Authigenic Albite in a Jurassic Alkaline, Saline Lake Deposit, Colorado Plateau— Evidence for Early Diagenetic Origin

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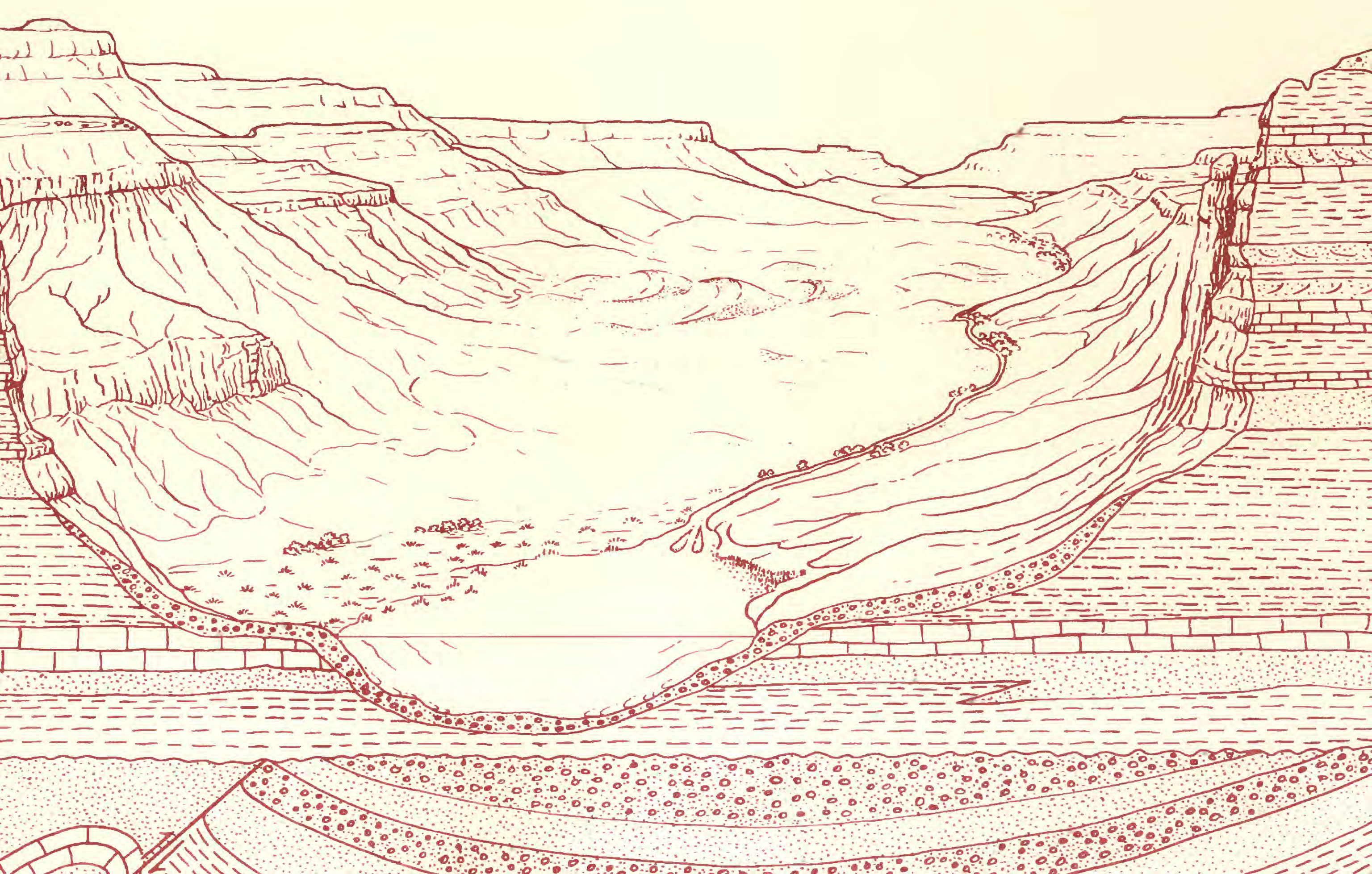

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Chapter P

Authigenic Albite in a Jurassic Alkaline, Saline Lake Deposit, Colorado Plateau—Evidence for Early Diagenetic Origin

By NEIL S. FISHMAN, CHRISTINE E. TURNER, and ISABELLE K. BROWNFIELD

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

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1995

For sale by
U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Fishman, Neil S.
Authigenic albite in a Jurassic alkaline, saline lake deposit, Colorado plateau—Evidence for early diagenetic origin/ by Neil S. Fishman, Christine E. Turner, and Isabelle K. Brownfield.
p. cm.— (U.S. Geological Survey bulletin ; 1808–P)
(Evolution of sedimentary basins—San Juan Basin; ch. P)
Includes bibliographical references.
1. Albite—Colorado. 2. Albite—New Mexico. 3. Geology, Stratigraphic—Jurassic. 4. Minerals—Colorado. 5. Minerals—New Mexico.
I. Turner, Christine E. II. Brownfield, Isabelle K. III. Title. IV. Series.
V. Series:
Evolution of sedimentary basins—San Juan Basin ; ch. P.
QE75.B9 no. 1808–P
[QE391.P55]
557.3 s—dc20 94–11339
[549'.68] CIP

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Authigenic Albite in a Jurassic Alkaline, Saline Lake Deposit, Colorado Plateau—Evidence for Early Diagenetic Origin

By Neil S. Fishman, Christine E. Turner, *and* Isabelle K. Brownfield

Abstract

Authigenic albite in the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau, probably formed at low (25°C–60°C), synsedimentary temperatures. This albite is present in tuff beds as the alteration product of silicic volcanic ash deposited in Jurassic Lake T'oo'dichi'. The albitic tuff beds form the central diagenetic mineral zone in a concentric progression that is, from lake margin basinward, smectite→clinoptilolite→analcime±potassium feldspar→albite. The conformity of the outer boundary of the albite diagenetic mineral zone with boundaries of the other diagenetic mineral zones suggests that albite formed in response to the same lateral hydrogeochemical gradient responsible for the formation of other authigenic minerals and, therefore, at low, synsedimentary temperatures. Although albite is reported in minor amounts in other alkaline, saline-lake settings, this is the first reported occurrence of albite as a distinct diagenetic mineral zone.

Fluvial sandstone beds interbedded with and underlying the albitic tuff beds contain abundant authigenic albite as overgrowths, pore-filling laths, and replacement of detrital feldspar grains. The close spatial association of albitic tuff beds and albitized sandstone beds suggests that pore water in sediments of Lake T'oo'dichi', in which cations were enriched from the alteration of silicic ash, moved into nearby sands during early diagenesis. The coarseness of the albite in the sandstone beds makes it more amenable to study than the aphanitic albite in the tuff beds. Microprobe analysis of the albite cement indicates a plagioclase composition of $<An_1$, almost pure $NaAlSi_3O_8$, and unit-cell determinations indicate that the albite is highly ordered. High minus-cement porosity in albite-cemented sandstone (as high as 33 percent) and the nature of grain contacts confirm an early diagenetic origin for the albite cement.

Alkaline, saline lakes may act as solar ponds because brine that develops by evaporative concentration has a high heat capacity. The high heat capacity of saline lakes may result in water temperatures higher than 25°C, perhaps as high as 50°C–60°C. Because warm lake water may have infiltrated into underlying sediments, we postulate temperatures between 25°C and 60°C for the formation of authigenic albite in Lake T'oo'dichi' tuff beds and associated sandstone beds. Pore-water chemistry can thus drive crystallization of albite at temperatures less than 85°C. Our results significantly expand the temperature range in which authigenic albite can form in sedimentary rocks and thus limit the use of albite as a geothermometer.

