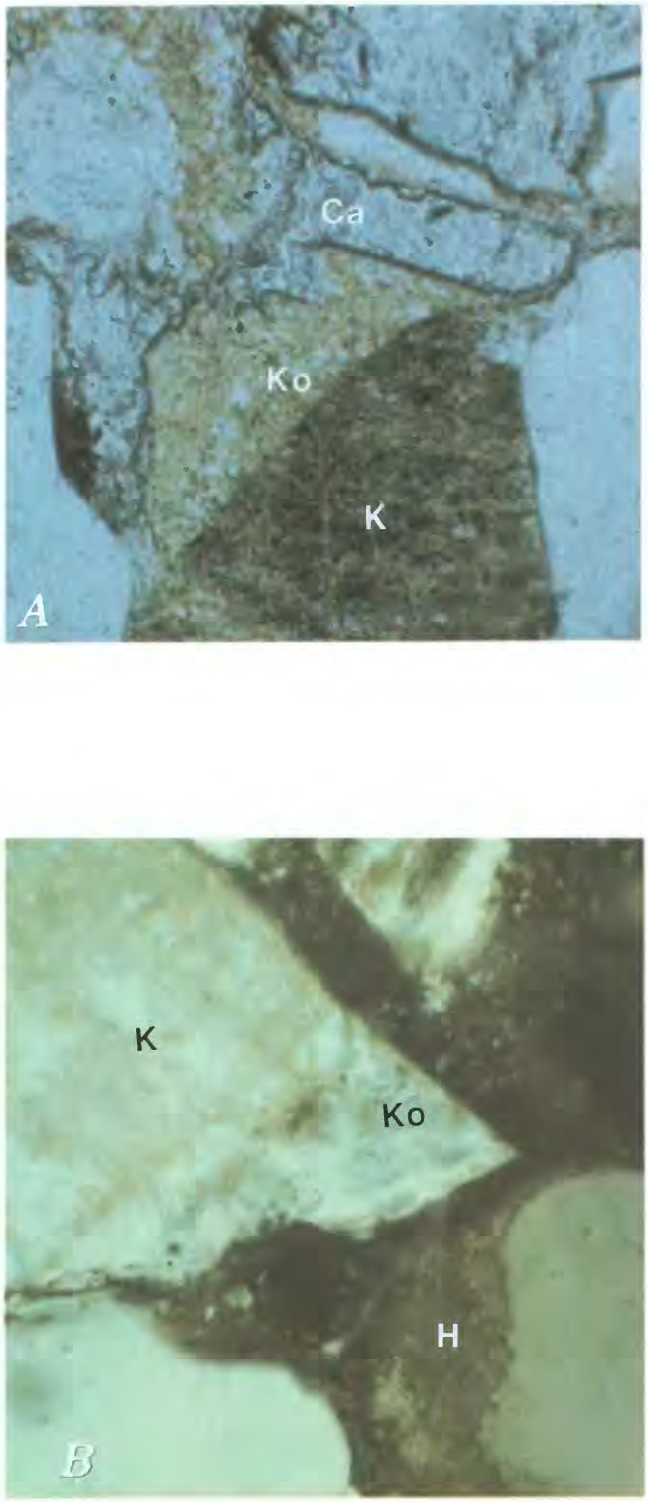


Figure 15. Photomicrographs showing potassium feldspar overgrowth on detrital potassium feldspar, Dennison-Bunn section. *A*, Early potassium feldspar overgrowth (Ko) on detrital potassium feldspar (K) in calcite-cemented (Ca) sandstone. Note floating grains and point contacts. Plane-polarized light; length of field, 0.2 mm. *B*, Potassium feldspar overgrowth (Ko) coated with hematite cement (H) in sandstone. K, detrital potassium feldspar. Plane-polarized light; length of field, 0.05 mm.

sandstone beds either have abundant analcime and few quartz or feldspar overgrowths or have abundant albite and quartz overgrowths and little or no analcime. Grains in the highest sandstones at Oak Springs contain fractures filled with analcime.

Clay minerals exhibit similar regional alteration patterns: to the south, mixed-layer clay minerals are highly expandable, whereas to the north and northwest they become increasingly illitic. In the northwestern part of the basin, at Beclabito dome, major I/S (>0.8I) and minor chlorite (fig. 22) occur in the lower half of the Brushy Basin Member; dominant chlorite and minor I/S (0.6–0.7I) and kaolinite occur in the upper half. The I/S is intergrown with authigenic quartz (fig. 23) and appears to overgrow clinoptilolite (fig. 24). At the top of the Brushy Basin Member, well-defined rectorite (0.6I) and minor kaolinite occur; no chlorite was observed. Just a few miles to the south at Oak Springs, sandstones of the lower Brushy Basin contain major chlorite and I/S (<0.1I) and minor kaolinite. In sandstones of the upper Brushy Basin at Oak Springs, I/S (0.3–0.6I) is the major clay mineral. The clay mineralogy of the northernmost section at Durango is similar to that of Beclabito dome in that I/S (>0.9I) is dominant.

Along the Nacimiento uplift, major authigenic clay minerals are kaolinite and expandable I/S (<0.1I); farther to the east, at Galisteo Dam, major kaolinite and minor I/S (0.85I; ISII stacking) are present. Chlorite is not a major phase in these eastern sections.

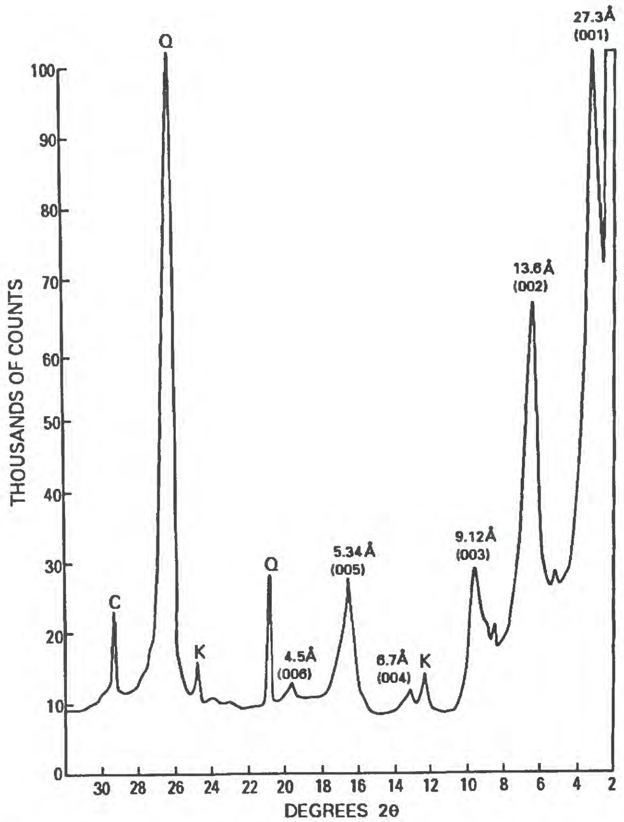


Figure 16. X-ray diffractogram of well-ordered I/S (rectorite; ISIS ordering) showing development of a superlattice reflection at 27.3 Å. Rectorite peaks are labeled in angstroms. Q, detrital quartz; K, kaolinite; C, calcite. Sample is from a sandstone near the top of the Westwater Canyon Member at Beclabito dome.

Figure 17. Scanning electron micrograph showing authigenic chlorite rosette (Ch) and intergrown illitic I/S filaments. Chlorite is resting on expandable I/S that has illitic overgrowths (I). Length of field, 35 µm. Sample is from the Westwater Canyon Member in the Chaco Canyon core (CC–12, fig. 1).

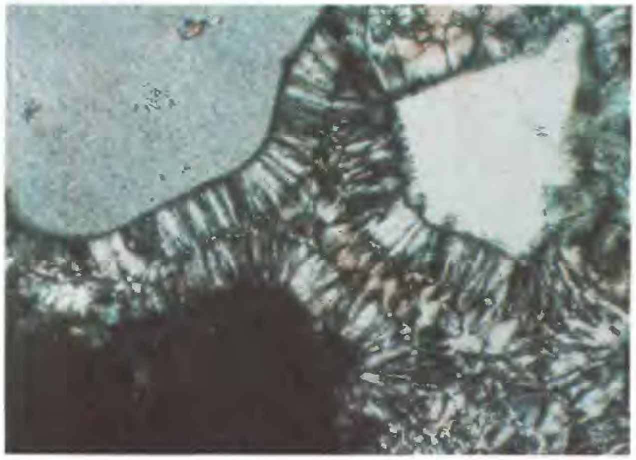


Figure 18. Photomicrograph showing several generations of chalcedony cement in sandstone of the Brushy Basin Member at the Piedra River section. Crossed polars; length of field, 0.2 mm.

