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Tamarugite, NaAl(SO₄)₂·6H₂O, from Te Kopia, New Zealand

TAMARUGITE, $NaAl(SO_4)_2 \cdot 6H_2O$, is one of a suite of secondary, water soluble, hydrated sulphates reported forming by oxidation of sulphides under dry, usually arid conditions (Palache *et al.*, 1951) although it has also been found near the sea at two localities with moderately high rainfall (Hutton, 1970; Segnit, 1976). In the Te Kopia geothermal area of New Zealand's North Island, where the average annual rainfall is 1165 mm and the climate temperate, the mineral occurs as part of an efflorescence currently forming on hot water altered ignimbrites now undergoing alteration by steam.

The Te Kopia geothermal area is large and vigorously active. It is located in the Taupo Volcanic Zone at latitude 38° 24' S, longitude 176° 13' E and lies astride the west-facing scarp of the upthrown eastern block of the active Paeroa Fault. Altered and steaming ground extends for over 2.5 km along the fault scarp and within 500 m of it Several areas of perched, shallow, steam-heated, acid-

sulphate ponds have developed in sub-circular depressions within extensively altered ground at the foot of the scarp (Bignall and Browne, 1994). It is on the eastern margin of the largest of these areas that the tamarugite-bearing efflorescence occurs.

The country rocks consist of three sub-horizontal ignimbrite sheets formed of rhyolitic pumice lapilli tuff. These have been subject to several hydrothermal episodes, each yielding a distinctive mineral suite (Bignall and Browne, 1994). The alteration that affected the rocks most intensely was caused by slightly alkaline but dilute chloride waters at temperatures between about 200 and 220°C (Browne *et al.*, 1994). The hydrothermal minerals produced include locally abundant adularia and quartz formed as replacements of primary andesine and the glassy groundmass of the rock. The altered rocks have been uplifted from the bowels of the still active geothermal field and are now undergoing another phase of hydrothermal alteration — this time by steam and gases, and their condensates. Hydrothermal minerals forming under the present thermal regime along the scarp include kaolinite, alunite and cristobalite plus silica residue. The tamarugite-bearing efflorescence coats rocks altered in this style and occurs as a soft powder up to 2 cm thick on surfaces at the base of the scarp. Here numerous vertical joints cut intensely silicified rocks that contain adularia or illite, or both, and pyrite and marcasite locally form narrow veins.

This efflorescence appears as an open, white, fluff of microplatelets, slender fibres, minute, extremely fine-grained, equigranular, irregular lumps, and solid, white, glistening, seemingly fibrous masses, that proved to be constructed largely of very thin platelets of tamarugite such as have been described by Segnit (1976).

X-ray powder diffraction of three bulk samples of the efflorescence, made using a Philips diffraction goniometer fitted with a graphite monochromator and employing Cu-*K*α radiation, show well-developed patterns for tamarugite, alunogen, meta-alunogen and quartz along with lower intensity peaks that correspond to major diffraction lines of potash alum, pickeringite and adularia. There are also some weak peaks possibly caused by small amounts of other sulphates such as halotrichite, anhydrite, epsomite and hexahedrite.

The X-ray diffraction pattern of the Te Kopia tamarugite corresponds closely with that of Robinson *et al.* (1966) although the intensities of some lines are affected by both preferred orientation and the co-existing phases. No appreciable broadening of diffraction lines occurred as reported by Segnit (1976) and all lines that were not partly overwritten by other phases were clearly resolved (cf. Lombardi and Sposato, 1981). The meta-alunogen pattern best

fits that given by the Joint Committee on Powder Diffraction Standards 18-0061.

Two scanning electron microscope mounts were prepared. In one the white fluff was dispersed with a fine brush over double-sided adhesive tape with the result that many soft and sectile crystallites were damaged. In the second, small clusters of the efflorescence were dropped into a thin, tacky film of clear nail polish. Both mounts were delicate and precarious but were successfully gold-coated and proved sufficiently stable to observe *in vacuo,* although crystallites on the upper surface of the second mount were prone to movement when disturbed by the beam.