INTRODUCTION

Authigenic albite is common in sedimentary rocks of various ages (Moore, 1950; Baskin, 1956; Milton,1957; Kastner and Waldbaum, 1968; Kastner, 1971; Desborough, 1975; Boles and Franks, 1979; Kastner and Siever, 1979; Cole, 1985; Saigal and others, 1988; Milliken, 1989), especially with increased depth of burial and temperature. Some rocks that have experienced burial temperatures of 100°C or greater show a dramatic increase in authigenic albite, as replacement of, or overgrowth on, detrital feldspar grains (Iijima and Utada, 1972; Merino, 1975; Boles, 1982; Helmold and van de Kemp, 1984; Milliken, 1985; Gold, 1987), although recent studies suggest that albite may form at about 85°C (Pittman, 1988) or slightly lower (Saigal and others, 1988).

The presence of authigenic albite in some lacustrine rocks suggests temperatures of formation lower than 85°C. Authigenic albite is in the Green River Formation (Moore, 1950; Milton, 1957; Desborough, 1975; Cole, 1985) in an area where vitrinite-reflectance data (Nuccio and Johnson, 1988) confirm a cool (<70°C) thermal history. Authigenic albite is in Miocene rocks near Boron, California, where it formed at temperatures of less than 58°C, as indicated by its coexistence with primary borax (Williamson 1987), a

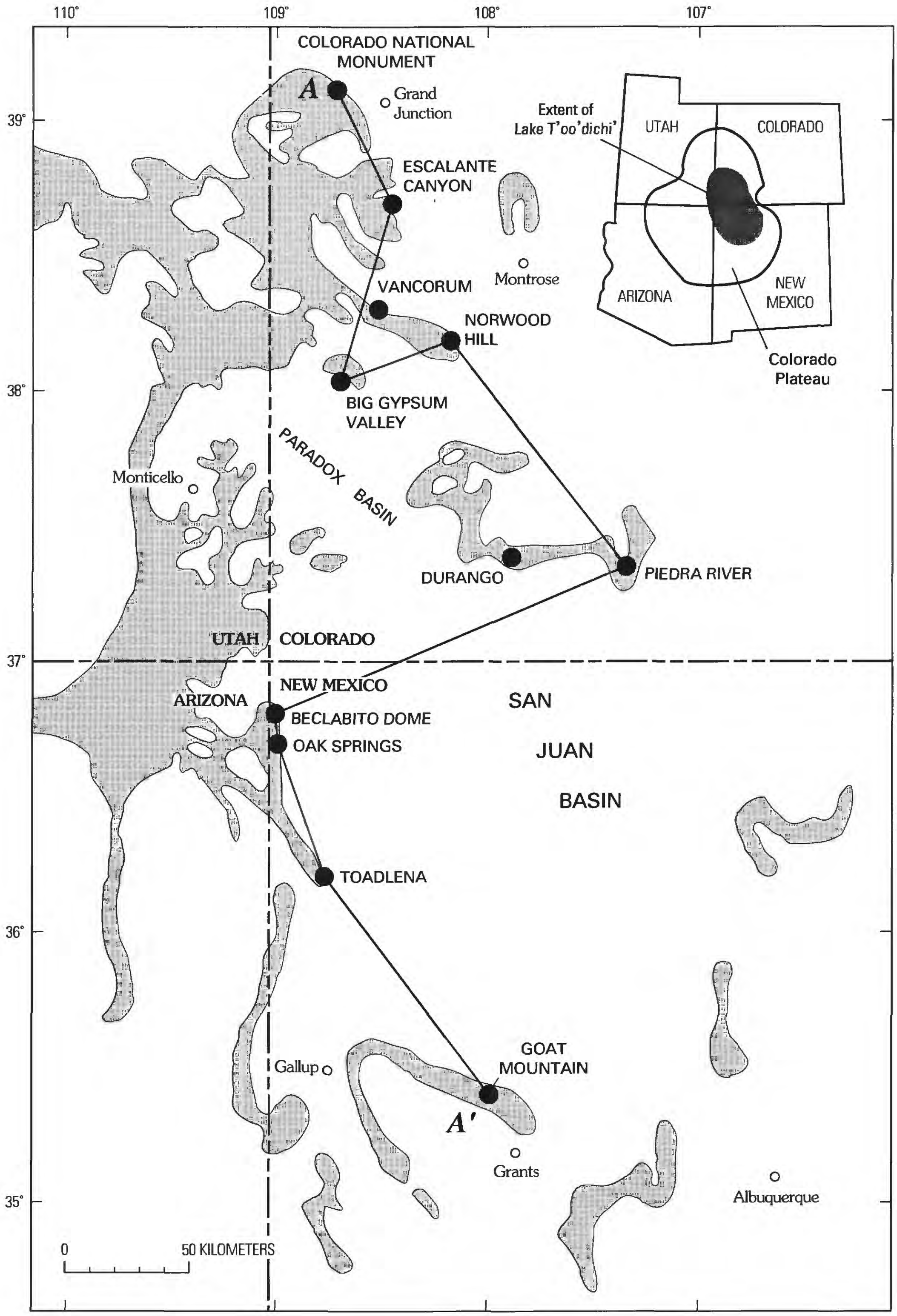


Figure 1. Map of the study area showing outcrops of the Upper Jurassic Morrison Formation (shaded areas) in the Colorado Plateau and locations of measured sections used for this report (solid circles). Line of section *A–A′* (fig. 2) is also shown.

mineral that alters to kernite at temperatures greater than 58°C (Christ and Garrels, 1959).

Studies of alkaline, saline lake deposits in the Brushy Basin Member of the Upper Jurassic Morrison Formation, eastern Colorado Plateau (fig. 1), indicate that authigenic albite is present in interbedded silicic tuff beds and sandstone beds (Fishman and others, 1986; Turner-Peterson and others, 1986; Turner-Peterson, 1987; Turner and Fishman, 1991). Both the confinement of albite primarily to the central lake facies and petrographic constraints suggest an early, low-temperature origin, probably related to the alkaline, saline pore-water chemistry. Because the albite seemed to have formed at low, synsedimentary temperatures, an integrated case study of the distribution, mode of occurrence, timing of formation, and thermal history of the albitic rocks was undertaken.

Acknowledgments.—Discussions, both in the laboratory and in the field, with Richard L. Hay (University of Illinois), Richard L. Sheppard (U.S. Geological Survey), and Blair F. Jones (U.S. Geological Survey) were extremely important and helpful and contributed much to our knowledge of alkaline, saline-lake systems. Vito Nuccio (U.S. Geological Survey) kindly performed vitrinite-reflectance studies on coal samples, and Joan Fitzpatrick (U.S. Geological Survey) kindly made unit-cell determinations. This manuscript was improved by the critical reviews by George Breit, Joan Fitzpatrick (U.S. Geological Survey), Arthur S. Trevena (Unocal), Earle M. McBride (University of Texas), and Enrique Merino (Indiana University).

METHODS

Samples of interbedded albitic tuff beds and sandstone beds were collected from four localities: Durango, Norwood Hill, Piedra River, and Vancorum, Colorado (fig. 1). The sections were measured and described in detail by Turner-Peterson (1987).

Petrologic studies were performed using X-ray diffraction, electron microprobe, scanning electron microscope, and petrographic microscopic techniques. Selected areas of thin sections were powdered in situ using a diamond-tipped objective, and the powdered material was then mounted on a gelatin fiber for X-ray analysis using a powder camera and CuKα radiation. Exposure times varied from 2 to 12 hours. This powder-camera technique allowed

Table 1. Electron microprobe data for authigenic albite from the Brushy Basin Member of the Morrison Formation, eastern Colorado Plateau.