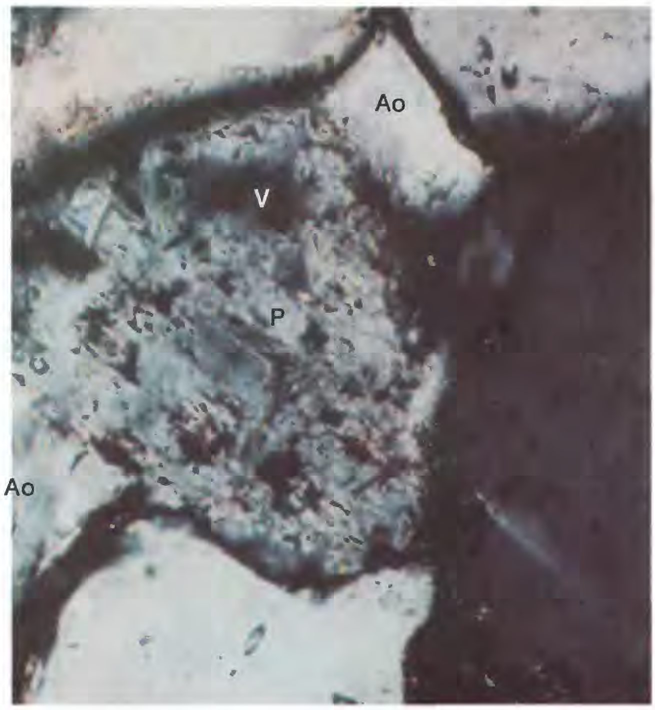


Figure 19. Photomicrograph showing authigenic pore-filling albite overgrowths (Ao) on albitized plagioclase (P) in a sandstone of the Brushy Basin Member at the Durango Hospital section. V, void. Crossed polars; length of field, 0.1 mm.

Jackpile Sandstone Member

At the Laguna type section, the Jackpile Sandstone Member is characterized by abundant kaolinite cement especially at the top, few plagioclase grains, and quartz grains displaying feathery dissolution edges. Toward the base, plagioclase grains commonly are albitized. This

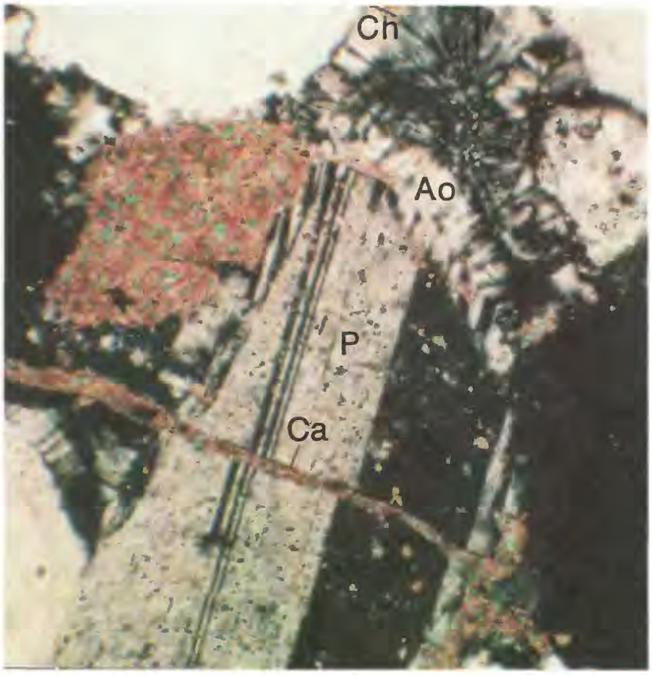


Figure 20. Photomicrograph showing detrital twinned plagioclase grain (P) with albite overgrowth (Ao) and later chalcedony cement (Ch) in pore and calcite (Ca) in fracture. Sample is from the Brushy Basin Member at the Durango Hospital section. Crossed polars; length of field, 0.15 mm.

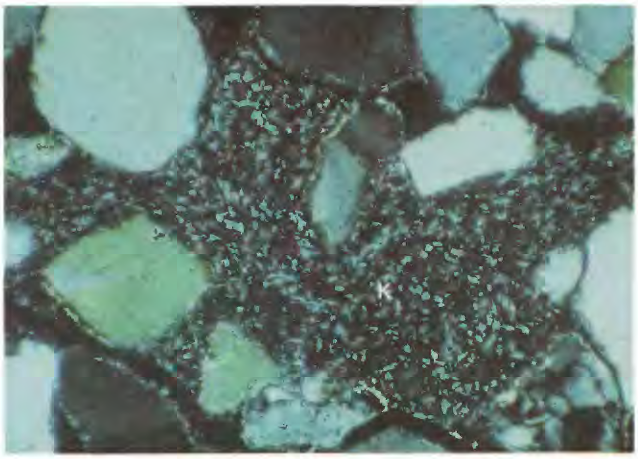


Figure 21. Photomicrograph showing pore-filling kaolinite cement (K) in sandstone at Laguna section. Crossed polars; length of field, 0.25 mm.

Figure 22. Scanning electron micrograph showing I/S (>0.8I) in sandstone of the Brushy Basin Member at Beclabito dome. Length of field, 45 μm.

distribution of kaolinite at the top and albite at the bottom was also noted by Nash (1968) and Adams and others (1974). Quartz overgrowths are locally abundant, and minor hematite cement is present. In nearby Encinal Canyon, the Jackpile contains kaolinite and minor I/S (<0.1I) and chlorite. Farther to the northeast, at White Mesa, two expandable I/S phases are present (0.3I and <0.1I). In contrast to Laguna, plagioclase grains are unaltered at White Mesa and sandstones are more silicic because thin quartz overgrowths are superseded by chalcedony cement. Farther to the north at San Pablo Canyon, two generations of (early) chalcedony commonly fill primary pores, and framework grains are fresh except for thin (early) potassium feldspar overgrowths on potassium feldspar.

Cretaceous sandstones

The overlying fluvial Cretaceous units, the Burro Canyon Formation (Lower Cretaceous) and the Encinal Canyon Member of the Dakota Sandstone (Upper Cretaceous), are more siliceous than most sandstones of the Morrison. The Cretaceous sandstones are comprised of quartz, chert, quartzite, and little or no plagioclase. Kaolinite is the most abundant clay mineral and is accompanied by minor detrital(?) I/S (>0.9I). At Beclabito dome, the overlying fluvial Cretaceous sandstones (Burro Canyon? Formation) have an authigenic smectite matrix.

BURIAL HISTORY

A map of vitrinite reflectance values (R_o) measured on coals in the Dakota Sandstone and Fruitland Formation in the San Juan basin (fig. 25) was constructed using data from many sources (Russell, 1979; Dow, 1982; Keal, 1982; Rice, 1983; Jacobson and others, 1985; Bayliss and Schwarzer, 1987, 1988; N.H. Bostick, USGS, written commun., 1988; V.F. Nuccio, USGS, written commun., 1988). Values increase from southwest to northeast across the basin, and lower values

Figure 23. Scanning electron micrograph showing intergrowth of illitic I/S (>0.8 I) needles and euhedral authigenic quartz (Q) in sandstone of the Brushy Basin Member at Beclabito dome. Length of field, 9 μm.

Figure 24. Scanning electron micrograph showing illitic I/S (>0.8I) clay (I) on clinoptilolite (Cl) in sandstone pore. Sample is from the Brushy Basin Member at Beclabito dome. Length of field, 25 μm.

are generally in the southern part of the basin and along basin margins. As Rice (1983) pointed out, lines of equal vitrinite reflectance curve in the northwestern part of the basin such that they appear to follow the trend of the Hogback monocline. Maximum burial of the Morrison Formation was approximately 2,300–3,200 m in the deepest part of the basin (Weeks and Garrels, 1959, table 1); however, maximum R_o values do not coincide with either maximum burial depths or the basin axis because the highest R_o values in the basin (>2.5) (Rice, 1983; V.F. Nuccio, written commun., 1988) in the basin are just south of Durango.

