MINERALOGICAL MAGAZINE, MARCH 1986, VOL. 50, PP. 75-84

Composition and structural state of coexisting feldspars, Salton Sea geothermal field

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ABSTRACT. Active metamorphism of fine grained sandstone in the *c.*16000 year old Salton Sea geothermal system has produced a suite of chemically equilibrated coexisting authigenic alkali feldspars and re-equilibrated detrital feldspars in the 250-360 °C temperature range. At *c.*335 °C the average compositions, 2 Vs, and (t_1o+t_1m) and Z ordering parameters of coexisting authigenic feldspars are $[Or_{0.52}Ab_{97.40}An_{2.08}$, $2V_x = 91.3 \pm 4.8$, $(t_1o+t_1m) = 0.89 \pm 0.05$, $Z = 0.79 \pm 0.09]$, and $[Or_{94.42}Ab_{5.10}An_{0.48}$, $2V_x = 70$, $(t_1o+t_1m) = 0.90$, $Z = 0.81]$. At *c.*360 °C authigenic albite becomes more An-rich and less ordered $[Or_{1.21}Ab_{92.83}An_{5.97}$, $2V_x = 87.5 \pm 3.4$, $(t_1o+t_1m) = 0.85 \pm 0.03$, $Z = 0.70 \pm 0.07]$ and K-feldspar is no longer stable. Detrital plagioclase (An up to 40%) is preserved metastably to temperatures up to *c.*190 °C in strongly carbonate-cemented sandstone which forms part of a geothermally produced permeability cap. It undergoes rapid alkali exchange at temperatures near 200 °C, and by 250 °C no plagioclase with An-content over 12% is observed. At > 250 °C authigenic and most detrital alkali feldspar compositions are in excellent agreement with the Bachinski and Muller (1971) microcline-low-albite solvus.

KEYWORDS: feldspar, sandstone, metamorphism, Salton Sea, California, USA.

INVESTIGATION of geothermally altered sandstone from the Elmore 1 borehole (fig. 1 of McDowell and Paces, 1985) in the Salton Sea geothermal field (McDowell and Elders, 1980, 1983) has shown that two authigenic alkali feldspars coexist in apparent equilibrium in the temperature range 250-360 °C, based on temperatures measured in the geothermal borehole. The purpose of this paper is to discuss the chemistry of both authigenic and re-equilibrated detrital feldspars, compare the coexisting feldspar compositions with experimentally determined solvii, and summarize the small amount of structural state data thus far obtained on the neoformed, authigenic feldspars.

Background. The active geothermal system is operating at depths of 350 m or more in a thick fluvial-deltaic section of fine-grained sandstone, siltstone, and mudstone that makes up the delta of the ancestral Colorado River system (Muffler and Doe, 1968; Muffler and White, 1969; van de Kamp, 1973). Sandstone from the least altered parts of the geothermal system is texturally, chemically, and mineralogically similar to sand from the modern Colorado River Delta. The initial major clastic components of the least altered sandstone are 56-65% quartz, 3-9% plagioclase, and 6-10% alkalic feldspar (in wt. %), based on quantitative X-ray diffraction analysis of sandstone from the shallow parts of nearby borehole Elmore 3. These values are very similar to modern Colorado River sands (van de Kamp, 1973) and are also similar to geothermally altered sandstone from the Cerro Prieto geothermal field (Lyons and van de Kamp, 1980) located on the south side of the Colorado Delta in Mexico, some 85 km south of the Salton Sea field. This stongly suggests that within the ancient delta complex the initial sandstone mineralogy can be considered to be quite homogeneous. No arkosic (30-40% total feldspar) sandstone typical of local basin-margin sources (van de Kamp, 1973) was noted in Elmore 1, and such sandstone is exceedingly rare in any of the wells examined thus far from the Salton Sea field. The original detrital quartz and feldspar grains are subangular to subround, moderately to well sorted, and average 0.13 ± 0.05 mm in size in sandstone. The maximum grain size is near 0.25 mm.

The active geothermal system has created its own self-sealing permeability cap in the form of a zone of strongly carbonate-cemented sandstone at depths of 475 m or less in the vicinity of Elmore 1. The break between this low porosity cap and the deeper, porous reservoir sandstone is very abrupt, and marks an exceedingly important boundary within the geothermal system. Chemically unreacted detrital minerals, including layer silicates such as chlorite, biotite, and muscovite (McDowell and Elders, 1983), plagioclase and alkali feldspar have been preserved to temperatures up to about 200 °C. The abrupt increase in porosity on increasing temperature and depth has allowed fluid access to the detrital phases and initiated reactions involving these minerals. Below the carbonate cap sandstone, porosities are typically 10–20 % and fluid access to all mineral phases is complete.

Geothermal alteration of sandstone has produced a sequence of metamorphic zones ranging from clay-carbonate facies in the carbonate cap ($\leqslant$ 190 °C, $\leqslant$ 439 m depth) through chlorite–calcite (190–325 °C, 439–1135 m) and biotite–actinolite (325–360 °C, 1135–2120 m) zones to an andradite garnet ($\geqslant$ 360 °C, $\geqslant$ 2120 m) zone of greenschist facies metamorphism. Authigenic albite and K-feldspar coexist in the 622 to 2120 m interval (251–360 °C) through the chlorite and biotite zones. On appearance of andradite garnet at the base of the borehole, all K-feldspar disappears and albite remains the only stable feldspar. In the same depth/temperature range the detrital feldspar grains interact with the fluid phase with respect to Na, K, and Ca exchange as well as Al–Si ordering. The authigenic feldspars are texturally distinct, forming either separate crystals in the pore spaces or overgrowths on pre-existing phases, and have formed as newly created minerals from the pervasive fluid phase. The separate crystals in particular have formed a new structure unaffected by any pre-existing structure. Authigenic overgrowths are presumably equilibrated with respect to alkali exchange, but their Al–Si distribution could be affected by that of the detrital feldspar on which they have nucleated. The detrital grains have clearly inherited both compositions and Al–Si ordering from their original source. Since alkali exchange appears to be considerably faster than Al–Si ordering (Smith and Parsons, 1974), the detrital grains can be expected to show more compositional and structural variability.