[Sample localities are shown in figure 1. n is number of data points per grain. Oxide abundances are in weight percent (Na_2O, ±0.15 percent; K_2O, ±0.01 percent; CaO, ±0.03 percent; SiO_2, ±0.34 percent; Al_2O_3, ±0.13 percent; Fe_2O_3, ±0.02 percent; BaO, ±0.03 percent). Anorthite (An) content is <1 mole percent for all samples]

Sample locality	Sample type	n	Na_2O	K_2O	CaO	SiO_2	Al_2O_3	Fe_2O_3	BaO	Total
Piedra River	Framework grain	14	12.40	0.03	0.05	68.19	19.61	0.02	0.03	100.33
Piedra River	Framework grain	5	11.66	0.04	0.04	67.36	19.48	0.04	0.02	98.63
Piedra River	Framework grain	3	11.64	0.03	0.12	67.27	19.64	0.01	0.03	98.74
Piedra River	Framework grain	5	11.83	0.01	0.06	67.01	19.58	0.03	0.01	98.53
Piedra River	Framework grain	5	11.77	0.04	0.03	67.28	19.79	0.05	0.00	98.96
Piedra River	Framework grain	2	11.81	0.01	0.05	67.67	19.60	0.00	0.04	99.18
Piedra River	Overgrowth	5	11.91	0.03	0.05	67.19	19.84	0.01	0.02	99.05
Durango	Framework grain	7	12.48	0.07	0.16	68.53	19.79	0.05	0.00	101.08
Durango	Framework grain	6	12.67	0.04	0.02	67.98	19.66	0.08	0.01	100.46
Durango	Framework grain	5	12.90	0.04	0.02	68.24	19.62	0.01	0.01	100.84
Durango	Overgrowth	2	12.64	0.02	0.03	67.99	19.68	0.02	0.00	100.38
Durango	Overgrowth	1	12.79	0.05	0.05	68.01	19.67	0.00	0.00	101.48
Durango	Overgrowth	1	12.63	0.05	0.00	67.38	19.76	0.01	0.00	99.83
Durango	Overgrowth	1	12.49	0.06	0.05	65.76	19.74	0.08	0.00	98.18
Durango	Overgrowth	1	13.01	0.08	0.02	66.43	19.79	0.00	0.04	99.37
Norwood Hill	Framework grain	5	12.17	0.01	0.03	67.21	19.40	0.01	0.01	98.84
Norwood Hill	Framework grain	5	12.12	0.00	0.06	66.79	20.02	0.02	0.00	99.01
Norwood Hill	Interstitial cement	1	12.21	0.03	0.03	67.19	19.96	0.00	0.00	99.39
Norwood Hill	Interstitial cement	1	12.40	0.03	0.05	67.55	20.05	0.00	0.03	100.11
Norwood Hill	Interstitial cement	1	12.32	0.02	0.06	67.52	20.30	0.00	0.00	100.22
Norwood Hill	Interstitial cement	1	12.48	0.02	0.00	66.83	19.78	0.05	0.07	99.23

for analysis of individual crystals or of areas that were also examined in thin section. All tuff samples were also powdered and X-rayed. Albitized detrital grains, identified by their white, opaque appearance, were picked by hand from a disaggregated sandstone sample, and the material was then used for determination of unit-cell parameters.

Major element (Na, K, Ca, Si, Al) and minor element (Ba, Fe, Sr) compositions of authigenic albite in sandstone beds were determined through quantitative analysis of grains in polished thin sections using an electron microprobe (accelerating voltage 15 keV, beam current 10 nA, beam size 5 μm) (table 1). The microprobe data were reduced using the methods described by Ziebold and Ogilvie (1964), Albee and Ray (1970), and Bence and Albee (1968). Strontium content was below the detection limit (0.02 percent) in all samples analyzed.

Forty-one thin sections were studied; most of these were stained with sodium cobaltinitrite for determination of potassium feldspar and with alizarine red S and potassium ferricyanide for determination of carbonate type and composition, respectively. Point counts (at least 300 points per section) were performed on the thin sections from sandstone samples. Selected samples were viewed using a scanning electron microscope that was equipped with an energy-dispersive X-ray analyzer.

The thermal history of the Morrison Formation was determined by study of the vitrinite reflectance of organic material chiefly from coal beds in the lower part of the

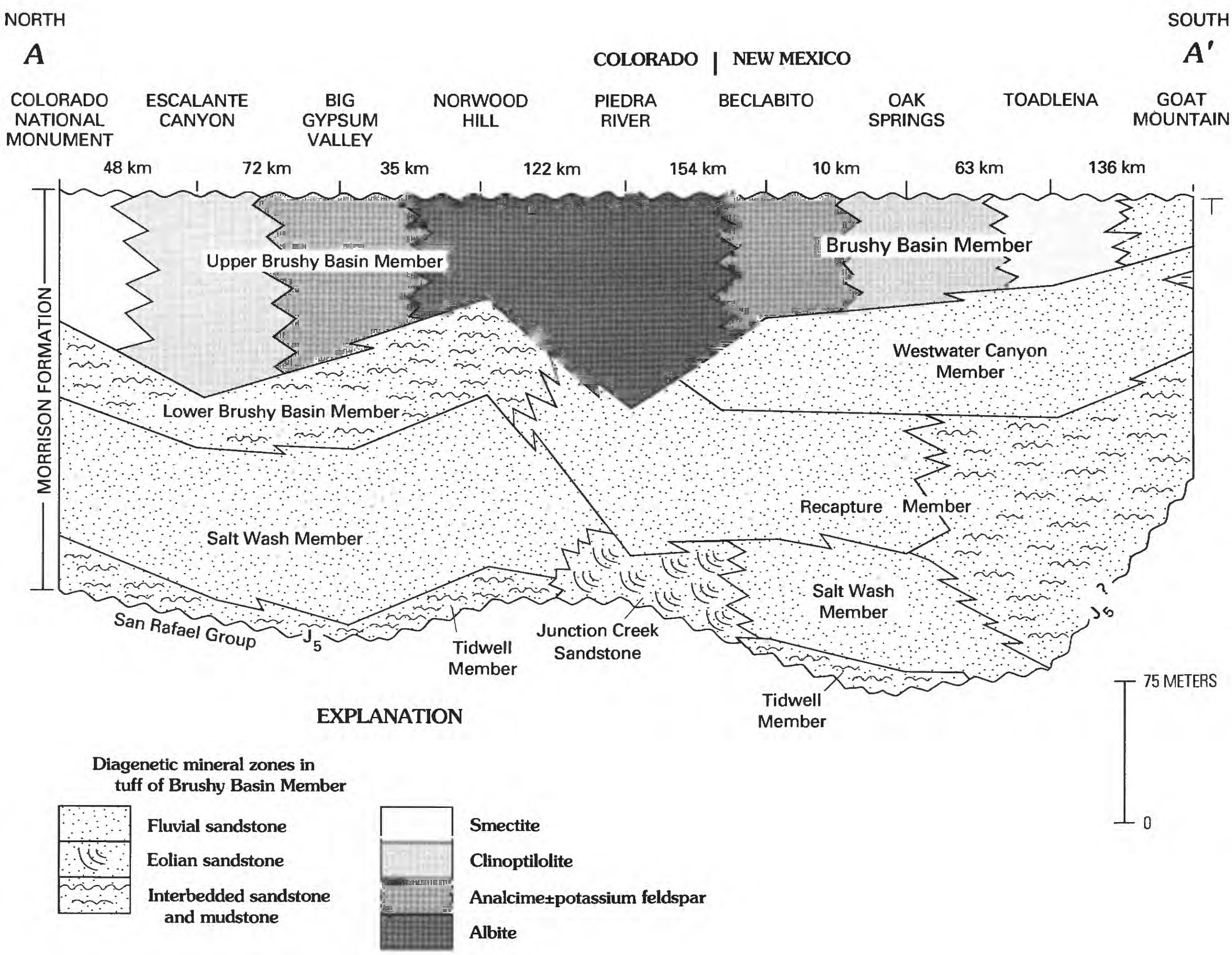


Figure 2. North-south stratigraphic section of the Morrison Formation in the Colorado Plateau. Diagenetic mineral zones in the alkaline, saline lake deposits in the Brushy Basin Member were determined from authigenic minerals in tuff beds (Turner-Peterson 1987). The relationship between the Junction Creek Sandstone and the Morrison Formation is uncertain. Line of section is shown in figure 1; datum is base of Cretaceous rocks. J_5 unconformity as described in Pipiringos and O'Sullivan (1978).