Fibres of alunogen occur both separately and in substantial clusters (Fig. 1*a*). Tamarugite is abundant in very thin, lamellar, euhedral platelets commonly 5–20 μm long but ranging upwards to 100 μm and rarely 200 μm (Figs 1*b*, *c*). The crystals are tabular on (010) and show neither alteration nor inclusions. In habit and form they closely resemble tamarugite illustrated by Lombardi and Sposato (1981) from Volcano. Books of parallel crystals joined on (010) (Fig. 1*d*) are not so well developed at Te Kopia as in the Volcano samples and this presumably reflects differences in the physical conditions of their crystallization.

The tamarugite platelets proved too finely crystalline to measure their optical properties.

A specimen of the efflorescence, hand-picked clean of obvious impurities such as black fungus fallen from overhanging *Leptospermum* (Kanuka, Manuka), contained 73.2% water soluble matter. Chemical analysis of the solution gave 13.0% Al_2O_3, 0.3% CaO, 0.3% MgO, 6.3% Na_2O, 0.31% K_2O, 40.2% SO_3 and <0.04% Fe2O3. If the traces of lime, magnesia, potash and iron are considered as derived mainly from pickeringite, potash alum, anhydrite and halotrichite, the result is consistent with a mixture of approximately 65% tamarugite, 10% alunogen and meta-alunogen, 4% pickeringite and halotrichite, 3% potash alum and <1% anhydrite. The shortfall in the total may be accommodated by water and ammonia.

Discussion

The hydrothermal alteration history of the Te Kopia geothermal system has been complex due to its long duration (~120,000 years; Bignall and Browne, 1994) and the strong control that movements on the Paeroa Fault have exercised on the hydrology of this still active geothermal system. The major alteration event recorded by the mineralogy of the rocks occurred within the reservoir, at least 170 m below the water table. This caused potassium metasomatism but also real depletion of the host ignimbrites in Ca
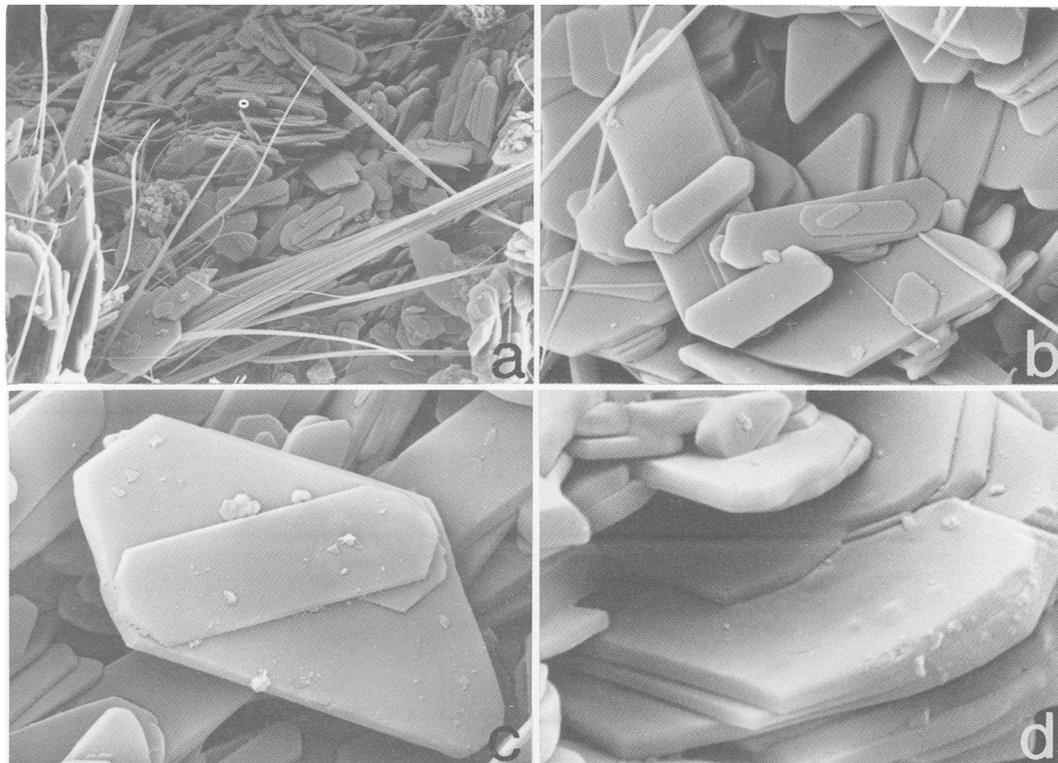
FIG. 1. Scanning electron micrographs of Te Kopia efflorescence.(a) Subparallel, tight-packed aggregate of tamarugite microcrystals with alunogen fibres. Base of photo is 180 μm. (b) Loose euhedral tamarugite microcrystals with sparse alunogen fibres. Base of photograph is 41 μm. Small, piggy-back crystal below centre of photograph is ∼3 μm along [001]. (c) Bladed euhedral tamarugite crystals lying on (010). Base of photograph is 28 μm. (d) Edge of rare book of thin, tabular, euhedral tamarugite microcrystals. Base of photograph is 14 μm.