The age of the geothermal system is about 16 000 years (Kistler and Obradovich, in Muffler and White, 1969), based on a whole-rock K–Ar age on obsidian from Obsidian Butte (fig. 1 of McDowell and Paces, 1985). Rhyolitic and basaltic volcanic material (Robinson *et al.*, 1976) has been observed in a number of wells, presumably in the form of thin intrusive bodies, and the Elmore 1 well bottomed in a rhyolitic unit that produced local contact metamorphic effects in sandstone. Both the volcanic and contact metamorphic rocks have been altered to mineral assemblages compatible with those observed in adjacent geothermally altered sandstone. Thus volcanism clearly predated and is presumed to have marked the initiation of the geothermal system. The geothermal system may therefore be thought of as a natural, long-time hydrothermal experiment in which authigenic feldspars had time to reach both alkali and possibly Al–Si equilibrium.

Analytical techniques. Feldspars were analysed by a variety of techniques. Complete and partial (Na + Ca + K) wavelength dispersive analyses (WDA) were made using the automated MAC5 microprobe at CalTech, and energy dispersive analyses (EDA) were also made on the same microprobe using a Tracor 880 system. In addition, EDA analyses were made at Michigan Tech. using a Kevex 5100 system on a MAC 400 microprobe located in the Institute of Mineral Research. All analyses were run at 15 kV using 10–15 μm spot sizes, specimen currents of 0.005 μa or less, and 100 sec counting times for EDA analyses and variable times (typically 15 to 90 sec) for WDA analyses. The same grains were reanalysed using the various instruments, and in general, agreement was excellent with EDA analyses showing two to three times the scatter of WDS analyses. Analyses for K-rich feldspars low in Na_2O (less than 0·4 %) were particularly difficult, and in this respect the Tracor instrument was distinctly superior to the Kevex instrument in that the former had a lower detection limit and behaved in a regular and predictable manner at low Na concentrations so that analyses could be corrected in a rational way if necessary.

Feldspar 2V measurements were made using extinction techniques, due to the small grain size of many of the authigenic feldspars. A 4-axis Leitz universal stage was used.

Authigenic feldspars. Neoformed, authigenic feldspar is rare in the geothermally altered sandstones. Clear overgrowths of albite or K-feldspar, with straight contacts against adjacent pore space, are most commonly observed in the 622–1000 m interval, and sporadically observed to depths of 1750 m. Small neoformed single crystals (fig. 1) which have formed in the pore spaces of sandstone occur sporadically at depths of 622 m or more, and occasionally aggregates of such grains are observed (fig. 1). Deeper in the well it is rarely possible to distinguish overgrowth from the original detrital grain, and aggregates of authigenic feldspar in the pore spaces give way to small grains which partially fill pore spaces and wrap around previously formed grains. In a general textural sense, the disappearance of detectable overgrowths and formation of large pore-filling grains suggests a gradual recrystallization and homogenization of all feldspar on increasing temperature and depth in the geothermal system.

Authigenic K-feldspar (fig. 1*B*, *C*, *D*) is first observed in pore spaces at 622 m as clusters of turbid subidiomorphic to xenomorphic blades and tablets up to 0.02 mm long filled with minute subparallel ovoid fluid inclusions. This is the dominant form of neoformed authigenic K-feldspar visible in thin section, although rare inclusion-free idiomorphic tablets are observed. Occasional thin K-feldspar overgrowths are also observed, and these are invariably clear and inclusion free. On increasing depth K-feldspar becomes less turbid, the fluid inclusions less numerous, and the grain size coarsens until large cement-like patches of inclusion-free K-feldspar are observed.