The Morrison Formation may have been subjected to a higher geothermal gradient in the northern San Juan basin because of proximity to the San Juan Volcanic Field (fig. 1). Bond (1984) constructed a Lopatin diagram of a well just south of Durango for which R_o values are the highest in the basin that led him to conclude that maximum burial of the geologic section coincided with a "heat flash" caused by Oligocene intrusive activity related to the San Juan Volcanic Field. If this is the case, however, R_o values should be elevated in the Durango area, but R_o values of Cretaceous coals are relatively low in the area of the San Juan Volcanic Field (Nuccio and Johnson, 1988) and in outcrops (0.8) (Rice, 1983) in the Durango area just north of the anomalously high values. As an alternate explanation for the high R_o values just south of Durango, Clarkson and Reiter (1987) suggested that a buried heat source (such as a magma) just south of Durango accounts for the disparity in R_o values over a distance of less than 24 km. Along the Hogback monocline, the Morrison Formation was exposed from Late Cretaceous to early Tertiary time (Kelley and Clinton, 1960). Thus, shallow burial may explain the low levels of maturity along the monocline, and the abnormally high maturity of the section in the area south of Durango may be explained by maximum heating having occurred during deepest burial. Coincidence of deepest burial with maximum heating of sediments results in rapid maturation and, in many cases, overwhelms the effects of time (Waples, 1985).

Regardless of the reason for the wide variation in R_o values, even at inferred minimum depths of burial (about 2,000 m) (Haun and Weimer, 1960) of the Morrison Formation along the Hogback monocline, temperatures would have been approximately 74–98 °C due to burial alone assuming a geothermal gradient of 27–34 °C for the Rocky Mountain region (American Association of Petroleum Geologists and U.S. Geological Survey, 1975).

INTERPRETATION OF DIAGENESIS

Regional diagenetic alteration patterns in sandstones of the Morrison Formation indicate that controls on diagenetic reactions were basinwide and included chemical gradients in saline, alkaline Lake T'oo'dichi'; updip migration of warm ground water due to compaction; differential burial; and influx of meteoric water. In addition, diagenetic alterations were influenced locally by chemical reactions related to concentrations of organic matter (Hansley, 1986b).

The refractory nature of the present-day detrital heavy-mineral assemblage reflects the silicic composition of source rocks, long-distance transport from source areas, and postdepositional diagenetic processes. Upward increases in euhedral apatite and zircon abun-

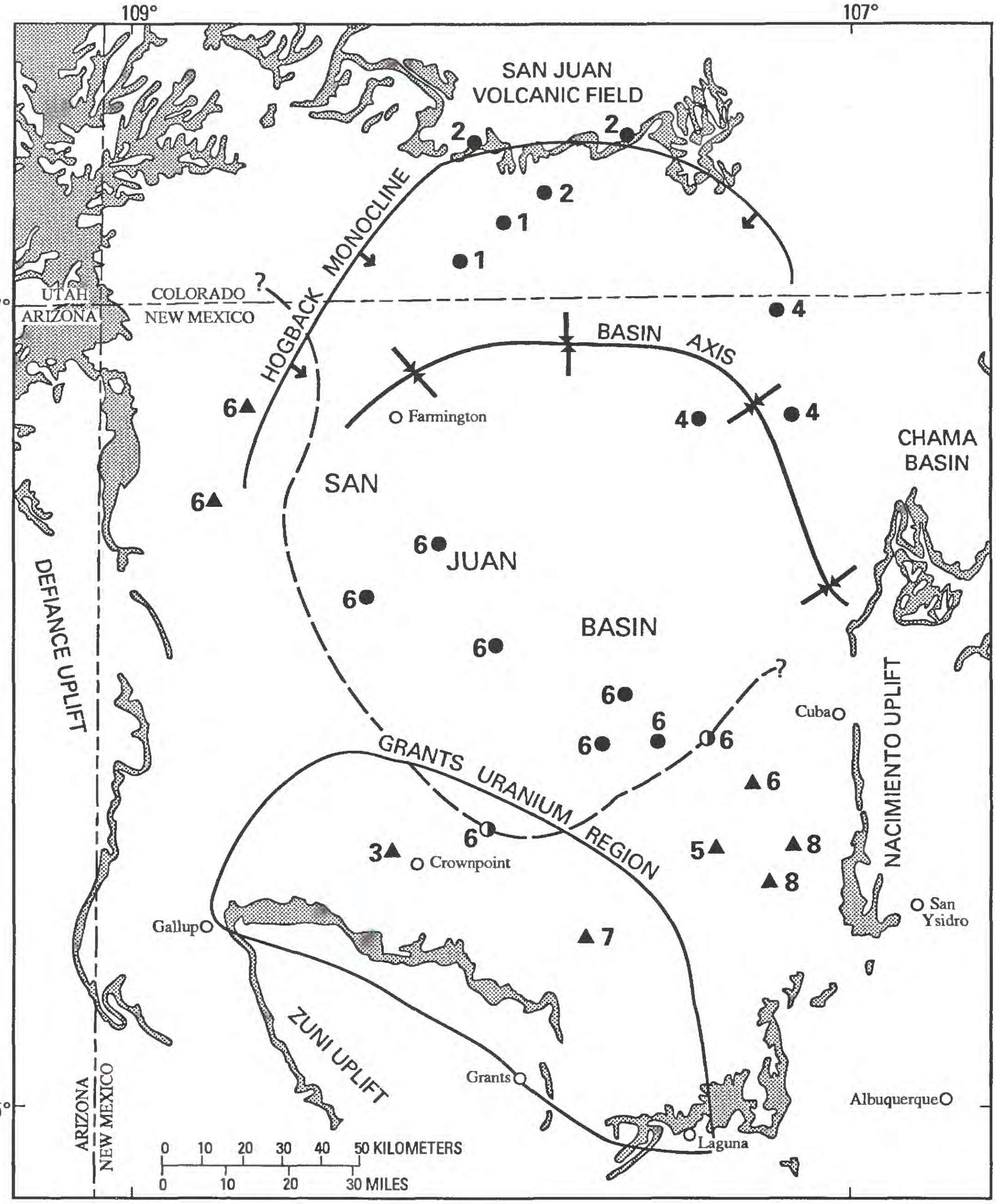


Figure 25. Vitrinite reflectance values for coals in the Upper Cretaceous Dakota Sandstone and Fruitland Formation, San Juan basin. Location of outcrops of Morrison Formation (pattern) also shown. Sources of data: 1, V.F. Nuccio (USGS, written commun., 1988); 2, Rice (1983); 3, N.H. Bostick (USGS, written commun., 1988); 4, Russell (1979); 5, Dow (1982); 6, Keal (1982); 7, Jacobson and others (1985); 8, Bayliss and Schwarzer (1987, 1988). Triangles indicate vitrinite reflectance value of less than 0.8 percent; half-filled circles indicates vitrinite reflectance value of 0.8 percent; solid circles indicate vitrinite reflectance value of greater than 0.8 percent. Dashed line delineates approximate boundary between immature (to the south) and mature (in oil generation window) parts of the Morrison Formation.

dances reflect an increased influx of volcanic material towards the end of Morrison deposition (Hansley, 1986a). The appearance of epidote, abundant staurolite, and sphene along the eastern margin of the basin suggests that a local source area contributed igneous and metamorphic detritus to the basin. The abundance of potassium feldspar, perthitic feldspars, and igneous rock fragments in the area supports this conclusion.

Influence of Lake T'oo'dichi'

The earliest authigenic phases, such as smectitic clay minerals, silica, zeolites, and feldspars, formed during alteration of the large amount of rhyolitic volcanic ash that was incorporated into the upper part of the Morrison Formation at the time of deposition. Relatively rapid dissolution of the labile ash created alkaline interstitial waters that quickly became saturated with respect to SiO_2, Na^+, and K^+. Diagenesis in upper sandstones of the Morrison commonly paralleled diagenesis in adjacent tuffaceous, fine-grained lacustrine beds, as alkaline and saline pore waters from the lake sediments escaped into adjacent sands due to salinity gradients and compaction. For example, sandstone beds adjacent to analcimized tuff beds in the Brushy Basin Member at Beclabito dome are cemented with analcime (fig. 13); sandstones adjacent to clinoptilolite-rich, altered tuff beds in the Brushy Basin Member at Senorita Canyon are cemented with clinoptilolite; and sandstones cemented with large albite overgrowths are adjacent to albitized tuff beds at the Durango Hospital section.