Upper Cretaceous Dakota Sandstone, a unit that either unconformably overlies the Morrison or is separated from the Morrison locally by the Lower Cretaceous Burro Canyon Formation (0–60 m thick). Even though an unconformity separates the Dakota from the Morrison, the Dakota coal samples would have experienced the same post-Late Cretaceous thermal history as the Morrison. Maximum burial depths occurred in the Tertiary, and the nearby San Juan volcanic field was active in the Tertiary. Thus, the Morrison's thermal history would be close to that of overlying Dakota coals. A single sample from an organic-rich horizon in the Brushy Basin Member of the Morrison Formation was also collected and used for vitrinite reflectance studies.

GEOLOGY

Stratigraphy

The Brushy Basin Member, except locally where overlain by the Jackpile Sandstone Member, is the uppermost member of the Morrison Formation on the Colorado Plateau and is recognized from the southern margin of the San Juan Basin northward to Grand Junction, Colorado (fig. 2). In the study area, it conformably overlies the fluvial Westwater Canyon, Recapture, or Salt Wash Members of the Morrison Formation. In an area north of the Colorado–New Mexico State line, beyond the depositional pinchout of the Westwater Canyon Member, beds equivalent to the Brushy Basin Member in New Mexico rest directly on beds that are equivalent to the Recapture Member (Turner-Peterson, 1987). The name Recapture is not extended much beyond the pinchout of the Westwater Canyon, and the entire interval of Morrison above the Salt Wash Member is mapped as Brushy Basin in this area (fig. 2).

Ancient Lake T'oo'dichi'

Deposits of a large, ancient alkaline, saline lake, Lake T'oo'dichi' (Turner-Peterson, 1987), have been recognized in the upper part of the Brushy Basin Member north of the Colorado–New Mexico State line and extend south to include the entire Brushy Basin Member in New Mexico (fig. 2). The lake sediments accumulated in a large, shallow basin that included the present-day San Juan and the ancestral Paradox Basins (Turner-Peterson, 1987) (fig. 3). The lake deposits are as thick as 100 m and contain intervals of altered volcanic ash (Turner-Peterson, 1987). The ash was derived from a magmatic arc several hundred kilometers to the west of the Colorado Plateau region (Burchfiel and Davis, 1975; Hamilton, 1978). Differential alteration of the ash, which reflects lateral hydrogeochemical gradients established during deposition in an alkaline, saline lake, resulted in development of four concentric diagenetic mineral zones. The zones are defined on the basis of the dominant diagnostic authigenic mineral(s) in tuff beds that were deposited in the lake. The three outer zones, which basinward are the smectite, clinoptilolite, and analcime±potassium feldspar zones, are similar to those recognized in Pliocene and Pleistocene alkaline, saline lake deposits studied by others (Sheppard and Gude, 1968; Surdam and Sheppard, 1978) and are part of the data that led to the interpretation of this interval of the Brushy Basin Member as lacustrine. However, a central albitic diagenetic mineral zone, such as occurs in deposits of Lake T'oo'dichi' (fig. 3), has not been described from other ancient alkaline, saline lake deposits.

Thermal History

Because high temperature (>85°C) is commonly considered necessary for albite formation, it is important to evaluate the thermal history of the Brushy Basin Member, which contains albitic tuff beds to determine if temperatures ever exceeded 85°C. Two factors, burial history and igneous activity, have contributed to the thermal history of the region.

Following deposition of the Morrison Formation, about 1,000 m of Cretaceous and Tertiary sediments accumulated. Burial depths of Morrison sediments were probably somewhat uniform until the Late Cretaceous and early Tertiary Laramide orogeny, during which time downwarping of the San Juan Basin occurred. Samples used to define the diagenetic mineral zones in Lake T'oo'dichi' were collected from outcrops of the Brushy Basin Member of the Morrison Formation that flank the San Juan Basin or are distant from the basin; therefore, the structural effects of the Laramide orogeny are negligible. On the basis of stratigraphic reconstruction, the maximum depth of burial for the outcrops sampled is uniformly about 2,000 m. Vitrinite reflectance data (fig. 4) indicate that outcrops containing albitic tuff beds never were subjected to temperatures in excess of 70°C (Barker and Pawlewicz, 1986), which is consistent with the relatively shallow burial. This inferred temperature is below the 85°C commonly considered to be the minimum temperature required for formation of authigenic albite.

The vitrinite reflectance data, in addition to recording burial history, would show thermal effects of igneous activity in the region. The San Juan volcanic field (fig. 4), which developed 35–20 Ma (Steven, 1975; Lipman and others, 1978), is thought by some workers to have left a regional thermal imprint; however, the uniformity of vitrinite reflectance data across the region indicates no thermal effects from the San Juan volcanic field.

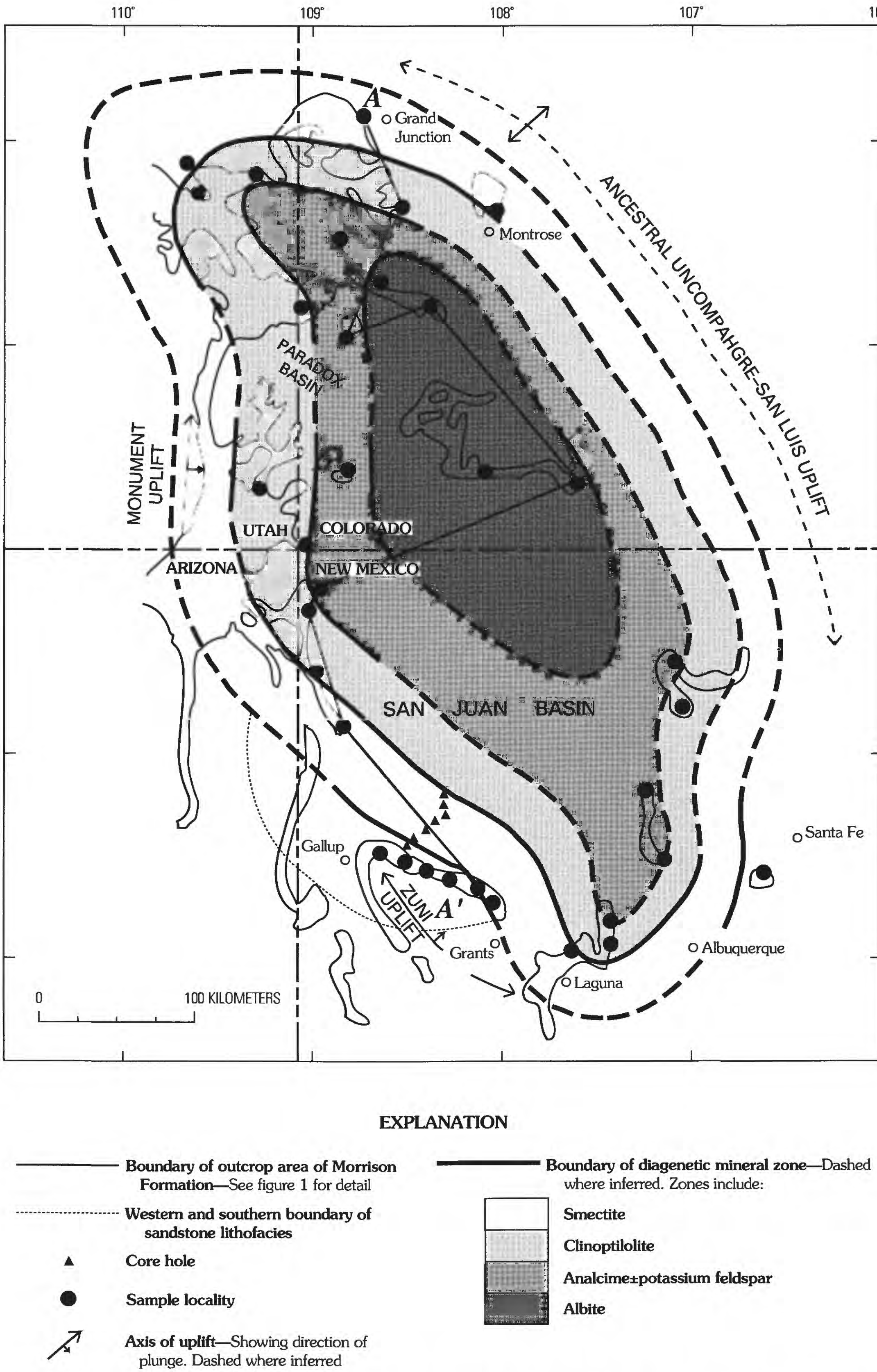


Figure 3. Map showing the distribution of diagenetic mineral zones in altered tuff deposited in Jurassic Lake T'oo'dichi'. Modified from Turner and Fishman (1991).