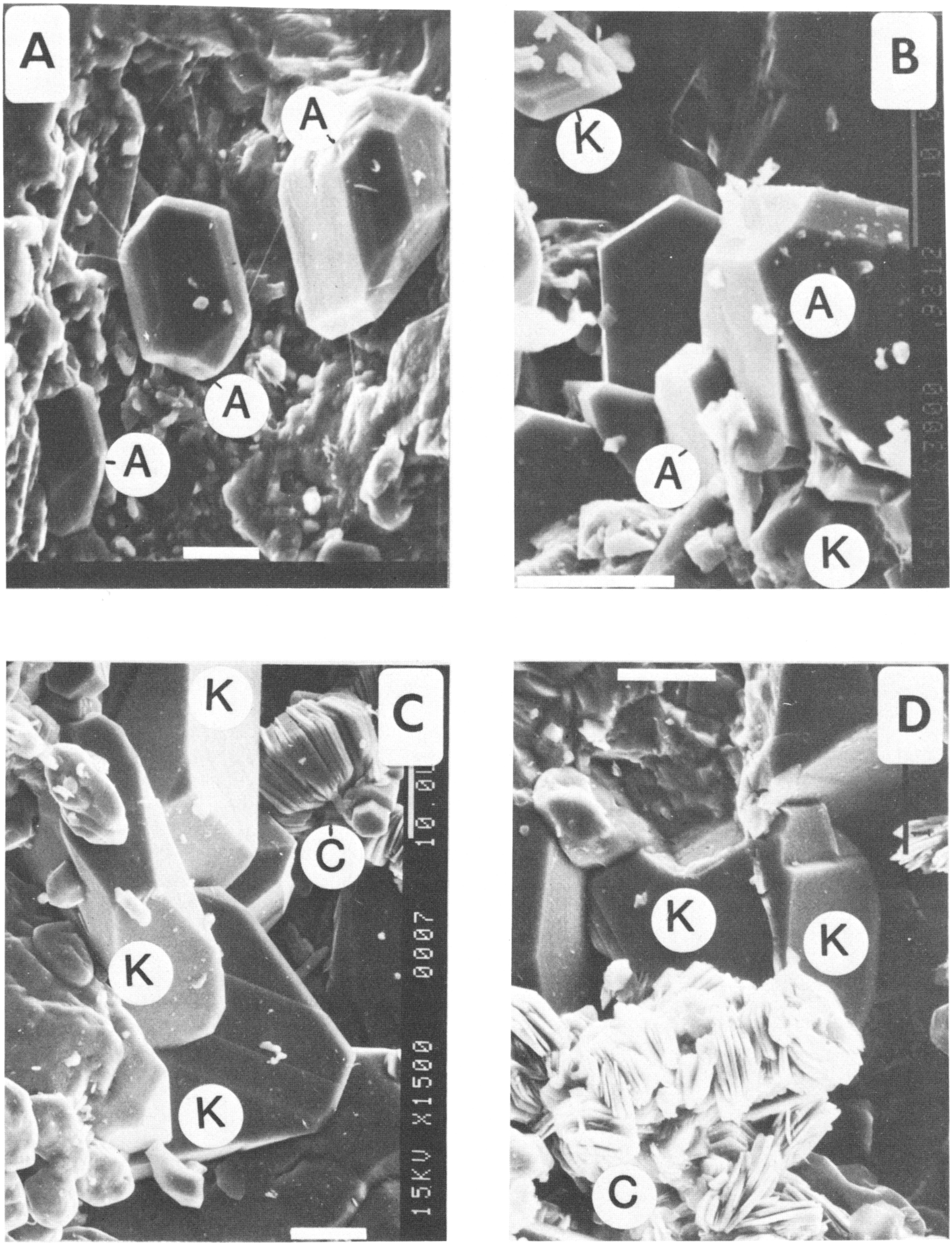

FIG. 1. SEM photographs of geothermal authigenic feldspars, white bar = 10 μm in all photographs: (*A*) Authigenic albite (A) growing on corroded detrital K-feldspar, rare hairs of actinolite visible, from Elmore 1, biotite zone, 325 °C+; (*B*) Authigenic albite (A) and K-feldspar (K), from IID2, 1536 m depth, 328 °C; (*C*) Authigenic K-feldspar (K) and chlorite (C), from River Ranch 1, 2016 m depth, 314 °C; and (*D*) Authigenic K-feldspar (K) [note penetration twin] and chlorite (C), same location as (*C*).

Most authigenic geothermal K-feldspar contains fine polysynthetic twinning, in contrast to the lack of such twinning in authigenic feldspars (Kastner, 1971). The dominant twin types observed are Albite or Carlsbad-Albite combinations, but Pericline and Carlsbad twins are also noted, and SEM investigations suggest that Baveno twins are also present. Where Albite and Pericline twins are both present in the same grain, the typical *M*-type microcline grid twinning with spindle-shaped twin lamellae terminations is not observed. Instead, adjacent areas in the same grain consist of one twin type with parallel-sided lamellae, and Albite-Pericline twin intersections tend to be blunt or slightly tapered, but not spindle-shaped. The twin pattern resembles the *T*-type combinations described in anorthoclase by Smith and MacKenzie (1958) which were thought to have formed within a triclinic structure. They are also quite similar to twins described by Flehmig (1977) in K-feldspar produced experimentally at low temperatures from gels aged in aqueous solutions with relatively high pH and alkali chloride contents.

Authigenic albite (fig. 1*A*, *B*) occurs as both overgrowths on plagioclase, and rarely alkali feldspar and quartz, as well as aggregates of twinned, 0.03 mm, subidiomorphic to idiomorphic grains nestled in portions of pores at all depths of 622 m or more. The albite is more abundant, distinctly more idiomorphic, rarely turbid, and contains fewer inclusions than authigenic K-feldspar. Well terminated tablets and blades are occasionally noted growing into pores perpendicular to the surfaces of overgrowths (fig. 1). Pore-filling aggregates of single albite crystals are particularly abundant in the 1762–1823 m depth interval, where they make up 12.4 ± 6.0 % of sandstone by volume. Textural relationships suggest a time sequence of growth from open skeletal crystals through slightly porous grains to grains filled with minute void inclusions that give the albite a speckled appearance. This sequence mimics the overall sequence observed at increasing depth in which overgrowths gradually become unidentifiable and pore-filling albite grains, as in the case of K-feldspar, form at increasing temperature. All authigenic albite is strongly and coarsely twinned on the Albite or Albite–Carlsbad twin laws.

The compositions of coexisting authigenic albite and K-feldspar are summarised in Table I and figs. 2 and 4. Only grains that could be unambiguously assigned to the neoformed authigenic category have been included in this table. The intra- and intercrystalline homogeneity of the various grains strongly suggests that these analyses represent a good estimate of equilibrium coexisting feldspars in the 250 to 360 °C temperature interval. Within the scatter of the analyses, all authigenic albites and K-feldspars have uniform compositions as indicated by the average values of all analyses in the table.