Formation of smectite from ash dominated early diagenesis on the southern, western, and eastern margins of the basin where pore waters were fresher. To the north, where Lake T'oo'dichi' waters were more saline and alkaline, early diagenetic products of ash dissolution include zeolites and I/S. Near the center of the lake (Beclabito dome and Durango Hospital sections), high minus cement porosity values (30–34 percent in this study) indicate that primary analcime and albite formed from ash dissolution products. This conclusion was also reached by Fishman and others (1986). Analcime in the northernmost cores in the southern part of the basin (fig. 1) coincides with hypothetical extension of the zeolite facies across the basin between outcrops on the western and eastern margins of the basin as mapped by Turner-Peterson (1987).

Smectite becomes increasingly illitic in altered tuff beds toward the center of ancient Lake T'oo'dichi' (Turner-Peterson and others, 1987). Data presented in this report show that smectite in associated sandstones also becomes illitic towards the center of the basin. Turner-Peterson and others (1987) concluded that early precipitation of I/S in the Brushy Basin Member was promoted by the extreme alkalinity and salinity of pore waters; thus, the most illitic clays, which are accompanied by authigenic analcime and albite, formed where interstitial waters were the most saline. This interpretation is in contrast to the classical "Gulf Coast" theory in which illitization is considered to be primarily a thermally driven process (Perry and Hower, 1970). In the current study of sandstone diagenesis in the Morrison, illitization of analcime cement where it is in contact with smectitic grain rims (fig. 26) indicates that I/S formed somewhat later than analcime; however, the parallelism between diagenesis in the tuffs and adjacent sandstones strongly suggests that I/S formed during early diagenesis.

Ordering of I/S may have occurred slightly later during burial diagenesis. Recent studies have shown that ordering occurs at about 60 percent illite when no smectite layers are bounded by other smectite particles (Nadeau and others, 1985) and involves dissolution and reprecipitation of new clay phases (Whitney and Northrup, 1988). The coexistence of two authigenic mixed-layer I/S phases exhibiting different degrees of ordering in many sandstones of the Morrison Formation is explained by this model.

Preservation of shard textures within analcime cement in sandstones of the Westwater Canyon Member at Senorita Canyon indicates that analcime precipitated during early diagenesis and may have directly replaced volcanic glass. Theoretical chemical activity diagrams indicate that zeolites may form directly from glass if silica activity is high enough (fig. 27). Additional evidence that analcime formed early is the presence of analcime-cemented rip-up clasts in fluvial sandstone of the Westwater Canyon Member at Beclabito dome. Although direct formation of analcime from glass may have occurred in some sandstones, the presence of thin smectite or clinoptilolite rims on the shards and clinoptilolite inclusions within the shards suggest that analcime replaced a precursor zeolite (in this case, clinoptilolite). Analcime-replaced shards in the Eocene and Oligocene Vieja Group in Texas were also interpreted to indicate that the analcime replaced clinoptilolite (Walton, 1975). This interpretation corroborates Sheppard's (1971) conclusion that analcime in sedimentary rocks does not form directly from glass. Analcime-filled stylolites and fractures in sandstones at Beclabito dome and at

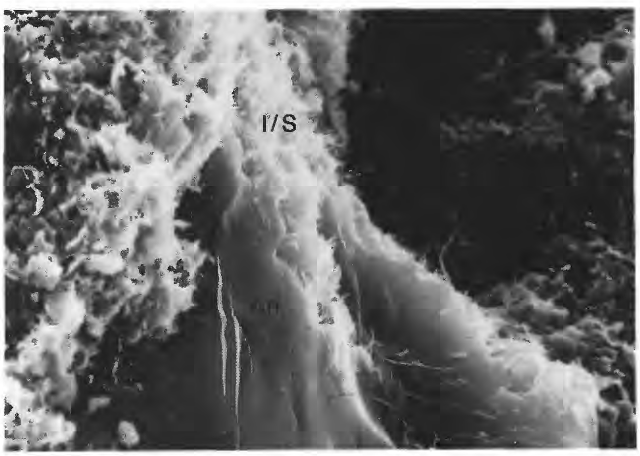


Figure 26. Scanning electron micrograph showing illitic I/S that has formed from the margins of analcime cement (An) in a sandstone pore. Length of field, 25 μm. Sample is from the Westwater Canyon Member at Beclabito dome.

Senorita Canyon formed somewhat later than the pore-filling analcime because major deformation in the region occurred during the Laramide orogeny (Late Cretaceous to early Tertiary) when the Morrison was buried under several hundred meters of Upper Cretaceous sediments.

The precipitation of at least some authigenic potassium feldspar in sandstones of the upper part of the Westwater Canyon Member and in the Brushy Basin Member is related to chemical gradients in Lake T'oo'dichi' (Hansley, 1984; Turner-Peterson, 1987). Where potassium feldspar overgrowths are best developed in outcrop sandstones (such as Oak Springs and Dennison-Bunn), sandstones lie in or under the zeolite and potassium feldspar altered tuff facies of the Brushy Basin Member. Potassic volcanic rock fragments and evolved pore fluids provided intrinsic sources of potassium for the overgrowths, and potassium may have also been supplied by fluids expelled from tuff beds. A potential problem with this interpretation is that the mixed-layer clay minerals in some sandstones that contain potassium feldspar overgrowths, notably those along the Nacimiento uplift, are expandable. If potassium-rich fluids had been in the sandstones, why wasn't smectite illitized? One possibility is that high silica activities ($>10^{-2.5}$) in these fluids (confirmed by widespread quartz overgrowths and chalcedony cement) inhibited the formation of illite (Garrels, 1984; Eslinger and Pevear, 1988). Smectite can coexist with potassium

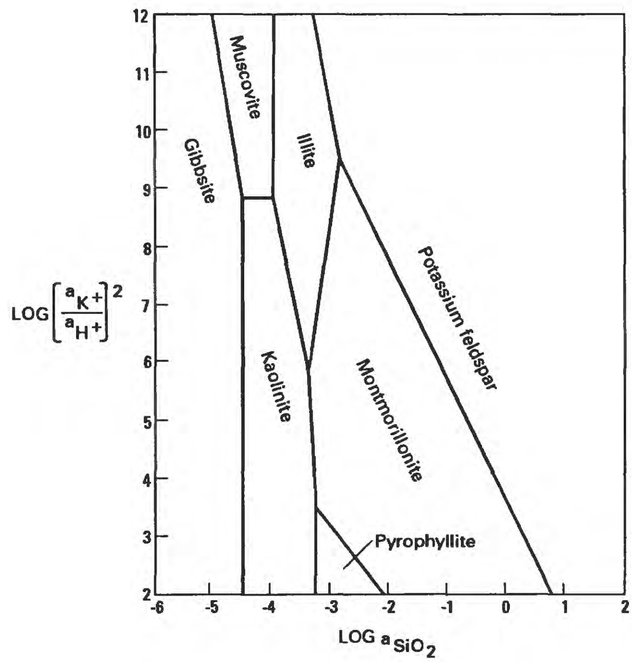


Figure 27. Ion activity diagram showing the relations between some common authigenic minerals in the Morrison Formation. Note that illite and montmorillonite are treated as two separate phases. Modified from Garrels (1984).

feldspar at high silica activities (fig. 27). Potassium feldspar forms early as an alteration of tuff beds in Cenozoic saline, alkaline lake deposits; potassium feldspar, which formed indirectly (through intermediate phases) from volcanic ash, has been dated as 60,000–100,000 years old (Hay, 1966). Because they formed in a similar closed basin setting, tuff beds in the Brushy Basin Member that have altered mostly to potassium feldspar and large potassium feldspar overgrowths in associated sandstones are inferred also to have formed during early diagenesis. Potassium feldspar overgrowths that formed later may have precipitated from K^+-rich magmatic waters because intrusions in the northwestern San Juan basin are minettes, which are enriched in potassium feldspar (Shoemaker, 1956).

Fishman and others (1986) concluded that albitization of tuffs and sandstones in the Brushy Basin Member was also a very early diagenetic process that took place in the most saline, alkaline facies of Lake T'oo'dichi'. Their conclusion is also partly on the presence of high minus-cement porosity values wherever albite occurs and partly on the cogenetic habit of the albite-quartz-chalcedony assemblage. Early albitization also took place in upper sandstones of the Westwater Canyon Member at Beclabito dome and in upper sandstones of the Recapture Member at the Durango Hospital section; minus-cement porosity values of from 30 to 34 percent in sandstones from these sections indicate that the albite and quartz overgrowths precipitated before compaction. Elevated Na^+ activity and low water activity in the central part of the lake facilitated early albitization. Analcimic textures of albitized tuff beds (Turner-Peterson, 1987) indicate that albite locally may have been an early product of analcime dissolution, and analcime remnants occur in calcite cement in albitized sandstones at Piedra River. Albite replaces analcime by dehydration and silicification: analcime + silica = albite + water (Liou, 1971). Elevated temperatures and (or) high salinity cause this reaction to proceed to the right, but in the Morrison Formation high salinity was the main factor in causing albite to form because temperatures were close to ambient during early diagenesis. Likewise in the Eocene Green River Formation, albite is inferred to have replaced analcime at the relatively low temperatures of 50–75 °C because of the high salinities of the pore waters (Hay, 1966).