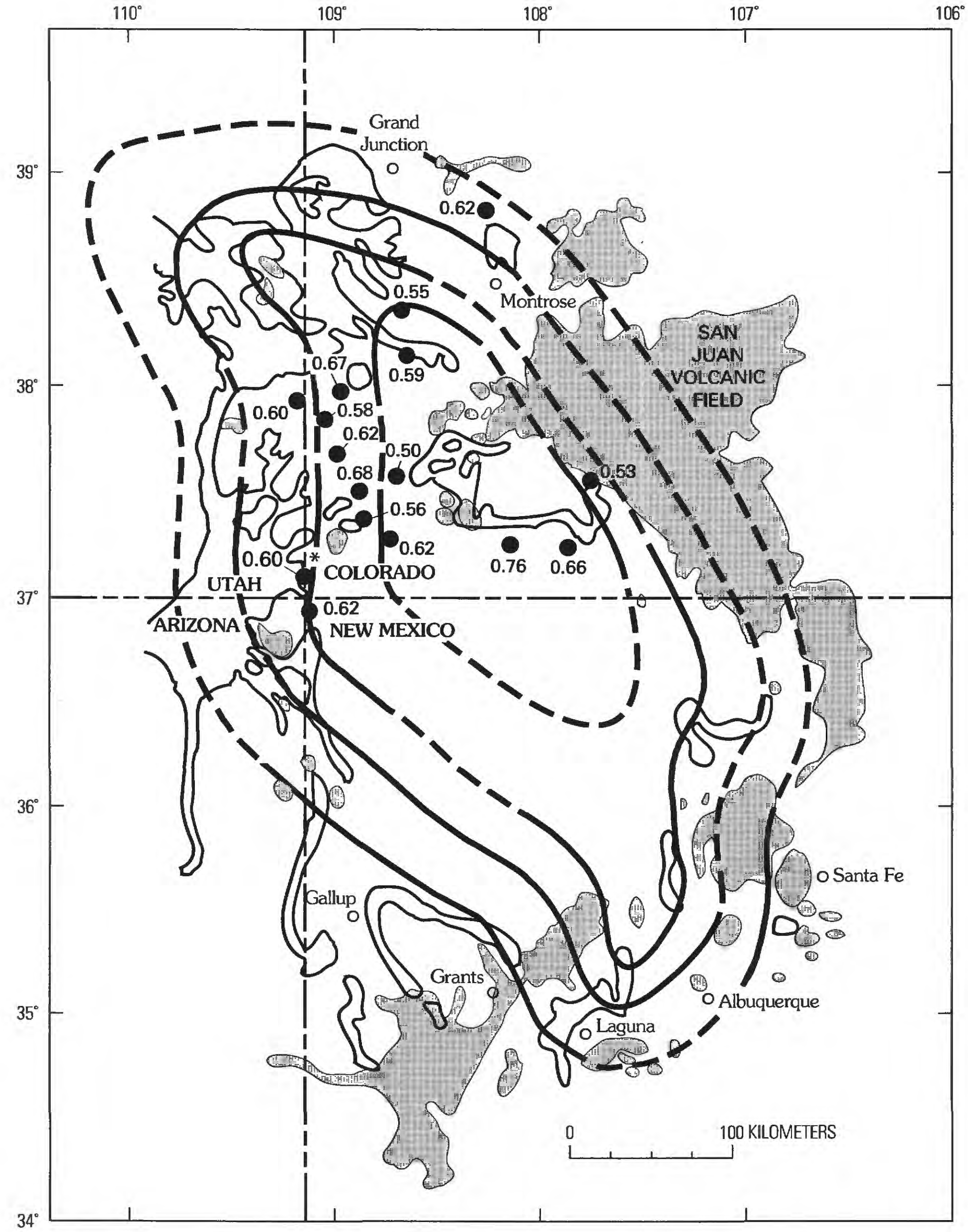


Figure 4. Map showing the distribution of Tertiary and Quaternary igneous intrusive and extrusive rocks (shaded areas) in the study area and vitrinite reflectance values (in percent) for coal samples from the Dakota Sandstone (solid circles), which overlies the Morrison Formation, and from a sample in the Brushy Basin Member of the Morrison Formation (indicated by asterisk). Note uniformity of vitrinite reflectance values across the region and the lack of thermal effects from the San Juan volcanic field; in fact, a vitrinite reflectance value of 0.53 percent is in coal from very near the volcanic field. Diagenetic mineral zone boundaries (heavy solid and dashed lines) in the Brushy Basin Member of the Morrison Formation (from fig. 3) are also shown; note how lithofacies boundaries are unaffected by proximity to volcanic field.

MODES OF OCCURRENCE OF AUTHIGENIC ALBITE

The coincidence of the outer boundary of the albitic diagenetic mineral zone with the boundaries of the other diagenetic mineral zones led us to infer an alkaline, saline lake origin for the albite in the Brushy Basin Member of the Morrison Formation. This conformity remains one of the more compelling arguments for a low-temperature, syndepositional origin for the albite. Additional lines of evidence are provided by petrographic observations of tuff beds and sandstone beds interbedded with and underlying tuff beds of the central albitic zone.

Albitic Tuff Beds

Albitic tuff beds are characteristically siliceous, well indurated, and aphanitic and form prominent ledges in steep cliff exposures (fig. 5). The tuff beds are grayish green (5G 5/2) on both fresh and weathered surfaces, a color produced by authigenic clays. Local weathering of the pyrite in the tuff beds gives them a light-brown color (10YR 7/2). Locally, shard morphologies are preserved in albitic tuff beds (fig. 6). A distinctive spherulitic texture, diagnostic of authigenic analcime, preserved in some albitic tuff beds suggests an analcime precursor. The abundance of shard morphologies observed in thin sections of albitic tuff beds (fig. 6) contrasts with the relative paucity of shard morphologies in the analcime diagenetic mineral zone (Turner-Peterson, 1987). If the growth of spherulitic analcime crystals destroys shard morphologies, then the abundance of shard morphologies in the albitic tuff argues for direct replacement of volcanic glass or clinoptilolite by authigenic albite. Scarcity of the spherulitic analcime texture further suggests a lack of an analcime precursor, although the conversion of analcime to albite might have destroyed the spherulitic texture. Some albitic tuff beds exhibit the spherulitic analcime texture; here the albite must have formed from an analcime precursor.

Albite Cement In Sandstone Beds

Thin sandstone beds (from several centimeters to several meters thick), which represent fluvial episodes in the development of the alkaline, saline lake, are interbedded with albitic tuff beds. Authigenic albite in the sandstone is present as overgrowths on detrital plagioclase grains, as intergranular cement, and as a replacement (albitization) of detrital feldspar grains. No evidence for precursor cements was observed in any of the albite-cemented sandstone samples. Albite overgrowths on detrital plagioclase grains generally are clear, have few or no vacuoles, and are well defined by sharp, euhedral faces (fig. 7*A*). The albite overgrowths typically are twinned, and twin planes commonly are aligned with those of the parent detrital core. Microprobe analysis indicates that the overgrowths are less than An_1, almost pure $NaAlSi_3O_8$ (see table 1). The overgrowths may be as long as 50 μm; they compose less than 2 percent of the volume of the sandstone.