In sandstone at 2155 m depth (361 °C) no K-feldspar is observed and andradite garnet becomes a major mineral phase. Garnet-free sandstone from the same and shallower depth intervals contains both K-feldspar and albite in the form of authigenic cement and identifiable grains of detrital origin. The total feldspar content of garnet-free and garnet-bearing sandstone is approximately the same. It thus appears that, when garnet became stable, all K-feldspar, including former large detrital grains, was replaced by albite. While

TABLE I. AVERAGE COMPOSITION OF AUTHIGENIC FELDSPARS

DEPTH(m)	TEMP(°C)	Or	Ab	An	# Anal.	$2V_x$	t_1o+t_1m	Z
ALBITE (COEXISTS WITH K-FELD)								
1143	329	0.75±.34	96.83±.66	2.40±.56	6-E*	86,90		
1280	339	0.43±.25	97.66±.61	1.90±.30	4-E	86,90,94,98		
1369	344	0.35±.06	97.70±.29		4-W			
avg. of above		0.52±.22	97.40±.49	2.08±.28	14	91.3±4.8	0.89±.05	0.79±.09
ALBITE (NO COEXISTING K-FELD)								
2155	361	1.21±.76	92.83±1.61	5.97±1.48	11-W	84,86,88,92 Avg.87 .5±3.4	0.85±.03	0.70±.07
K-FELD (COEXISTS WITH ALBITE)								
622	251	95.85±.59	4.09±.57	0.05±.04	3-E			
1143	329	94.41±2.74	5.10±2.64	0.48±.28	6-E	70	0.90	0.81
1600	353	94.3	5.2	0.5	1-E			

IN MOL %. t_1o+t_1m from Figure 5, Z from Equation 2. *E=EDS, W=WDS analyses.

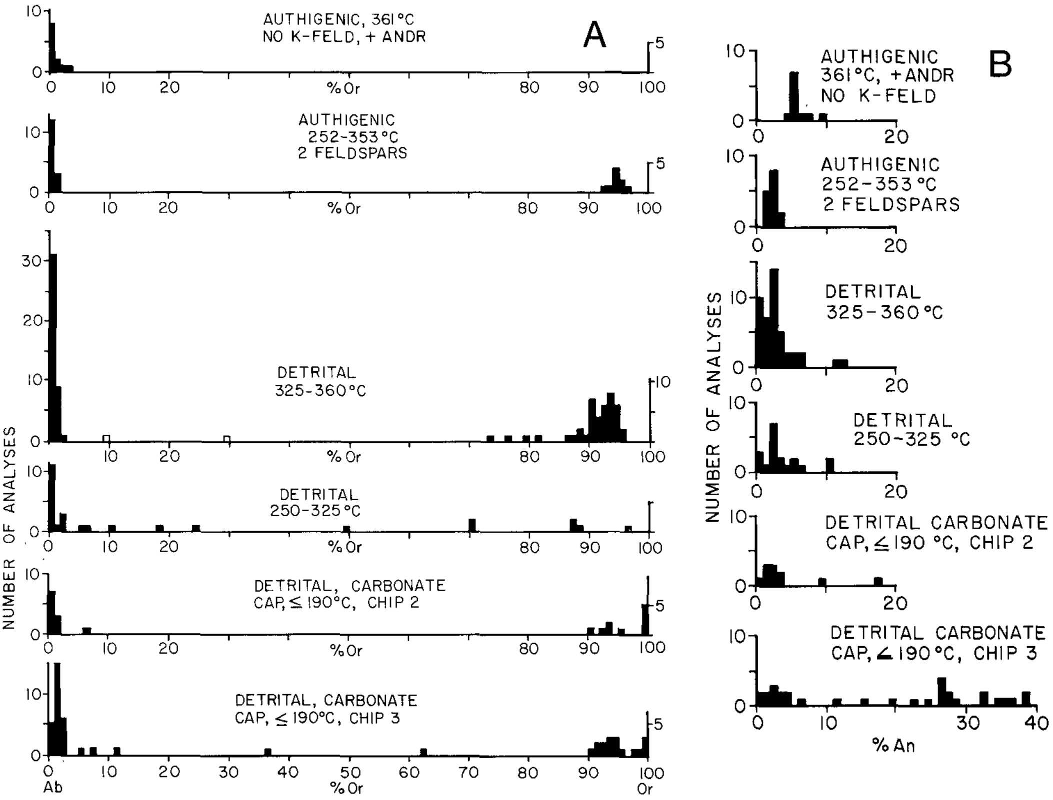

FIG. 2. Histograms of authigenic and detrital feldspar compositions (mol. % in Or-Ab-An system) for selected temperatures (°C) and feldspar types as indicated. A Composition along Ab-Or join; B Composition along Ab-An join.

detrital *vs.* pore-filling quartz, feldspar, and other phases may still be recognized in garnet-free sandstone, in garnet-bearing sandstone this distinction is poorly defined and the rock has a more equigranular hornfelsic texture. The albite in garnet-bearing sandstone ranges from clear, polygonal grains with abundant epidote and some biotite inclusions, to slightly clouded more irregular shaped grains with few inclusions. It is suggested that the more polygonal grains formed by complete replacement of K-feldspar, while the more irregular grains represent former plagioclase grains at lower temperature.