To estimate the temperature at which authigenic albite in the Morrison Formation formed, albite overgrowths in sandstones of the Brushy Basin Member from the Durango Hospital section were examined for fluid inclusions, but no vapor phases were found in any of the tiny (<10 μm) inclusions. If the albite were formed during later diagenesis at elevated temperature, the lack of vapor bubbles could be due to the difficulty in nucleation of vapor bubbles in small inclusions (Roedder, 1981). Burial history reconstruction (Bond, 1984) shows that maximum temperatures in the Durango area were about 75 °C, high enough to form vapor phases in inclusions. However, textures indicate that the albite formed early, either as a direct precipitate from saline pore waters or as an early replacement of analcime.

The assemblage of authigenic chlorite, potassium feldspar, I/S, and quartz (overgrowths and idiomorphic crystals) commonly observed in sandstones of the Morrison Formation in this study and in the Morrison in the Grants uranium region (Hansley, 1986b) is interpreted to have formed during burial diagenesis. Chlorite precipitation may be explained by the release of Mg^{2+}, Fe^{3+}, and silica during dissolution of random I/S and reprecipitation of ordered I/S. This process provides an explanation for the lack of significant chlorite in samples containing expandable I/S on the western, southern, and eastern margins of the basin.

Alterations Related to Meteoric Water

Thick (about 5 μm) hematite rims underlying chlorite rims and quartz overgrowths on detrital sand grains in the Morrison Formation along the southern margin of the San Juan basin indicate that early oxidation occurred before the formation of chlorite and quartz overgrowths (Hansley, 1986b). Dissolution of plagioclase grains and precipitation of kaolinite in the uppermost part of the Morrison Formation along the western and southern margins of the basin may have been caused by downward percolation of acidic, oxidizing meteoric water during Early Cretaceous erosion. The occurrence of increasingly higher percentages of detrital plagioclase in the Morrison Formation proceeding downward from the unconformity indicates that the dissolution episode was related to exposure and erosion either during the time represented by the unconformity or slightly later due to corrosive solutions emanating from the Dakota Sandstone. Dissolution of plagioclase and precipitation of kaolinite may have been caused by acidic solutions derived from overlying Dakota coals and carbonaceous shales (Schlee and Moench, 1961; Granger, 1962). This idea remains speculative, however, because neither Flesch (1975) nor Schlee (1957) found an obvious relationship between kaolinite in the Jackpile and the presence of coal in the overlying Dakota Sandstone. Some later oxidation and additional(?) plagioclase dissolution may have occurred during the period late Tertiary to the present (Saucier, 1980), as evidenced by limonite and (or) hematite cement on potassium feldspar and oxidized pyrite in outcrops and shallow sandstones.

Comparison of Diagenetic Interpretations

Previous diagenetic studies of the Morrison Formation in the southern part of the San Juan basin identified early alteration patterns that were attributed to chemical gradients in Lake T'oo'dichi' (Hansley, 1984, 1986b). Continuation of the same patterns northward into the central and northern parts of the basin supports this conclusion. In previous studies (Whitney and Northrop, 1987), updip movement of warm, deep-basin fluids through the Westwater Canyon Member was inferred by stable isotope data that indicated that cogenetic ordered I/S and chlorite precipitated from interstitital fluids at temperatures exceeding 100 °C. Deeply etched garnets occur in precisely the same zone as the isotopically distinct clay minerals (Whitney and others, 1986; Hansley, 1987). In laboratory experiments, warm (>75 °C), oxalic acid-bearing solutions produced systematic etch features on garnets identical to those on naturally etched garnets (Hansley, 1987). Because the Morrison Formation contains garnets throughout the Colorado Plateau (Cadigan, 1967), the present lack of garnets at Durango was apparently caused by complete dissolution of detrital garnets. Burial history data indicate that temperatures during diagenesis in the Durango area were as high as 75 °C; thus, warm pore waters were available to facilitate dissolution of the garnets. Whether organic acids are necessary for dissolution or were involved in dissolution of garnets at Durango is unknown.

A diagenetic mineral assemblage (idiomorphic quartz, adularia, chlorite, ordered I/S) similar to that in the zone of elevated temperature noted above occurs in the upper Salt Wash Member at Beclabito dome and Oak Springs. Oligocene intrusive bodies in the Four Corners area apparently did not elevate formation temperatures because vitrinite reflectance values of Cretaceous rocks just downdip from Morrison Formation outcrops on the western margin of the basin are relatively low. Furthermore, diagenetic maturity varies dramatically in a sequence of tuff beds at Beclabito dome: some beds are zeolitized, some have been altered to potassium feldspar, and others have remained pure smectite (Turner-Peterson, 1987). This diagenetic assemblage may have formed as a result of action by organic acids generated from local concentrations of organic matter within the Salt Wash Member, movement of warm (organic acid-bearing?) fluids through the Salt Wash Member, or unknown causes.

In earlier studies of core material in the southern part of the basin, amorphous, epigenetic interstitial organic matter enriched in uranium and other metals was found to be locally abundant (Leventhal, 1980; Hansley, 1986b). During early diagenesis, the organic matter was solubilized by alkaline fluids and was then precipitated in sandstone pores. In subsequent diagenetic reactions, bacterially mediated sulfate reduction resulted in precipitation of pyrite and carbonates, as seen in most of the cores from the southern part of the basin. Samples in the present study, however, contain only trace amounts of amorphous organic matter, although evidence of reactions involving organic matter (coffinite, pyrite) exists in several of the cores that were examined. By analogy, detrital organic matter in the Salt Wash Member also influenced diagenetic reactions in that hydrolysis of volcanic ash created alkaline waters favorable for leaching soluble organic matter from decaying plant material. In the vicinity of organic matter (detrital or epigenetic), therefore, chemical reactions were facilitated by the release of soluble organic complexes during low-temperature bacterial metabolism. Soluble organic complexes have been shown in experiments (Surdam and Crossey, 1985) and in natural settings (Bennett and Siegel, 1987) to dramatically increase the solubility of chemical species, including silica. This process may explain the abundance of potassium feldspar and quartz overgrowths in the vicinity of ore zones.

The alteration patterns in the Jackpile Sandstone Member reflect basinwide depositional and diagenetic patterns. Albitization at the base of the Jackpile is a result of saline fluids migrating into basal sandstones from the playa facies of the Brushy Basin Member, and kaolinization of the upper part of the Jackpile was caused by fluids migrating downward during exposure in the Early Cretaceous Epoch. Adams and others (1978) reached the same conclusions during their study of diagenesis in the Jackpile Sandstone Member.

CHEMISTRY

During early diagenesis of the Morrison Formation, interstitial waters were moderately alkaline (pH about 8.5) due to the dissolution of volcanic ash. Formation of early authigenic phases, such as smectite and zeolites, was controlled by several variables including the activities of Na^+, K^+, $H_4SiO_4^0$, and $Al(OH)_4^-$, pH, and total ionic strength of pore waters. Of these, silicic acid ($H_4SiO_4^0$) and aluminate ion ($AlOH_4^-$) activities are the most important because most early diagenetic phases were aluminosilicates. Aluminate ion solubility increases dramatically above a pH of 7, whereas silica solubility does not increase markedly until a pH of 9.9 at 25 °C (Drever, 1982; Donahoe and Liou, 1985). The solubility of aluminum, therefore, increases more rapidly than the solubility of silica between pH 7 and 9.9. Above pH 9.9, silica solubility becomes a dominant control of the Si/Al ratios in aluminosilicate minerals. Aluminate activity thus was probably a major factor in diagenetic reactions because pH values were almost certainly below 9.9 except in the most saline, alkaline conditions near the center of the lake. In addition, the presence of soluble organic matter in early interstitial waters further increased the solubility of aluminum because of the excellent complexing ability of the organics. Aluminate ion concentration is considered to be a constant in many published chemical reactions, a practice that seems unrealistic considering the normal pH range of most sediments.