Albite intergranular cement has been identified optically, by microprobe, and by X-ray diffraction. It fills primary intergranular pores and is present as euhedral, tabular crystals (>5 μm long) that generally are clear, contain no vacuoles, and compose between 1 and 15 percent of the volume of the sandstone beds on the basis of point counts (see table 2). The interstitial albite generally is twinned and forms a network of intergrown crystals (figs. 7*B, C*). Similar to albite overgrowths, the pore-filling albite has an anorthite composition of less than An_1 (table 1).

Albitization of detrital plagioclase grains is widespread, and albitization of detrital potassium feldspar grains was observed in varying abundance. Microprobe (table 1) and X-ray diffraction (table 3) analyses confirm that detrital feldspar is albitized. Determination of the original composition of detrital feldspar was made by examining unaltered grains in sandstone distant from the albite diagenetic mineral zone (N.S. Fishman and P.L. Hansley, unpub. data, 1984; Fishman and Reynolds, 1986). These unaltered

Figure 5. Albite diagenetic mineral zone of the Brushy Basin Member of the Morrison Formation at Piedra River locality (fig. 1). Prominent ledges are predominantly stacked tuff beds that contains authigenic albite and silica. Some of the ledges are thin (<1 m) sandstone beds, which also are cemented with albite and silica.

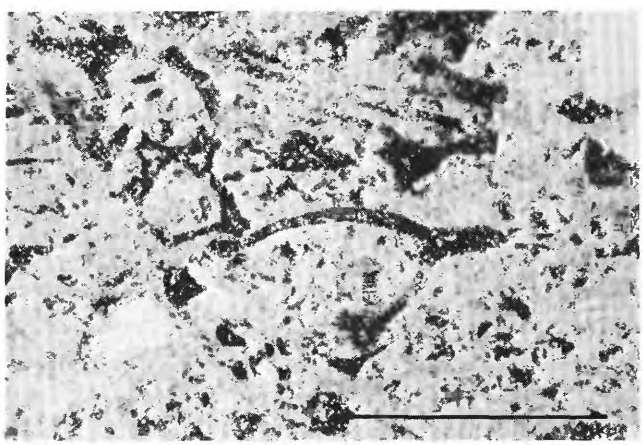


Figure 6. Photomicrograph of albitic tuff beds from Norwood Hill locality (fig. 1). Albite is in groundmass, whereas shards (dark, curved shapes) are filled mostly with iron oxide minerals, chalcedony, and minor albite. Note preservation of delicate shard morphologies. Bar is 0.40 mm long.

Table 2. Modal analyses of selected samples of sandstone interbedded with and underlying albitic tuffs in the Brushy Basin Member of the Morrison Formation, eastern Colorado Plateau.

[In volume percent. Sample localities are shown in figure 1. Abbreviations: Qtz, quartz; K-spar, potassium feldspar; Plag, plagioclase; Diss, dissolved grain; Rk. frag, rock fragments; QO+chal, quartz overgrowths+chalcedonic quartz; Alb, albite as overgrowths and pore-filling cement; Cal, calcite. Leaders (--) indicate not present]

	Detrital grains					Authigenic cement					Percent
Sample locality	Qtz	K-spar	Plag	Diss	Rk. frag	QO+chal	Alb	Cal	Clays	Void	minus-cement porosity
Norwood Hill	52	2	7	--	9	16	4	8	2	--	30
Norwood Hill	35	--	10	6	26	4	3	13	3	--	23
Norwood Hill	49	--	6	1	15	18	3	--	3	5	28
Norwood Hill	57	--	--	5	9	28	--	1	--	--	29
Norwood Hill	55	--	11	4	12	13	11	3	1	1	29
Durango	51	1	4	1	11	10	15	--	7	--	32
Durango	57	--	8	1	5	24	1	4	--	--	27
Durango	43	5	2	1	21	18	--	10	--	--	29
Piedra River	52	4	2	3	15	6	--	14	4	3	25
Piedra River	48	7	4	5	14	7	3	6	4	2	23
Piedra River	40	5	3	--	18	29	3	--	1	--	33
Piedra River	47	1	7	--	11	24	3	4	1	--	32
Piedra River	51	--	5	--	13	24	2	4	--	1	31

grains include microcline, orthoclase, sanidine, and calcic plagioclase (as much as 4.5 weight percent CaO, equivalent to An_{22}). Even the detrital plagioclase grains that are albitized commonly retain their original textural features (such as twinning characteristics). Some albitized grains were observed to have chessboard (checkerboard in appearance) twinning (fig. 7*D*), but these grains contain no obvious relicts of the original grains and no K_2O; thus, it is impossible to discern the composition of the chessboard grain prior to albitization. Grains of similar appearance in other rocks have been described as albitized potassium feldspar (Walker, 1984; Gold, 1987; Pittman, 1988; Saigal and others, 1988), and in the Morrison some detrital potassium feldspar grains may have been completely albitized, leaving only the chessboard texture. X-ray diffraction analyses reveal that the unit-cell parameters of the albitized grains are similar to those of authigenic albite reported from other sedimentary geological environments (table 3). In addition, on the basis of the separation of the 131-$1\bar{3}1$ peaks, the tetrahedral aluminium-silicon distribution of the albite in the Morrison is highly ordered, similar to that of authigenic albite in other sedimentary rocks (Kastner and Waldbaum, 1968; Kastner, 1971), with the exception of authigenic albite in the Green River Formation (Desborough, 1975).

Point counts of albite-cemented sandstone beds reveal high minus-cement porosity in samples where albite and quartz are the dominant cements (table 2). The minus-cement porosity ranges from 29 to 33 percent, almost as high

Table 3. Unit-cell parameters for authigenic albite from the Brushy Basin Member of the Morrison Formation and from other sedimentary rocks.

[Standard deviation ($\times10^{-4}$) is given in parentheses. Cell dimensions a, b, and c are in angstroms, and lattice angles α, β, and γ are in degrees. Unit-cell volume (v) is in cubic angstroms. The d_{131}–$d_{1\bar{3}1}$ separation is in angstroms]

Sample locality	a	b	c	α	β	γ	V	d_{131}–$d_{1\bar{3}1}$
Norwood Hill[1]	8.140(2)	12.796(3)	7.159(2)	94.220(3)	116.62(2)	87.93(3)	664.9(2)	1.15
Greece[2]	8.138(14)	12.788(13)	7.157(8)	94.230(13)	116.61(9)	87.81(13)	664.1(20)	1.14
Crete[2]	8.135(19)	12.781(15)	7.156(8)	94.206(14)	116.58(12)	87.82(16)	663.6(26)	1.14
Greece[3]	8.137(21)	12.785(18)	7.158(13)	94.170(25)	116.61(14)	87.81(25)	664.0(32)	1.13
Wyoming[4]	8.164(9)	12.804(6)	7.143(4)	93.923(4)	116.58(3)	88.86(4)	666.2(6)	1.46

[1]Albitized detrital plagioclase (this study).
[2]Kastner and Waldbaum (1968).
[3]Kastner (1971).
[4]Desborough (1975).