The composition of albite in garnetiferous sandstone $Or_{1.2}Al_{92.8}An_{6.0}$ (Table I, fig. 2) is quite uniform and distinctly more calcic than that of albite which coexists with K-feldspar at lower temperatures. Because of its distinct composition and pervasive evidence for recrystallization, all albite in the garnet-bearing sandstone is presumed to be authigenic. The composition of this plagioclase locates it within, but near the sodic limit of the peristerite field. No evidence of a second, more calcic plagioclase has yet been detected, and the albite is very homogeneous. If this albite is compositionally equilibrated, its higher An-content suggests that the sodic limit of the peristerite field lies at compositions more An-rich than An_6 at 360 °C. This in turn suggests, in light of the more sodic (An_{0-3}) albites that coexist with oligoclase in peristerites at higher temperature (Smith, 1983), that the sodic limit of the 'strain-free' peristerite region becomes more calcic on decreasing temperature. This favours the concept of a binary loop rather than a solvus. It is entirely possible that continued investigation of this geothermal system will provide information on the calcic limit of the peristerite region, especially if deeper, hotter samples become available.

Detrital feldspars. In carbonate cemented sandstone of boreholes Elmore 1 and 3 at temperatures of 200 °C or less, detrital feldspar shows slight to moderate embayment and replacement by carbonate cement. Many feldspars show straight to smoothly curved original detrital margins on part of a grain, and considerable embayment by carbonate on other parts of the same grain margin. Any visible compositional zoning in feldspar is independent of carbonate embayment boundaries, suggesting relatively little internal compositional change of the feldspar during marginal solution and carbonate deposition at low temperatures. Occasional, highly embayed, almost skeletal feldspar grains were observed, and these seem to be dominated by the more calcic plagioclase or rare coarse perthitic alkali feldspar. Feldspar is usually significantly more angular than quartz, and often rectangular feldspar grains with straight margins and sharp corners are noted which have the appearance of unmodified volcanic phenocrysts. Where these grains are broken, embayment is commonly observed along the broken surface.

At higher temperatures the detrital feldspar grains are clear, show little sericitic alteration, and are not strongly compositionally zoned. Occasional turbid plagioclase and alkalic feldspar grains are observed. The alkali feldspar is rarely perthitic, and if so, the perthite is usually very fine in scale. Microcline is uncommon, and most alkali feldspar is orthoclase with uniform to mottled extinction. Features characteristic of plutonic rocks, such as coarse perthite, myrmekite or graphic textures, microcline grid twinning, and sericitic alteration are rare except in cuttings in a single sample interval (460–464 m) in Elmore 3, where up to a third of the feldspars show such features.

The compositions of detrital feldspar from very low porosity (less than 5 %) carbonate cemented sandstone at 439 m ($\leqslant$ 190 °C) Elmore 1 have been summarized in figs. 2 (chip 3) and 3. The lack of evidence of alteration of these feldspars, as well as detrital layer silicate grains (McDowell and Elders, 1983), suggests that these compositions might represent unmodified detrital material preserved metastably to temperatures near 190 °C by lack of fluid access to the detrital grains.

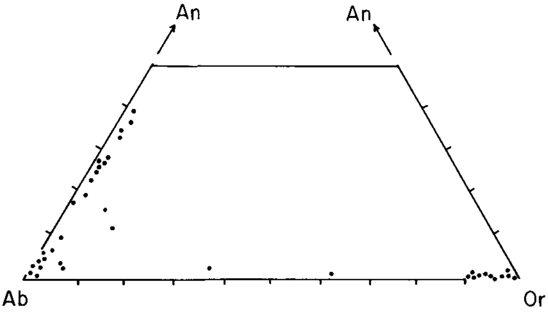

FIG. 3. Composition of all detrital feldspars at 439 m depth (about 190 °C) in carbonate-cemented sandstone, in mol. %.

Detrital plagioclase compositions in the carbonate cap sandstone are distinctly more anorthitic than those observed deeper in the geothermal system. The detrital plagioclase in chip 3 shows a broad spread of An-contents up to 39 % An (fig. 2*B*), and Or-contents that are slightly greater than those of authigenic albite at temperatures over 250 °C (fig. 2*A*). The few grains with compositions in the peristerite region also have a significant Or-content. The contrast between detrital plagioclase in this chip and detrital-sized plagioclase at temperatures over 250 °C is distinct. The complete disappearance of all detrital plagioclase with An-contents greater than 12 % by 250 °C strongly suggests relatively rapid re-equilibration of plagioclase to produce compositions that approach that of authigenic albite in the time available for reaction. Thus detrital plagioclase at > 250 °C, which in texture and general appearance is identical to plagioclase at 190 °C in highly cemented sandstone, is apparently almost completely exchanged with regard to Na, Ca, and thus probably Al and Si.

The detrital plagioclase compositions in chip 2 at about 190 °C show a restricted compositional range with maxima similar in both An- and Or-content to detrital or authigenic plagioclase at temperatures over 250 °C. While this may simply reflect a different original detrital plagioclase population, the fact that chip 2 has a distinctly higher porosity (about 10 %) than chip 3 from similar temperatures may indicate that plagioclase from chip 2 has undergone significant re-equilibration with the geothermal fluid phase. If so, this suggests very rapid transformation of the relatively large (about 0·1 mm) detrital plagioclase grains once enough carbonate cement is removed to allow sufficient fluid access. Unfortunately, no sandstone cuttings are available in Elmore 1 between 439 m (190°) and 22 m (251°) depth, so that the details of this transformation are unavailable in this well.

The composition of most detrital K-feldspar in the carbonate cap is grossly similar to both detrital K-feldspar in the 325–360 °C range or authigenic K-feldspar. However, the detrital K-feldspar from both chips 2 and 3 at about 190 °C show a bimodal compositional distribution (fig. 2*A*). One group (Or_{90-96}) completely overlaps the composition of higher temperature detrital and authigenic K-feldspar, while a second group ($Or_{>99}$) is unique and is not duplicated at higher temperatures.