The solubility of silica in alkaline solutions is controlled by the solubility of amorphous silica rather than by that of quartz (Garrels and Christ, 1965). It follows, therefore, that in Cenozoic saline/alkaline lacustrine deposits zeolites and glass are associated with amorphous silica (such as opal) (Hay, 1966). Opal has not been found in Morrison sediments because in the time elapsed since early diagenesis it would have converted to a more stable, crystalline form of silica such as quartz or chert. The high silica activity in tuffaceous sediments may explain the occurrence of zeolites in some samples without significant clay mineral development (Boles and Surdam, 1979).

A puzzling aspect of diagenetic assemblages in sandstones of the upper Morrison sandstones and associated fine-grained beds, in view of the alkaline chemistry, is the paucity of early carbonate minerals. Cenozoic saline, alkaline lakes and playa-lake facies of the Eocene Green River Formation have abundant authigenic carbonate and bicarbonate minerals (Milton and Eugster, 1959). The lack of preserved authigenic carbonate minerals in the Morrison Formation is partly due to replacement by later diagenetic phases because in many samples remnants of carbonate cement are present

Organic complexes are very soluble in moderately alkaline water. Therefore, during early diagenesis, when pH values were buffered to moderately basic values by the dissolution of volcanic ash, the concentration of organics in solution was locally high, particularly where detrital organic matter was present. During later diagenesis, locally elevated temperatures (>75 °C) again favored the solubility of organic complexes, and the resultant acid pore waters (combined with the excellent complexing ability of organic acid anions) caused dissolution of framework grains and cements.

KINETIC MODEL FOR DIAGENESIS

Dibble and Tiller (1981) stated that "chemical equilibrium***is least likely to be attained in sedimentary rocks containing volcanic glass." Thus, diagenetic reactions in the Morrison during early diagenesis were mostly kinetically, rather than equilibrium controlled (Senderov, 1983) because at the time of deposition the Morrison Formation contained an abundance of unstable volcanic material. Dissolution of volcanic glass was rapid relative to formation of alteration products; therefore, as glass dissolved, interstitial solutions quickly became supersaturated with respect to many mineral phases. The phases that precipitated under conditions of supersaturation were metastable, fast-growing phases such as smectite, aluminosilicate gels, and disordered zeolites and feldspars (Dibble and Tiller, 1981). The thermodynamic drive of water-rock systems is toward the lowest free energy state (Garrels and Christ, 1965). The total free energy of a system is decreased most rapidly by precipitation of fast-growing, metastable phases rather than by formation of slow-growing, stable phases (Dibble and Tiller, 1981). Ordered feldspars and I/S formed somewhat later than earliest diagenesis through transformation of earlier phases in conditions of lower supersaturation rather than directly from dissolution of glass. These phases formed earlier, however, than in normal marine sediments because of the favorable chemistry of interstitial waters in the upper part of the Morrison Formation.

SUMMARY AND CONCLUSIONS

Widespread preservation of vitric textures in sandstone matrix and of early zeolite cements in primary pores for 100 million years or more is remarkable. The dissolution of volcanic ash coupled with chemical gradients in Lake T'oo'dichi' were the major variables that determined the composition of authigenic mineral phases in the upper members of the Morrison Formation (descending: Jackpile Sandstone, Brushy Basin, and upper part of the Westwater Canyon Members) at a particular locality in the basin during the first stages of diagenesis. Early diagenetic alterations in the upper part of the Morrison Formation in the San Juan basin are well preserved in distinct, concentric patterns that were relatively unaffected by subsequent burial history as indicated by the lack of correlation between vitrinite reflectance values and diagenetic patterns. Later diagenesis in sandstones was influenced by elevated thermal gradients caused by burial diagenesis, by updip migration of warm waters from deeper parts of the basin, by local influence of organic acids derived from the diagenesis of organic matter, and by downdip migration of meteoric waters due to uplift of recharge areas. Sandstones in the lower members, the Salt Wash and Recapture, contain predominantly early calcite and (or) anhydrite cements and exhibit little grain alteration except where uranium enrichment is found.

In the closed-basin environment of high ionic strength and alkalinity that existed near the center of Lake T'oo'dichi' in late Morrison time, the interval between formation of metastable and stable phases was foreshortened. The first authigenic phases to form were those that grew the fastest at ambient temperatures and pressures (such as disordered zeolites, feldspars, and clay minerals), but these phases were not the most stable thermodynamically. In some sandstones near the center of the lake, disordered(?) albite and quartz overgrowths apparently precipitated directly from solution. In other sandstones, dissolution of metastable phases such as analcime and random I/S was followed by precipitation of stable phases such as albite and ordered I/S in response to favorable chemical conditions well before maximum burial and diagenetic temperatures were achieved.

REFERENCES CITED

Adams, S.S., Curtis, H.S., and Hafen, P.L., 1974, Alteration of detrital magnetite-ilmenite in continental sandstones of the Morrison Formation, New Mexico, *in* Formation of uranium deposits: Vienna, International Atomic Energy Agency Proceedings IAEA–SM–183/36, p. 219–253.

Adams, S.S., Curtis, H.S., Hafen, P.L., and Salek-Nejad, H., 1978, Interpretation of postdepositional processes related to the formation of the Jackpile-Paguate uranium deposit, northwest New Mexico: Economic Geology, v. 73, no. 8, p. 1635–1654.

Adams, S.S., and Saucier, A.E., 1981, Geology and recognition criteria for uraniferous humate deposits, Grants uranium region, New Mexico: U.S. Department of Energy Report GJBX–2(81), 225 p.

American Association of Petroleum Geologists and U.S. Geological Survey, 1975, Geothermal gradient map of North America: Geothermal Survey of North America Subcommittee of American Association of Petroleum Geologists Research Committee, scale 1:5,000,000.

Aubrey, W.M., 1986, The nature of the Dakota-Morrison boundary, southeastern San Juan basin, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 93–104.

Austin, S.R. 1963, Alteration of the Morrison sandstone, *in* Kelley, V.C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 38–44.

______ 1980, Dissolution and authigenesis of feldspars, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 107–115.

Bayliss, G.S , and Schwarzer, R.R., 1987, Hydrocarbon source rock evaluation of EPNG Elliott State, Sec. 36, T19N, R2W, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 298, 14 p.

______ 1988, Hydrocarbon source rock evaluation of Shell Oil No. 41 Wright, Sec. 26, T17N, R3W, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 329, 14 p.

Bell, T.E., 1983, Deposition and diagenesis of the Brushy Basin and upper Westwater Canyon Members of the Morrison

Formation in northwest New Mexico and its relationship to uranium mineralization: Berkeley, Calif., University of California, Ph.D. thesis, 102 p.

______ 1986, Deposition and diagenesis in the Brushy Basin Member and upper part of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 77–92.

Bennett, P., and Siegel, D.I., 1987, Increased solubility of quartz in water due to complexing by organic compounds: Nature, v. 326, no. 6114, p. 684–686.

Boles, J.R., and Surdam, R.C., 1979, Diagenesis of volcanogenic sediments in a Tertiary saline lake; Wagon Bed Formation, Wyoming: American Journal of Science, v. 279, p. 832–853.

Bond, W.A., 1984, Application of Lopatin's method to determine burial history, evolution of the geothermal gradient, and timing of hydrocarbon generation in Cretaceous source rocks in the San Juan basin, northwestern New Mexico and southwestern Colorado, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 433–447.

Brown, G., and Brindley, G.W., 1980, X-ray diffraction procedures for clay mineral identifications, *in* Brindley, G.W., and Brown, G., eds., 1980, Crystal structures of clay minerals and their X-ray identification: Mineralogical Society of London Monograph 5, p. 305–359.

Cadigan, R.A., 1967, Petrology of the Morrison Formation in the Colorado Plateau region: U.S. Geological Survey Professional Paper 556, 113 p.

Clarkson, G., and Reiter, M., 1987, The thermal regime of the San Juan basin since Late Cretaceous times and its relationship to San Juan Mountains thermal sources: Journal of Volcanology and Geothermal Research, v. 31, p. 217–237.

Condon, S.M., and Peterson, Fred, 1986, Stratigraphy of Middle and Upper Jurassic rocks of the San Juan basin; historical perspective, current ideas, and remaining problems, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 7–26.

Cooley, M.E., and Davidson, E.S., 1963, The Mogollon highlands; their influence on Mesozoic and Cenozoic erosion and sedimentation: Arizona Geological Society Digest, v. 6, p. 7–35.

Craig, L.C., Holmes, C.N., Cadigan, R.A., Freeman, V.L., Mullens, T.E., and Weir, G.W., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region, a preliminary report: U.S. Geological Survey Bulletin 1009–E, p. 125–168.

