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Genesis of hydrothermal K-feldspar (adularia) in an active geothermal environment at Wairakei, New Zealand

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SUMMARY. Hydrothermal almost pure potassium feldspar (adularia) forms incrustations on fissured wall rocks in an active geothermal environment. Measured max. temperature, 265 °C, and concentration of K^+ and Na^+ cations in the geothermal fluid require K-feldspar and Na-feldspar to be deposited under equilibrium conditions. On fissure walls only K-feldspar is precipitated, whereas andesine phenocrysts of host rocks are replaced by both K-feldspar and Na-feldspar, and groundmass of host rock is replaced by K-feldspar.

Optical data indicate that K-feldspar forming incrustations is partly monoclinic, partly triclinic. The triclinic material displays polysynthetic and 'microcline'-like twinning, though X-ray diffractograms indicate only monoclinic structure. A primary origin for the triclinic adularia is postulated. Wairakei hydrothermal K-feldspar, max. 0·5 Myr old, is compared with Arkansas adularia 287 or 214 Myr old, also containing both monoclinic and triclinic material. The comparison suggests that, after crystallization, the structural state of adularia changes little, if at all, during geological time.

IN studying hydrothermal rock alteration of drill cores recovered during exploration for geothermal steam at Wairakei in the North Island of New Zealand (Steiner, 1953, 1955, 1968; Steiner and Rafter, 1966) it has been found that almost pure potassium feldspar (adularia) is a common hydrothermal mineral. Apart from the economic importance of hydrothermal K-feldspar as an indicator of the presence of geothermal steam and hot water, its occurrence in an active geothermal environment is also useful from a genetic point of view, because the *T–P–X* conditions controlling its formation are known. The composition of the geothermal fluid depositing K-feldspar has been determined by chemical analysis (Ellis, 1961; Mahon and Glover, 1965) and the prevailing temperatures measured (temperature measurement sheets, Ministry of Works, Wellington; unpublished). The water-vapour pressures, corresponding to measured temperatures, have been determined from steam tables (Chemical Rubber Publishing Co., 1951), and the load pressures calculated from the average specific gravity of the rocks penetrated (2·06).

K-feldspar occurs in hydrothermally altered wall rocks, usually in and near buried fault fissures, through which geothermal fluid ascends. The altered, predominantly silicic rocks of Pliocene to Pleistocene Age were originally glassy volcanics of rhyolitic composition and related aquagene tuffs and breccia. Hydrothermal K-feldspar replaces primary andesine phenocrysts and groundmass, and also forms incrustations on fissured wall rocks. The replacement of phenocrysts is sometimes not complete.

Intense deposition of quartz is usually associated with the formation of hydrothermal K-feldspar.

The measured maximum temperature of the geothermal fluid, a mixture of hot water and steam, is 265 °C. The most significant chemical characteristics of the geothermal fluid, tapped in fault fissures, are its comparatively high mK^+/mH^+ and mNa^+/mH^+ ratios, and low mNa^+/mK^+ ratio, saturation in silica with respect to quartz, and tendency to saturation with $CaCO_3$.