The first group may represent either K-feldspar that has equilibrated within the geothermal system at temperatures below 190 °C, or original detrital compositions. The second group is most probably unmodified, original detrital K-feldspar. The fact

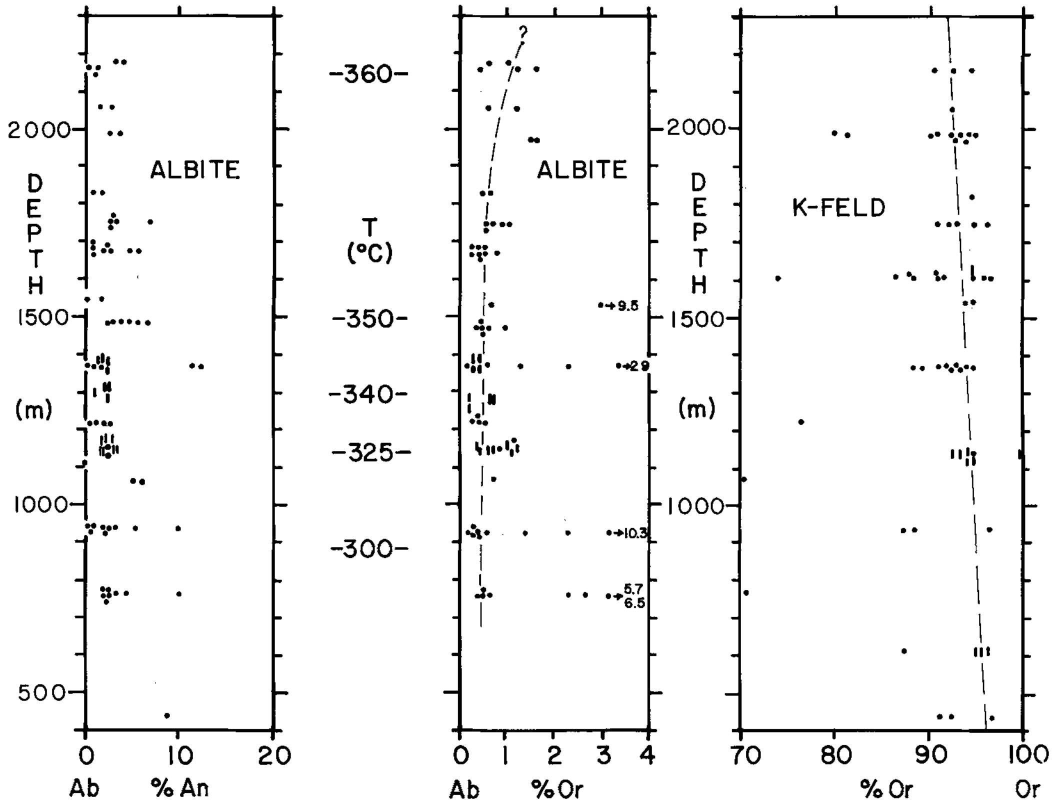

FIG. 4. Composition (mol. % in Or–Ab–An system) of individual analyses of all authigenic (vertical bars) and detrital (solid circles) as function of depth in meters. Temperature distribution in deg. C indicated. Trend lines drawn by eye. Analyses plotting off diagram indicated by arrows with composition as indicated.

that this group is strongly represented in both chips 2 and 3 is consistent with the generally held opinion that K-feldspar reacts more slowly than its sodic counterpart (Smith and Parsons, 1974). At temperatures above 250 °C the detrital K-feldspar analyses tend to cluster about a reasonable trend line in fig. 4 (drawn by eye) on increasing depth or temperature, which is compatible with the potassic limb of the feldspar solvus.

The compositional spread of detrital feldspar suggests a mixture dominated by plutonic, 'granitic' feldspar, with some grains consistent with hypabyssal or volcanic alkaline igneous rocks. Many of the latter are of intermediate Or-content and are finely perthitic, although homogeneous grains were noted. The very high Or-content of detrital K-feldspar, and low Or-content of plagioclase, imply low temperatures if these phases coexisted in the original source rocks. This is particularly true of those alkali feldspars which are essentially pure albite or K-feldspar.

The general tendency toward agreement of detrital and authigenic feldspar compositions at temperatures over 250 °C suggests that those detrital feldspars whose compositions cluster about authigenic compositional trends can be regarded as having equilibrated with respect to Na–K–Ca exchange. In Table II all such detrital compositions as well as neoformed authigenic grain compositions have been combined into groups consisting of all apparently chemically equilibrated feldspars at adjacent depths. The average Or-contents for these groups of coexisting alkali feldspars presumably represent the position of an equilibrium alkali feldspar solvus. While the An-content of the albite is low, plots of specific sample depths in which the An-content varies from 0 to 7% indicate that the Or-content is effectively constant over that range: that is, the albite limb of the alkali feldspar solvus projects into the ternary Or–Ab–An system along lines of approximately constant Or-content.

TABLE II. AVERAGE OR-CONTENT OF COEXISTING FELDSPARS FOR AUTHIGENIC AND EQUILIBRATED DETRITAL GRAINS IN SELECTED DEPTH INVERVALS.