Dibble, W.E., Jr., and Tiller, W.A., 1981, Kinetic model of zeolite paragenesis in tuffaceous sediments: Clays and Clay Minerals, v. 29, no. 3, p. 323–330.

Dickinson, W.R., 1981, Plate tectonic evolution of the southern Cordillera, *in* Dickinson, W.R., and Payne, W.E., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 113–135.

Donahoe, R.J., and Liou, J.G., 1985, An experimental study of the process of zeolite formation: Geochemica et Cosmochimica Acta, v. 49, p. 2349–2360.

Dow, W.G., 1982, Geochemical evaluation of the James P. Dunigan No. 1 Santa Fe, McKinley County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 267, 25 p.

Drever, J.I., 1982, The geochemistry of natural waters: Englewood Cliffs, N.J., Prentice-Hall, 388 p.

Eslinger, Eric, and Pevear, David, 1988, Clay minerals for petroleum geologists and engineers: Society of Economic Paleontologists and Mineralogists Short Course Notes 22, 413 p.

Fishman, N.S., Turner-Peterson, C.E., and Hay, R.L., 1986, Authigenic albite in the Upper Jurassic Morrison Formation; evidence for early diagenetic formation: Society of Economic Paleontologists and Mineralogists, Annual Midyear Meeting, Abstracts, v. 3, p. 37.

Flesch, G.A., 1975, Stratigraphy, sedimentology, and environments of deposition of the Morrison (Upper Jurassic) Formation, Ojito Spring quadrangle, Sandoval County, New Mexico: Albuquerque, N. Mex., University of New Mexico, M.S. thesis, 106 p.

Folk, R.L., 1974, Petrology of sedimentary rocks: Austin, Tex., Hemphill's, 182 p.

Garrels, R.M., 1984, Montmorillonite/illite stability diagrams: Clays and Clay Minerals, v. 32, no. 1, p. 161–166.

Garrels, R.M., and Christ, C.L., 1965, Solutions, minerals, and equilibria: New York, Harper and Row, 450 p.

Goldhaber, M.B., Hemingway, B.S., Mohaghegi, Ali, Reynolds, R.L., and Northrop, H.R., 1987, Origin of coffinite in sedimentary rocks by a sequential adsorption-reduction mechanism: Societe Francaise de Mineralogie et de Cristallographie Bulletin de Mineralogie, v. 110, p. 131–144.

Granger, H.C., 1962, Clays in the Morrison Formation and their spatial relation to the uranium deposits at Ambrosia Lake, New Mexico, *in* Geological Survey Research 1962: U.S. Geological Survey Professional Paper 450–D, p. D15–D20.

Grant, Keith, and Owen, D.W., 1974, The Dakota Sandstone (Cretaceous) of the southern part of the Chama basin, New Mexico; a preliminary report on its stratigraphy, paleontology, and sedimentology, *in* Siemers, C.T., ed., Central-northern New Mexico: New Mexico Geological Society Silver Anniversary Guidebook, p. 239–249.

Hamilton, Warren, 1978, Mesozoic tectonics of the western United States, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 33–70.

Hansley, P.L., 1984, Feldspar alteration patterns in the Upper Jurassic Morrison Formation, northwestern New Mexico: Society of Economic Paleontologists and Mineralogists, National Midyear Meeting, 1st, Technical Program, p. 37.

_____ 1986a, Relationship of detrital, nonopaque heavy minerals to diagenesis and provenance of the Morrison Formation, southwestern San Juan basin, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 257–276.

_____ 1986b, Regional diagenetic trends and uranium mineralization in the Morrison Formation across the Grants uranium region, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 277–302.

_____ 1987, Petrologic and experimental evidence for the etching of garnets by organic acids in the Upper Jurassic Morrison Formation, northwestern New Mexico: Journal of Sedimentary Petrology, v. 57, no. 4, p. 666–681.

Haun, J.D., and Weimer, R.J., 1960, Cretaceous stratigraphy of Colorado, *in* Weimer, R.J., and Haun, J.D., eds., Guide to the geology of Colorado: Geological Society of America, Rocky Mountain Association of Geologists, and Colorado Scientific Society, p. 58–65.

Hay, R.L., 1966, Zeolites and zeolitic reactions in sedimentary rocks: Geological Society of America Special Paper 85, 123 p.

Hicks, R.T., 1981, Diagenesis of the Westwater Canyon Member, Morrison Formation, East Chaco Canyon drilling project, New Mexico: Albuquerque, N. Mex., University of New Mexico, M.S. thesis, 131 p.

Hilpert, L.S., and Moench, R.H., 1960, Uranium deposits of the southern part of the San Juan basin, New Mexico: Economic Geology, v. 55, no. 3, p. 429–464.

Jacobson, S.R., Saxton, J.D., and Tully, K.M., 1985, Organic geochemical analyses of Superior Oil Co. No. 1–14 San Mateo Well, McKinley County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 260, 16 p.

Kastner, Miriam, 1971, Authigenic feldspar in carbonate rocks: American Mineralogist, v. 56, p. 1403–1442.

Keal, J.E., 1982, Geochemical analysis of the Brinkerhoff Drilling Co. No. 1 Cabezon-Government (Sandoval County), Great Western Drilling Co. No. 1 Hospah-Santa Fe (McKinley County), Magnolia Petroleum Corp. No. 1 Hutchinson-Federal (Sandoval County), Union Oil Co. of California No. 1 M-13 USA (Sandoval County), Sun Oil Co. No. 1 Navajo Lands (San Juan County), Apache Corp. No. 1 Foshay (San Juan County), Shell Oil Co. No. 113–17 Carson Unit (San Juan County), Skelly Oil Co. No. 1 Navajo O (San Juan County), Texaco, Inc. No. 1 Navajo Al (San Juan County), Amerada Petroleum Corp. No. 1 Navajo Tract 20 (San Juan County), and Delhi Oil Corp. No. 4 Ute (San Juan County) Wells, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 268, 117 p.

Kelley, V.C., 1951, Tectonics of the San Juan basin, *in* Guidebook of the south and west sides of the San Juan basin, New Mexico and Arizona: New Mexico Geological Society, Field Conference, 2nd, p. 124–131.

Kelley, V.C., and Clinton, N.J., 1960, Fracture systems and tectonic elements of the Colorado Plateau: University of New Mexico Publications in Geology 6, 104 p.

Kirk, A.R., and Condon, S.M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico; a subsurface study, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 105–144.

Leventhal, J.S., 1980, Organic geochemistry and uranium in Grants mineral belt, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, v. 38, p. 75–85.

Liou, J.G., 1971, Analcime equilibria: Lithos, v. 4, p. 389–402.

Lowy, R.M., 1982, Provenance and sediment-dispersal patterns, Westwater Canyon sandstones, western San Juan basin, New Mexico: Albuquerque, N. Mex., University of New Mexico, M.S. thesis, 203 p.

Ludwig, K.R., Simmons, K.R., and Webster, J.D., 1984, U-Pb isotope systematics and apparent ages of uranium ores, Ambrosia Lake and Smith Lake districts, Grants mineral belt, New Mexico: Economic Geology, v. 79, p. 322–337.

Martinez, Ruben, 1979, Provenance study of the Westwater Canyon and Brushy Basin Members of the Morrison Formation between Gallup and Laguna, New Mexico: Albuquerque, N. Mex., University of New Mexico, Ph.D. thesis, 58 p.

Milton, Charles, and Eugster, H.P., 1959, Mineral assemblages of the Green River Formation: Research in Geochemistry, v. 1, p. 118–150.

Moench, R.H., and Schlee, J.S., 1967, Geology and uranium deposits of the Laguna district, New Mexico: U.S. Geological Survey Professional Paper 519, 117 p.

Nadeau, P.H., Wilson, M.J., McHardy, W.J., and Tait, J.M., 1985, The conversion of smectite to illite during diagenesis; evidence from some illitic clays from bentonites and sandstones: Mineralogical Magazine, v. 49, p. 393–400.

Nash, J.T., 1968, Uranium deposits in the Jackpile Sandstone, New Mexico: Economic Geology, v. 63, p. 737–750.

Nuccio, V.F., and Johnson, R.C., 1988, Surface vitrinite-reflectance map of the Uinta, Piceance, and Eagle basins area, Utah and Colorado: U.S. Geological Survey Map MF–2008–B, 22 p.

Owen, D.W., Walters, L.J., Jr., and Beck, R.G., 1984, The Jackpile Sandstone Member of the Morrison Formation in west-central New Mexico; a formal definition: New Mexico Geology, v. 6, no. 3, p. 45–52.