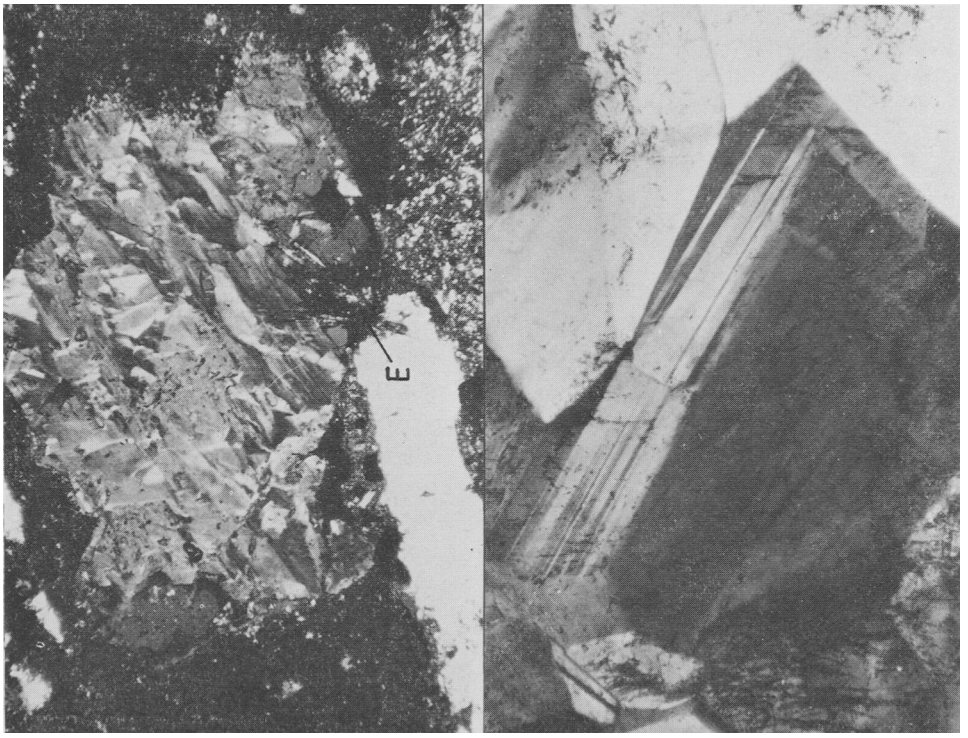
When plotting the ratios mK^+/mH^+ or mNa^+/mH^+ of the geothermal fluid against its max. temperature on the diagrams showing the stability fields of alkali feldspars (Hemley and Jones, 1964), the points lie in the stability field of K-feldspar and albite respectively (Steiner, 1968). In spite of a considerably higher concentration of Na^+ ions than K^+ ions in the geothermal fluid, K-feldspar but not Na-feldspar is deposited on fissure walls. Both alkali feldspars, however, replace andesine phenocrysts in the wall rocks.

Occurrence and optical data. The K-feldspar that replaces the groundmass occurs in minute anhedral to euhedral crystals, frequently rhombic in cross-section. Pseudomorphs after plagioclase phenocrysts made up of K-feldspar show a streaky extinction or a 'tile'-like structure (Nowakowski, 1959) suggesting that the pseudomorphs consist of numerous minute individual but overlapping crystals with rhombic cross-section (fig. 1). Occasionally, the pseudomorphs display faint 'microcline'-like twinning. The average refractive indices α and γ are $1{\cdot}518 \pm 0{\cdot}001$ and $1{\cdot}524 \pm 0{\cdot}001$. Where determined, the optic axial plane was parallel to (010), and $2V_\alpha$ about 30–45°.

In comparison, K-feldspar forming incrustations on fissured wall rocks occurs in clear or translucent crystals with {110} faces dominant, and in average about 2·5 mm across. Its refractive indices α and γ do not differ from those of the K-feldspar replacing andesine phenocrysts and groundmass. Under crossed nicols some crystals appear to be homogeneous, or are simple twins, many show patchy extinction, and some display faint diffuse 'microcline'-like or polysynthetic twinning. Whether the 'microcline'-like twinning is identical with the combined albite and pericline twinning of microcline is at present not known. However, in the thin section made from the incrustation recovered from a depth of 2550 ft in drill-hole 225 two crystals display sharp polysynthetic twinning. Moreover, K-feldspar from another incrustation, at 1012 ft in drill-hole 80, shows a blue interference colour, resembling that of zoisite (Bambauer and Laves, 1960).