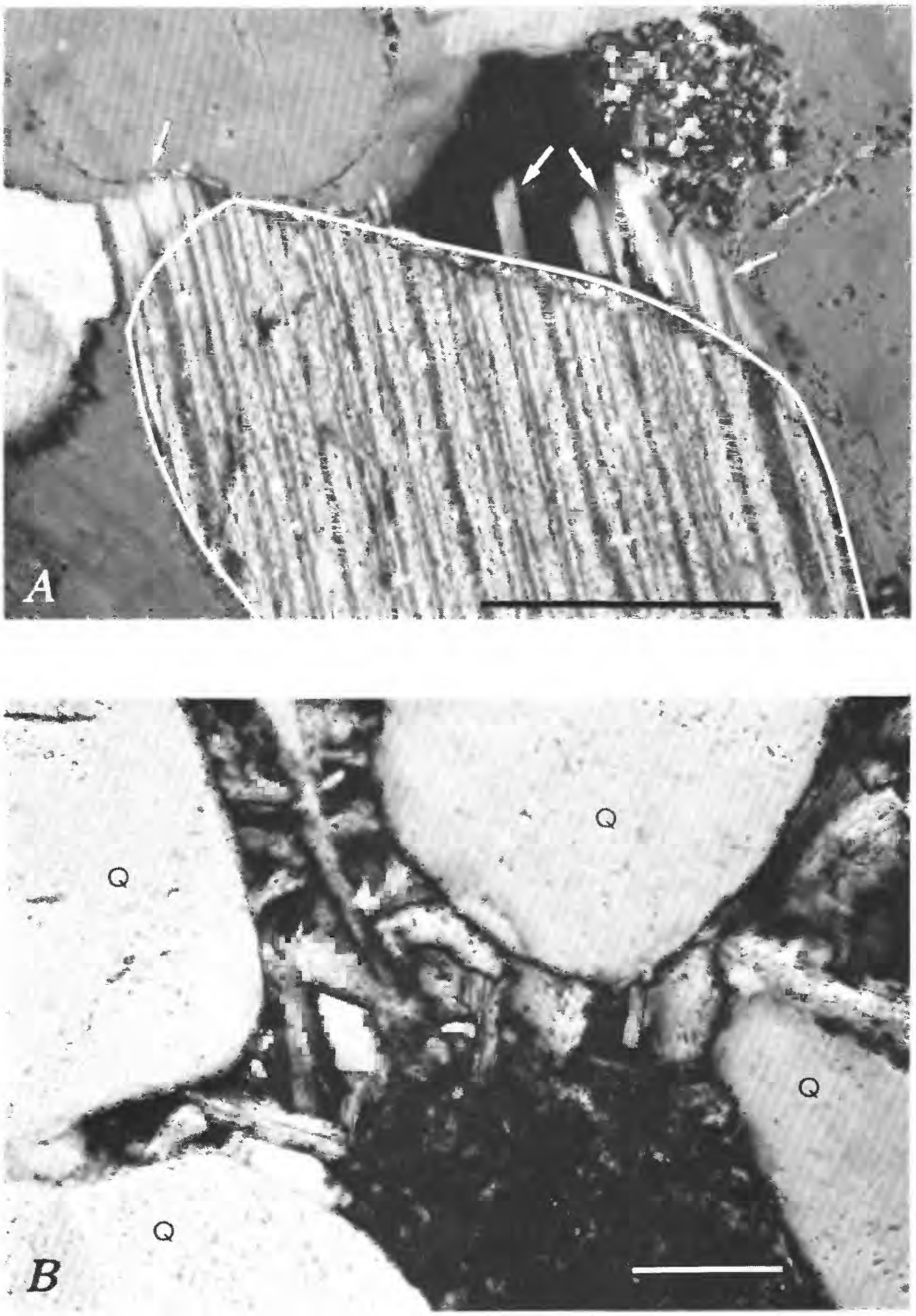
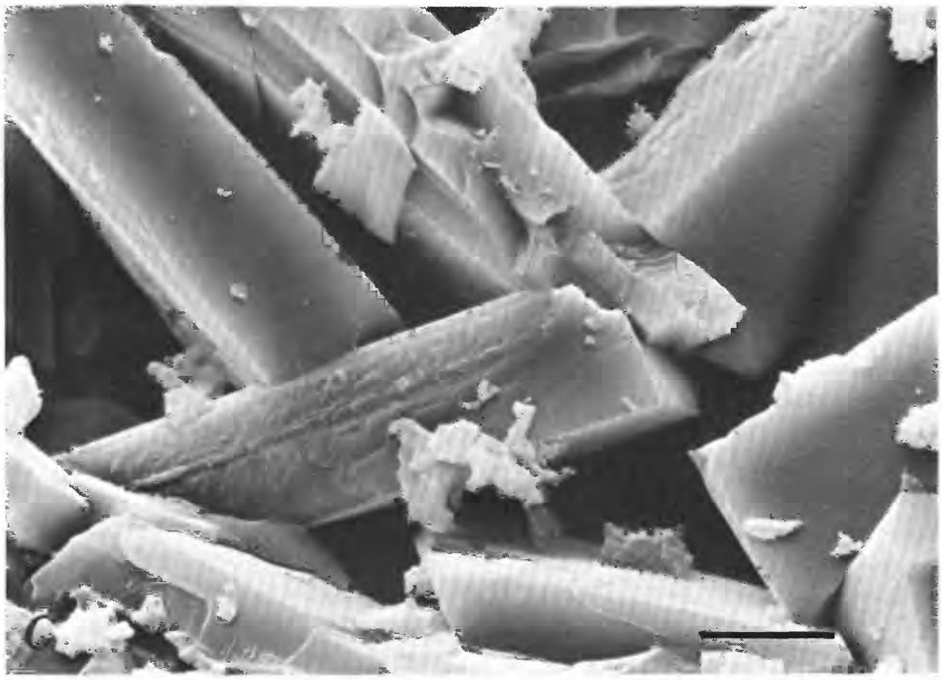
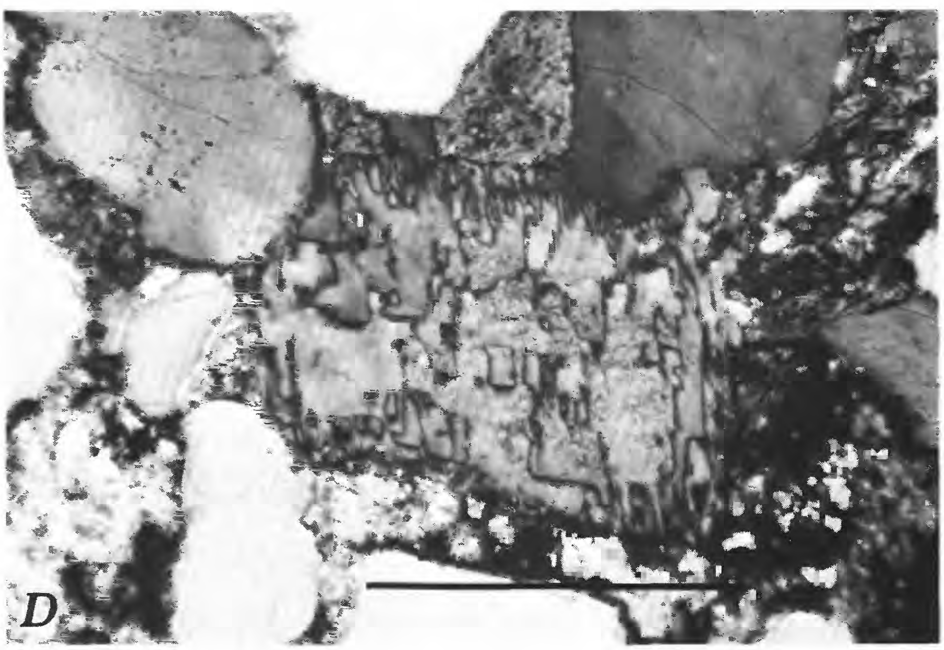


Figure 7 (above and facing page). Various types of authigenic albite in sandstone interbedded with tuff in the albite diagenetic mineral zone of the Brushy Basin Member of the Morrison Formation. See figure 1 for sample localities. *A*, Photomicrograph of albitized detrital plagioclase (outlined area) with large twinned albite overgrowth (arrows). Durango locality. Bar is 0.13 mm long. *B*, Photomicrograph of large, twinned albite laths filling large primary pores between detrital quartz grains (Q). Norwood Hill locality. Bar is 0.26 mm long. *C*, Scanning electron microscope photograph of large, pore-filling albite laths in sandstone enclosed within a sequence of albitic tuff. Norwood Hill locality. Bar is 5 μm long. *D*, Photomicrograph of albitized detrital potassium feldspar(?) grain displaying chessboard-twinning texture. Textural features of this grain are similar to those described by Walker (1984) for albitized potassium feldspar; however, no relicts of potassium feldspar are in the grain. Piedra River locality. Bar is 0.13 mm long.





as primary porosity for medium to poorly sorted, fine- to medium-grained sandstone beds (Beard and Weyl, 1973). The high minus-cement porosity indicates that the albite and quartz cements filled available pore space before significant reduction in primary porosity, which suggests early cementation. The character of grain contacts corroborates early cementation; floating grains are common and grain contacts are chiefly point to point.