Perry, E., and Hower, J., 1970, Burial diagenesis in Gulf Coast pelitic sediments: Clays and Clay Minerals, v. 13, p. 165–178.

Peterson, Fred, 1984, Fluvial sedimentation on a quivering craton; influence of slight crustal movements on fluvial processes, Upper Jurassic Morrison Formation, western Colorado Plateau: Sedimentary Geology, v. 38, no. ¼, p. 21–49.

Reynolds, R.C., 1980, Interstratified clay minerals *in* Brindley, G.W., and Brown, G., eds., 1980, Crystal structures of clay minerals and their X-ray identification: Mineralogical Society of London, Monograph 5, p. 249–304.

Reynolds, R.L., Fishman, N.S., Scott, J.H., and Hudson, M.R., 1986, Iron-titanium oxide minerals and magnetic susceptibility anomalies in the Mariano Lake–Lake Valley cores; constraints on conditions of uranium mineralization in the Morrison Formation, San Juan basin, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 303–314.

Rice, D.D., 1983, Relation of natural gas composition to thermal maturity and source rock type in San Juan basin, northwestern New Mexico and southwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 87, no. 8, p. 1199–1218.

Ridgely, J.L, 1977, Stratigraphy and depositional environments of Jurassic-Cretaceous sedimentary rocks in the southwest part of the Chama basin, New Mexico, *in* Fassett, J.E., ed., San Juan Basin III: New Mexico Geological Society Field Conference, 28th, Guidebook, p. 153–158.

Roedder, Edwin, 1981, Origins of fluid inclusions and changes that occur after trapping, *in* Hollister, L.S., and Crawford, M.L., eds., Fluid inclusions; applications to petrology: Mineralogical Association of Canada Short Course, p. 101–137.

Ruetschilling, R.L., 1973, Structure and stratigraphy of the San Ysidro quadrangle, Sandoval County, New Mexico: Albuquerque, N. Mex., University of New Mexico, M.S. thesis, 79 p.

Russell, J.A., 1979, Vitrinite reflectance and kerogen analyses of the Great Western Drilling Co. No. 1 Hospah-Santa Fe (McKinley County), Continental Oil Company No. 1 South Dulce (Rio Arriba County), El Paso Natural Gas Company No. 50 San Juan Unit 29–5 (Rio Arriba County), and Pan American Petroleum Corporation No. 1 Pagosa Jicarrilla (Rio Arriba County) Wells, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 265, 9 p.

Santos, E.S., 1975, Lithology and uranium potential of Jurassic formations in the San Ysidro-Cuba and Majors Ranch areas, northwestern New Mexico: U.S. Geological Survey Bulletin 1329, 22 p.

Santos, E.S., and Turner-Peterson, C.E., 1986, Tectonic setting of the San Juan basin in the Jurassic, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 27–34.

Saucier, A.E., 1974, Stratigraphy and uranium potential of the Burro Canyon Formation in the southern Chama basin, New Mexico, *in* Siemers, C.T., ed., Central-northern New Mexico: New Mexico Geological Society Silver Anniversary Guidebook, p. 211–217.

_____ 1980, Tertiary oxidation in the Westwater Canyon Member of the Morrison Formation, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 151–157.

Schlee, J.S., 1957, Petrology of the Jackpile sandstone, New Mexico: Geological Society of America Bulletin, v. 68, p. 1793.

Schlee, J.S., and Moench, R.H., 1961, Properties and genesis of "Jackpile" sandstone, Laguna, New Mexico, *in* Peterson, J.A., and Osmond, J.C., eds., Geometry of sandstone bodies: American Association of Petroleum Geologists, p. 135–150.

Schmitt, L.J., 1982, Petrographic study of sandstones from measured sections of the Morrison Formation and related units, southwestern San Juan basin, New Mexico: U.S. Geological Survey Open-File Report 82–991, 58 p.

Senderov, E.E., 1983, Metastable systems in zeolite formation: Geochemistry International, v. 20, no. 6, p. 66–74.

Sheppard, R.A., 1971, Zeolites in sedimentary deposits of the United States; a review, *in* Flanigen, E.M., and Sand, L.B., eds., Molecular sieve zeolites I: American Chemical Society Advances in Chemistry Series 101, p. 279–310.

Shoemaker, E.M., 1956, Occurrence of uranium in diatremes on the Navajo and Hopi Reservations, Arizona, New Mexico, and Utah, *in* Page, L.R., Stocking, H.E., and Smith, H.B., compilers, Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland 1955: U. S. Geological Survey Professional Paper 300, p. 179–185.

Steele, B.A., 1984a, Preliminary report on the petrography of the Upper Jurassic Morrison Formation, Mariano Lake-Lake Valley Drilling Project, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 84–170, 40 p.

_____ 1984b, Preliminary report on the petrography of the Upper Jurassic Morrison Formation from four surface sections, southwestern San Juan Basin, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 84–780, 29 p.

Surdam, R.C, and Crossey, L.J., 1985, Mechanisms of organic/inorganic interactions in ss/sh sequences, *in* Relationship of organic matter and mineral diagenesis: Society of Economic Paleontologists and Mineralogists Short Course 17, p. 177–279.

Turner-Peterson, C.E., 1986, Fluvial sedimentology of a major uranium-bearing sandstone; a study of the Westwater Canyon Member of the Morrison Formation, San Juan basin, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study;

the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 47–76.

______ 1987, Sedimentology of the Westwater Canyon and Brushy Basin Members, Upper Jurassic Morrison Formation, Colorado Plateau, and relationship to uranium mineralization: Boulder, Colo., University of Colorado, Ph.D. thesis, 168 p.

Turner-Peterson, C.E., and Fishman, N.S., 1986, Geologic synthesis and genetic models for uranium mineralization in the Morrison Formation, Grants uranium region, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 357–388.

Turner-Peterson, C.E., Fishman, N.S., and Owen, D.E., 1987, Zonation of clay minerals in a Jurassic playa-lake setting; a case for low-temperature formation of illite: Society of Economic Paleontologists and Mineralogists, Annual Midyear Meeting, Abstracts, v. 4, p. 85.

Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., 1986, A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, 388 p.

Walker, T.R., 1984, 1984 SEPM Presidential address; diagenetic albitization of potassium feldspar in arkosic sandstones: Journal of Sedimentary Petrology, v. 54, no. 1, p. 3–16.

Walton, A.W., 1975, Zeolitic diagenesis in Oligocene volcanic sediments, Trans-Pecos, Texas: Geological Society of America Bulletin, v. 86, p. 615–624.

Waples, D.W., 1985, Geochemistry in petroleum exploration: Boston, International Human Resources Development Corporation, 232 p.

Waters, A.C., and Granger, H.C., 1953, Volcanic debris in uraniferous sandstones, and its possible bearing on the origin and precipitation of uranium: U.S. Geological Survey Circular 224, 26 p.

Weeks, A.D., and Garrels, R.M., 1959, Geologic setting of Colorado Plateau ores, *in* Garrels, R.M., and Larson, E.S., 3rd, compilers, Geochemistry and mineralogy of Colorado Plateau ores: U.S. Geological Survey Professional Paper 320, p. 3–11.

Whitney, C.G., 1986, Petrology of clay minerals in the subsurface Morrison Formation near Crownpoint, southern San Juan basin, New Mexico; an interim report, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 315–330.

______ 1988, Experimental investigation of the smectite to illite reaction; dual reaction mechanisms and oxygen-iostope systematics: American Mineralogist, v. 73, p. 77–90.

Whitney, C.G., and Northrop, H.R, 1987, Diagenesis and fluid flow in the San Juan basin, New Mexico; regional zonation in the mineralogy and stable isotope composition of clay minerals in sandstone: American Journal of Science, v. 287, p. 353–382.

Whitney, C.G., Northrop, H.R., and Hansley, P.L., 1986, The use of mineral alteration patterns and stable isotope compositions to infer a paleohydrologic regime, *in* Carter, L.M.H., ed., USGS Research on Energy Resources—1986, Program and Abstracts: U.S. Geological Survey Circular 974, p. 73–74.

Williams, Howell, Turner, F.J., and Gilbert, C.M., 1954, Petrography: San Francisco, W.H. Freeman, 406 p.

Woodward, L.A., and Schumacher, O.L., 1973, Morrison Formation of the southeastern San Juan basin, New Mexico: New Mexico State Bureau of Mines and Mineral Resources Circular 129, 7 p.

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