Two different orientations of the optic axial plane are characteristic of the K-feldspar forming incrustations. This plane is parallel to (010) if the crystals are homogeneous or show patchy extinction. Straight extinction, parallel to (010), and the absence of visible multiple twinning indicate a monoclinic mineral; the dispersion is $r < v$. On the other hand, the optic axial plane is perpendicular to (010) if the crystals show faint 'microcline'-like cross-hatching. In either case, the optic axial angle $2V_\alpha$ does not vary greatly, having values between about 20° and 45°. In one crystal of the incrustation (fig. 2) from drill-hole 225, sharp polysynthetic twin lamellae appear to be morphologically oriented parallel to one face of {110} (Bambauer and Laves, 1960). The twin

lamellae, though petering out somewhat, resemble polysynthetic twinning in triclinic feldspars. The extinction angle of two lamellae extinguishing simultaneously deviates 10° from (010). The optic axial plane of these lamellae is perpendicular to (010), and 2 V_α is about 45°. A third lamella is too narrow for determination of the orientation



FIGS. 1 and 2: Fig. 1 (left). Photomicrograph showing 'tile'-like structure of a pseudomorph made up of minute adularia crystals, replacing andesine phenocrysts. Small black patches are epidote (E). Drill-hole 219, depth 1800 ft. Crossed nicols, ×60. Fig. 2 (right). Photomicrograph of an adularia crystal from incrustation at 2550 ft in drill-hole 225. Outer, sharp polysynthetic twin lamellae oriented parallel to {110} and very faint, diffuse polysynthetic twin lamellae in the centre. Crossed nicols, ×60.

of its optic axial plane but its extinction is parallel to (010). The centre of the crystal displays very faint, diffuse, polysynthetic twin lamellae (fig. 2), which are parallel to the outer sharp twin lamellae (Bambauer and Laves, 1960).

Thus the oblique extinction, together with cross-hatching and polysynthetic twinning, suggests that at least some of the incrustation material is triclinic. However, X-ray powder diffractograms (table I and fig. 3) indicate a monoclinic lattice. It is inferred, therefore, that the over-all obliquity of the triclinic portion of the K-feldspar forming incrustations is very small or the amount of material that is triclinic is not sufficient to effect the X-ray pattern.

Chemical data. The result of partial wet chemical analysis of a pure sample of hydrothermal K-feldspar from an incrustation in drill-hole 80 at 1012 ft is: SiO_2 65·1, Al_2O_3 18·9, K_2O 16·0, and Na_2O 0·2 weight %.[1] The K_2O and Na_2O contents of pure feldspar from drill-hole 225 at 2550 ft, determined by flame photometry, are 14·52 % and 0·57 % respectively. Thus the hydrothermal K-feldspar forming incrustations on fissured wall rocks is almost a pure potassium feldspar. This is indicated also by X-ray powder diffraction data.

TABLE I. *X-ray powder diffraction data of hydrothermal K-feldspar from Wairakei drill-holes 80 and 225. Scanning speed 1°/min. Indices according to Borg and Smith (1969, table 5)*

80			*225*				*80*			*225*			
2θ	*d*	*I/I*$_0$	*2θ*	*d*	*I/I*$_0$	*hkl*	*2θ*	*d*	*I/I*$_0$	*2θ*	*d*	*I/I*$_0$	*hkl*
13·3	6·66Å	5	13·4	6·61Å	5	110	34·8	2·58Å	30	34·9	2·57Å	30	{221 $\bar{2}$41
13·6	6·51	15	13·7	6·48	5	{020 001	35·3	2·54	10	35·3	2·54	15	112
15·1	5·87	5	15·2	5·83	5	$\bar{1}$11	35·6	2·52	5	35·7	2·51	5	310
19·3	4·60	< 5	—	—	—	021	—	—	—	—	—	—	240
21·0	4·23	35	21·1	4·21	45	$\bar{2}$01	37·2	2·42	5	37·2	2·42	10	$\bar{1}$51
22·6	3·93	20	22·6	3·93	20	111	37·7	2·39	5	37·7	2·39	10	$\bar{3}$31
—	—	—	—	—	—	200	38·8	2·32	5	38·9	2·31	10	$\bar{1}$13
23·5	3·78	85	23·6	3·77	65	130	—	—	—	39·7	2·27	< 5	$\bar{3}$32
24·6	3·62	15	24·7	3·60	15	$\bar{1}$31	—	—	—	—	—	—	$\bar{2}$23
25·2	3·53	5	25·3	3·52	10	$\bar{2}$21	—	—	—	—	—	—	132
25·7	3·46	55	25·8	3·45	45	$\bar{1}$12	40·9	2·21	< 5	41·0	2·20	< 5	{330 151
26·8	3·33	75	27·0	3·30	80	220							
27·2	3·28	50	27·3	3·27	55	$\bar{2}$02	41·6	2·17	35	41·6	2·17	25	{060 003
27·4	3·25	70	—	—	—	040							
27·6	3·23	100	27·7	3·22	100	002	42·5	2·13	< 10	42·6	2·12	10	241
29·9	2·99	60	30·0	2·98	55	131	—	—	—	—	—	—	$\bar{4}$01
30·5	2·93	< 10	30·6	2·92	10	$\bar{2}$22	—	—	—	—	—	—	$\bar{4}$02
30·8	2·90	30	30·9	2·89	35	{041 022	—	—	—	—	—	—	{$\bar{1}$33 202
—	—	—	—	—	—	311	43·8	2·07	5	43·8	2·07	5	311
32·4	2·76	20	32·5	2·75	20	$\bar{1}$32	44·0	2·06	5	44·1	2·05	5	061
34·5	2·60	10	34·5	2·60	15	$\bar{3}$12	45·1	2·00	5	45·2	2·01	5	$\bar{4}$22
							46·1	1·97	10	—	—	—	222