Sandstone beds that contain carbonate cements (ferroan and nonferroan) and minor albite and quartz have somewhat lower minus-cement porosity (table 2). The calcite cement is paragenetically later than albite and quartz; thus some compaction occurred after introduction of the early albite and quartz cements and before precipitation of calcite.

DISCUSSION

Because high temperature is commonly thought to be required for formation of albite in sedimentary rocks, the albitic tuff beds and albite-cemented sandstone beds in the Brushy Basin Member were considered in light of the thermal history of the region. Several lines of evidence preclude a high-temperature (>85°C) origin for the albite in this study. First, the vitrinite reflectance data indicate that the Morrison Formation never was subjected to temperatures much greater than 70°C, either as a result of burial or from local igneous sources, including the San Juan volcanic field. Moreover, if the authigenic albite had formed in response to heat caused by deeper burial, the boundary of the albite diagenetic mineral zone would not coincide with the other boundaries of diagenetic mineral zones in the alkaline, saline-lake deposits (fig. 3). Similarly, if hot fluids from the San Juan volcanic field or other igneous sources had been responsible for albite formation, the albite zone would have formed a halo around the sources of hot fluids, which it does not (fig. 4).

The petrographic evidence also constrains the origin of the albite. Minus-cement porosity in the albite-cemented sandstone beds is almost as high as that expected for initial primary porosity of the sandstone beds, which suggests an early diagenetic origin for the albite. To infer a high-temperature origin for this albite would imply that high primary porosity was preserved through a 70–100-m.y. burial history, from deposition of the Morrison Formation until either the Laramide orogeny (for an origin by burial diagenesis) or batholithic activity associated with the San Juan volcanic field (for generation of hot fluids). The hypothesis that a precursor cement filled primary pore spaces and was subsequently completely replaced by albite and quartz, leaving no relicts, is possible but not probable. If this had occurred, the restriction of albite overgrowths to detrital plagioclase grains would be difficult to explain. This selectivity is readily explained if it is assumed, as it is here, that albite precipitated directly as a primary cement because albite overgrowths on plagioclase grains are common in the rock record. Thus, the contrived scenarios required to support a late, hot origin for the authigenic albite, such as vanished precursors or maintenance of high primary porosity over millions of years, highlight the difficulties in proposing such an origin.

An early, low-temperature, syndepositional origin for the albite in both the albitic tuff beds and albite-cemented sandstone beds in the Brushy Basin Member readily accommodates all of the observations. In the tuff beds the conformity of the outer boundary of the albite diagenetic mineral zone with boundaries between other diagenetic mineral zones (fig. 3) implies that all the zones formed during early diagenesis in alkaline, saline lake sediments. We infer that the albite in ancient Lake T'oo'dichi' formed in the central part of the lake basin, in response to lateral hydrogeochemical gradients in the pore waters. These same hydrogeochemical gradients caused the volcanic ash to alter to authigenic clays, zeolites, and feldspar in the other diagenetic mineral zones (fig. 3); such alterations are thought to occur between 1,000 and 500,000 years after deposition in alkaline, saline lakes (Hay, 1966, 1986; Sheppard and Gude, 1968; Taylor and Surdam, 1981), and it is reasonable to infer a similar time span for precipitation of the albite.

Albite cement in sandstone beds that underlie the albitic tuff beds in Lake T'oo'dichi' probably formed by the downward flux of alkaline, saline pore water. Density, as well as elevation, is a factor in determining hydrologic head. In modern alkaline, saline lakes, the increased density of lake water due to evaporative concentration can create a net downward flux of waters into underlying sediments (Hardt and others, 1972; Friedman and others, 1982). A density-driven, downward movement of pore waters from the sediments of Lake T'oo'dichi' is suggested by the presence of albite-cemented sandstone beds underlying albitic tuff beds; this mechanism of albite authigenesis is consistent with the nonmarine volcaniclastic model for albite formation in sandstone beds advanced by Kastner and Siever (1979).

Although we propose a low-temperature, syngenetic origin for the albite, the temperature of formation may not have been as low as 25°C because the behavior of alkaline, saline lakes as solar ponds can result in water temperatures as high as 56°C (Milton and Eugster 1959). The warm lake water may have infiltrated below the sediment-water interface during albite precipitation and may have helped to overcome any kinetic inhibition of the reaction to form albite. Because we have no way of knowing whether Lake T'oo'dichi' behaved as a solar pond, we can only postulate the extant temperatures during albite formation. To include the possibility of warmer lake water temperatures, in line with an inferred arid to semi-arid paleoclimate (Turner-Peterson, 1987), we postulate temperatures of albite formation in sediments of Lake T'oo'dichi' between 25°C and 60°C.

Although the interpretation of albitic tuff beds in the context of an alkaline, saline lake environment best fits all of our data and observations, albite is not commonly reported from other alkaline, saline lakes. Authigenic albite has been reported from tuff beds in the Eocene Green River Formation (Moore, 1950; Milton, 1957; Desborough, 1975; Cole, 1985) and from middle Miocene tuffaceous lacustrine deposits from Boron, California (Williamson, 1987), but not from Pleistocene Lake Tecopa, California (Sheppard and Gude, 1968), or from the Pliocene Big Sandy Formation, Arizona (Sheppard and Gude, 1973). Albite, an anhydrous mineral, is thermodynamically favored over analcime, a hydrous mineral, under conditions of increased salinity or decreased activity of water (Hay, 1966; Surdam and Sheppard, 1978). Also, assuming a favorable Na^+/K^+ ratio, the increase in activity of silica with an increase in pH favors albite with respect to analcime (Garrels and Christ, 1965). These factors may account for the formation of albite in tuff beds of the central diagenetic mineral zone of Lake T'oo'dichi'. Similar conditions may account for the presence of authigenic albite in lacustrine rocks of both the Green River Formation and the middle Miocene deposits near Boron, California.

CONCLUSIONS

1. Albitic tuff beds and albite-cemented sandstone beds, which are interbedded with and underlie the tuff beds, are restricted to a zone in the central part of Lake T'oo'dichi', an ancient alkaline, saline lake in the Brushy Basin Member of the Jurassic Morrison Formation, Colorado Plateau.

2. The spatial relationship between the albite zone and other diagenetic mineral zones in the lake deposits resulted from differential alteration of silicic volcanic ash in response to lateral hydrogeochemical gradients that developed in Lake T'oo'dichi'.

3. Petrographic observations indicate an early diagenetic and, therefore, low-temperature origin for the authigenic albite cement in sandstone beds. Vitrinite-reflectance data corroborate a low-temperature origin for albite because the tuff beds and sandstone beds were never subjected to temperatures in excess of about 70°C.

4. Albite-cemented sandstone beds that underlie the albitic tuff beds in Lake T'oo'dichi' provide evidence for downward movement of pore water similar to that which occurs in modern lakes characterized by dense brines.

5. Because Lake T'oo'dichi' may have behaved as a solar pond, we must allow for somewhat elevated temperatures (>25°C) for lake water and possibly pore water in the underlying sediments. We therefore postulate a temperature between 25°C and 60°C for albite formation.

6. Our results indicate that pore-water chemistry can facilitate formation of authigenic albite at temperatures well below 85°C. This, in turn, significantly expands the temperature range in which authigenic albite can form in sedimentary rocks and thus limits the use of albite as a precise geothermometer.

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Published in the Central Region, Denver, Colorado
Manuscript approved for publication March 18, 1994
Edited by Judith Stoeser
Graphics and photocomposition by Mari L. Kauffmann
Tables typeset by Judith Stoeser

☆U.S. GOVERNMENT PRINTING OFFICE: 1995-673-046/86086

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