DEPTH RANGE (m)	TEMPERATURE RANGE (°C)	AVERAGE OR% AND STD. DEV.	# ANALYSES
ALBITE			
2056-2169	360-361	0.94 ± 0.43	7
1747-1840	358-359	0.69 ± 0.19	7
1673	355	0.45 ± 0.16	8
1472-1533	348-351	0.58 ± 0.20	7
1370	344	0.37 ± 0.14	6
1295	340	0.43 ± 0.25	4
1216	335	0.42 ± 0.10	4
1143	329	0.56 ± 0.16	4
925	306	0.37 ± 0.14	6
760	280	0.50 ± 0.08	4
K-FELDSPAR			
1980-2155	359-360	92.18 ± 1.77	11
1747-1825	358-359	93.40 ± 1.86	6
1533-1605	351-353	93.70 ± 2.16	9
1370	344	92.14 ± 2.11	9
1143	329	94.36 ± 2.51	7
622	251	95.87 ± 0.59	3

Mol % in Or-Ab-An system

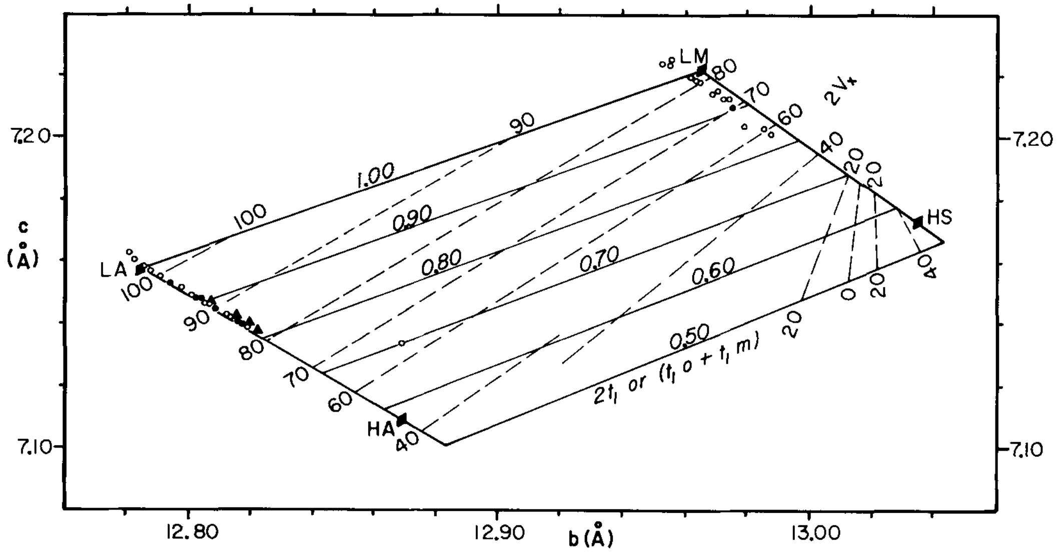

FIG. 5. Plot of *b* and *c* unit cell dimensions of feldspars in Å, with contours of ordering parameter ($t_1o + t_1m$) after Kroll and Ribbe (1983) and $2V_x$ after Stewart and Ribbe (1983). Coexisting geothermal authigenic albite and K-feldspar as solid circles, authigenic albite at 360 °C as solid triangles, and detrital feldspars as open circles. All data points obtained via $2V_x$ and compositional determinations using compositional data in Kroll and Ribbe (1983). LA = low albite, HA = high albite, LM = low microcline, HS = high sanidine.

Feldspar structural state. The work of Weitz (1972) indicates that the optic axial angle (2V) is a sensitive measure of the structural state of alkalic feldspars. The recent summaries of Stewart and Ribbe (1983), Kroll and Ribbe (1980, 1983), and Su *et al.* (1984) have allowed determination of the *b* and *c* unit cell dimensions and the value of the (t_1o+t_1m) ordering parameter of alkali feldspars from $2V_x$ measurements of feldspars of known composition. The 2V measurements were made on as many of the analysed alkali feldspars, both detrital and neoformed, as was possible. The fine grain size and complex twinning of the neoformed authigenic feldspars made this particularly difficult. For instance, only one reliable 2V measurement was obtained on neoformed K-feldspar due to the fine polysynthetic twinning prevalent in these grains. The individual 2V measurements, average values, and the resulting average (t_1o+t_1m) ordering parameter have been summarized in Table I and plotted in fig. 5. Since

$$(t_1o+t_1m)+(t_2o+t_2m) = 1. \quad (1)$$

The ordering parameter Z (Thompson, 1969; originally defined for monoclinic feldspars) becomes:

$$Z = 2\,(t_1o+t_1m)-1. \quad (2)$$

This parameter has also been listed for the average values in Table I. Both ordering parameters indicate that the neoformed authigenic albite, and probably the alkali feldspar, have similar highly ordered but still intermediate states of order at temperatures near 335 °C ($Z = 0.79$ for albite, 0.81 for K-feldspar). Note that the average ordering parameters indicate that albite at 360 °C is more disordered ($Z = 0.70 \pm 0.07$) than that near 335 °C ($Z = 0.79 \pm 0.09$). The trend is in the direction expected on increasing temperature only if it is assumed that fully ordered albite is the stable phase at less than 300 °C, and that ordering occurs over a large temperature interval. Recent reversed experiments at high pressures (17–19 kbar) and in the presence of a carbonate flux (Goldsmith and Jenkins, 1984), however, support earlier unreversed experiments (see Smith, 1983, for summary) which indicate that fully ordered low albite is stable to temperatures near 680 °C, and the transition from ordered low albite to disordered high albite occurs over a relatively narrow 100 °C temperature interval. This suggests that the highly ordered but still intermediate geothermal feldspars have not attained structural equilibrium and represent arrested Al–Si ordering states. The fact that they have attained as high a degree of order as is observed, in comparison to sedimentary authigenic feldspars (Kastner, 1971), may be due to accelerated Al–Si ordering in the presence of very NaCl-rich geothermal brines (25–30 wt. % NaCl equivalent, or about 53 000 ppm Na, 16 500 ppm K, 29 000 ppm Ca, and 155 000 ppm Cl; Helgeson, 1968) in this young, active geothermal system.