X-ray powder diffraction data. A portion of each analysed sample has been examined by X-ray diffraction, using Cu-*K*α radiation and scanning speed 1°/min. The results of both samples are almost identical, though reflections 040 and 002 were not separated when scanning the sample from drill-hole 225 (table I). The observed 2θ values of both samples agree well with the corresponding calculated values given by Borg and Smith (1969, table 5).

The samples produced sharp peaks at 21·0° and 21·1°, respectively, and at 22·6° (table I), the peak at about 21·0° being characteristic of almost pure potassium

[1] Analyst: J. A. Ritchie, Chemistry Division, D.S.I.R., Lower Hutt.

feldspar (Bowen and Tuttle, 1950; Donnay and Donnay, 1952). Thus the X-ray data is in agreement with the results of chemical analyses. In addition, the critical section 2θ between 20° and 36° has been scanned at low speed, $\frac{1}{4}$° per min. The samples again give very similar patterns. The diffractogram of the sample from drill-hole 225, obtained at a speed $\frac{1}{4}$° per min is reproduced in fig. 3. It shows that on scanning at low speed the peaks at 21·0° and 22·6° are broadened but not split. The peak at 21·0° can safely be ascribed to K-feldspar as optical and infra-red examinations indicate that quartz is absent. The broadening of this peak may suggest a slight variation in K-content whereas broadening of the peak at 22·6 may be due to a small amount of triclinic material.

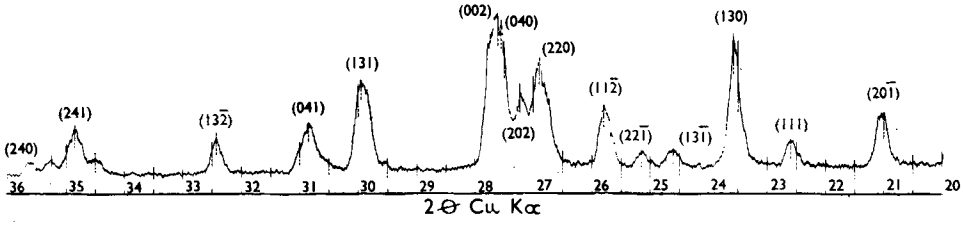


FIG. 3. Diffractogram of adularia from drill-hole 225, depth 2550 ft. Scanning speed $\frac{1}{4}$° per min. The apparent splitting of the peak 130 is due to superposition of two marker lines.

It is emphasized that when scanning at low speed, $\frac{1}{4}$° per min, reflections 130 (2θ = 23·60°) and 131 (2θ = 29·95°) of both samples show no splitting but are slightly broadened and asymmetrical (fig. 3). In contrast, the peak 002 (2θ = 27·6°) is a distinct doublet due to separation of the 040 from 002 reflection by 0·05° (Borg and Smith, 1969). Although optically some of the material appears triclinic, the absence of separate $1\bar{3}0$ and $1\bar{3}1$ reflections would suggest that a major portion of the K-feldspar is monoclinic, at least to X-ray powder diffraction (MacKenzie, 1952; Goldsmith and Laves, 1954; Borg and Smith, 1969) or may be due to the departure from monoclinic symmetry being very slight.

Infra-red absorption spectra. The hydrothermal K-feldspar from drill-hole 80 at 1012 ft gives the following infra-red absorption bands: 1130, 1040, 780, 730, 640, 590, 550, and 430 cm^{-1}. The pattern is very similar to that of sanidine and synthetic K-feldspar obtained by Lyon (1963, his fig. 8, samples 3154 and 3051). It is also comparable with pattern 3B of Hafner and Laves (1957). The characteristic quartz doublet at 798 and 779 cm^{-1} is absent.

Origin of hydrothermal, triclinic K-feldspar. Both chemical and X-ray data indicate that K-feldspar precipitated by the geothermal fluid, and forming incrustations on fissured wall rocks, is almost a pure potassium feldspar. Further, it should be noted that all drill-cores were examined only 3 to 5 days after recovery from their natural geothermal environment. It can be concluded that the 'microcline'-like and polysynthetic twinning of the K-feldspar is not due to Si–Al ordering taking place after crystallization (Bambauer and Laves, 1960), since the ordering would have to be very rapid on cooling below 230 to 265 °C. Because adularia is formed at temperatures far

below the order–disorder transformation temperature (Laves, 1952, p. 448), it appears that the polysynthetic and 'microcline'-like twinning of triclinic adularia is of primary origin (Ansilewski, 1958). Based on age determination and X-ray study, Bass and Ferrara (1969) also inferred a primary origin of triclinic adularia.

However, hydrothermal activity at Wairakei has been going on for about 0·5 Myr. This may suggest that monoclinic K-feldspar alone crystallized as early as 0·5 Myr ago, and then slowly changed partly to triclinic. That the structural state of adularia after crystallization changes little, if at all, is evident on comparing the maximum age of Wairakei adularia (0·5 Myr) with the age of 287 or 214 Myr, determined by Bass and Ferrara (1969) for adularia from Arkansas that, like the Wairakei adularia, consists of monoclinic and triclinic material. Although at variance with the suggestion of Gubser and Laves (1967, p. 187), it also follows from the comparison that geological time is not an important factor as far as formation of triclinic adularia is concerned.

Chemical composition and measured temperature of the geothermal fluid, tapped in buried fault fissures, require K-feldspar to be precipitated under equilibrium conditions (Steiner, 1968). Mineral solubility tests carried out in Wairakei drill-holes (pers. comm., Dr. A. J. Ellis) have confirmed deposition of K-feldspar as indicated by petrological (Steiner, 1968) and experimental results (Hemley and Jones, 1964). Crystallization of triclinic adularia almost simultaneously with monoclinic adularia could be due to minor departures from thermodynamic equilibrium. Small, though seemingly significant fluctuations of temperature and somewhat varying ion concentrations are known to occur in the Wairakei geothermal fluid. Continuous fluctuations around equilibrium would most likely take place under dynamic conditions that are characteristic of an open system such as fault fissures carrying geothermal fluid. Thus, fluctuations in temperature or ion concentrations or possibly other factors may cause the postulated minor departures from the thermodynamic equilibrium. In contrast, Bambauer and Laves (1960) consider that the various structural states of adularia are not stable at any temperature under equilibrium conditions.

It is concluded that either monoclinic and triclinic adularia are precipitated almost concomitantly, or triclinic K-feldspar alone is formed and the associated monoclinic structure is only apparent, being simulated by very fine twinning that is optically not detectable. If so, hydrothermal, pure potassium feldspar may have any degree of Si–Al ordering on crystallization.

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