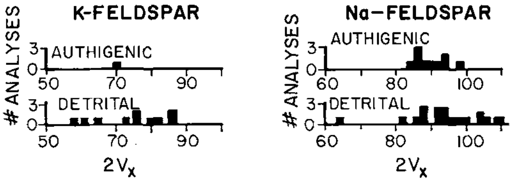

FIG. 6. Histogram of $2V_x$ determinations of authigenic and detrital K-feldspar and albite.

The $2V_x$ measurements of neoformed authigenic feldspars, and detrital feldspars, are summarized in fig. 6 for temperatures over 250 °C. There is a tendency for detrital grains to have higher $2V_x$ than the authigenic grains. The average $2V_x$ of all detrital albites is 95.1 ± 7.8, higher but overlapping that of authigenic albite (Table I). Thus there is a suggestion that the detrital grains are slightly more ordered, but more data is clearly needed on this point. There is no trend of $2V_x$ change with depth or temperature discernible for the detrital grains. It thus appears that the detrital grains are equilibrated in most cases with respect to Na–K exchange, but may not be fully equilibrated with respect to Al–Si ordering.

Alkali feldspar solvus. The coexisting feldspar data in Table II has been plotted in fig. 7 relative to the monoclinic, disordered sanidine-high albite solvus of Smith and Parsons (1974) and the triclinic, ordered microcline-low albite solvus of Bachinski and Muller (1971). The general agreement between the compositions of the highly ordered geothermal feldspars and the microcline-low albite solvus is excellent, and implies that the thermodynamic extrapolation of the higher temperature experimental data is quite reasonable. In detail, the fact that the geothermal feldspar compositions lie just within the fully ordered solvus is entirely consistent with the fact that they are approximately 80 % ordered and would be expected to lie on a metastable solvus characteristic of that degree of ordering and located just inside the fully ordered solvus.

Acknowledgements. This investigation was supported by National Science Foundation Grants EAR 7822755 and

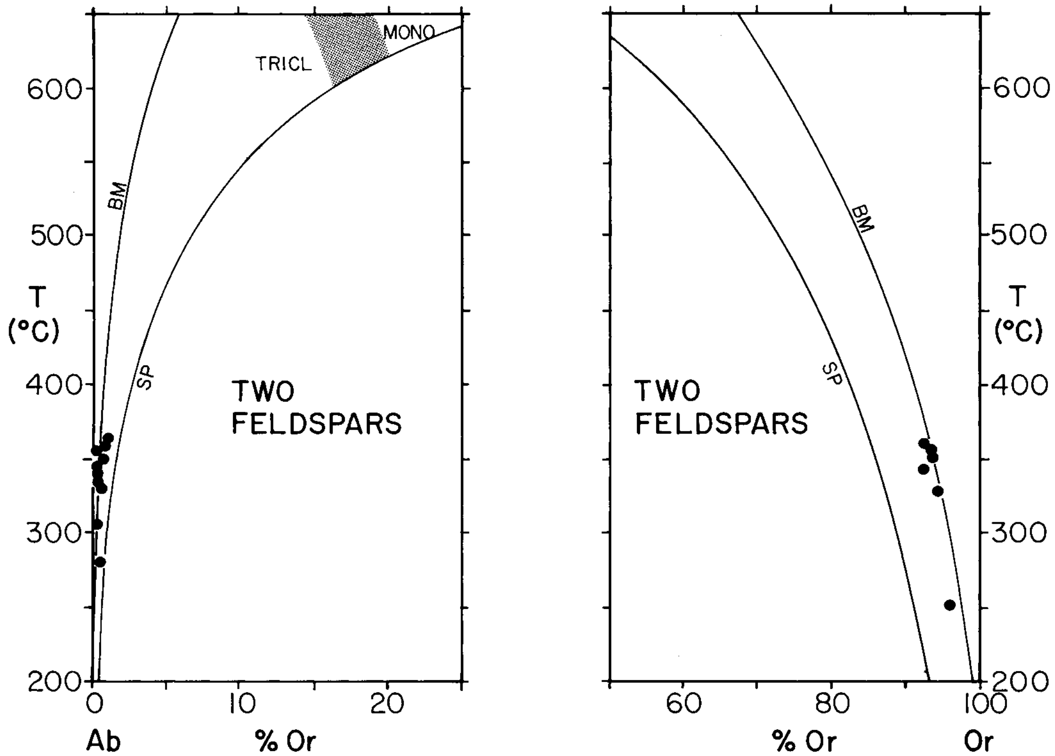

FIG. 7. Comparison of coexisting geothermal alkali feldspar compositions (solid circles) with experimental sanidine-high albite solvus of Smith and Parsons, 1974 (light line SP) and microcline-low albite solvus of Bachinski and Muller, 1971 (light line BM). Note different compositional scales.

8120821, and US Geological Survey Grant 1408001G-430. Thanks to A. A. Chodos (CalTech), and W. Hockings and J. Paces (Michigan Tech) for aid in microprobe analyses. The petrological observations of J. Paces are especially appreciated, as was a very informative review by an anonymous reviewer.

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[*Manuscript received 17 October 1984;*
revised 27 March 1985]