and Na. Abundant quartz and minor pyrite formed at this stage with Al remaining immobile.

At present the rocks are undergoing further alteration by acid water whose composition is dominated by sulphate derived from oxidation of both the earlier-formed pyrite but also, and dominantly, from H_2S ascending from chloride water boiling ∼200 m below the present ground surface (Bignall and Browne, 1994).

The warm acid waters (the water being largely steam condensate but admixed with rain water) dribbles over the previously altered rocks and reacts with them to produce the suite of sulphate minerals, cristobalite, kaolinite and silica. The sulphate phases include the tamarugite whose aluminium and sodium are extracted from the host ignimbrites although these have already been substantially depleted in Na. The minerals form continuously. In heavy rain, the efflorescence dissolves and largely disappears to

return during the next dry spell, a situation similar to the occurrence of tamarugite and alunogen in Anglesea, Australia (Segnit, 1976).

Samples of the Te Kopia tamarugite efflorescence have been deposited at the Australian Museum, Sydney, sample no 49781, and the Auckland University Department of Geology Mineral Collection, sample no 3284.

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Formation of chlor- and fluor-apatite in layered intrusions: A comment

IN a recent paper, Cawthorn (1994) presented a model for the formation of chlorapatite and fluorapatite in layered intrusions that differs from those presented by myself and my colleagues. In brief, Cawthorn suggests that apatite in intercumulus liquids initially crystallizes as a F-rich apatite, and that Cl-rich apatite forms mainly by reequilibration with trapped interstitial liquid. This process is analogous to that by which cumulus mafic minerals may become more Fe-rich on reequilibration with intercumulus liquids during solidification. In this interpretation, the high-Cl apatite that characterizes much of the lower stratigraphic sections of the Stillwater and Bushveld complexes can be explained solely as the result of more extensive reequilibration with intercumulus liquid than is seen in any other intrusions. In addition, Cawthorn suggests that the general decrease in the Cl/F ratio of apatite with stratigraphic height seen in many intrusions may simply represent a decreasing (trapped liquid)/ (apatite) ratio with increasing stratigraphic height and need not require any fluid fractionation as suggested by myself and my colleagues.

In a review of an early draft of this paper, I pointed out several problems both in the representation of our earlier work and problems with the interpretation

suggested by Cawthorn. None of these were addressed in the published manuscript, hence this comment. Here I will take note of two points of contention. The first has to do with a misinterpretation of my earlier work regarding the volatile content of the parent magma(s) of layered intrusions that contain high-Cl apatite such as the Stillwater and the Bushveld complexes. The second and more serious point has to do with the evidence for the role of reequilibration of intercumulus liquid as a significant cause for the stratigraphic decrease in the Cl/F ratio common to many intrusions.

Cawthorn misrepresents the assumptions and consequences of the model presented by Boudreau (1992). In this paper, it was suggested that degassing of fluid-saturated intercumulus liquids can give rise to fluid overpressures that can form pothole structures as these fluids escape from the crystal pile. It was suggested that potholes form in a manner analogous to pockmarks on the sea floor, which are also generally explained as gas-release structures (e.g. Hovland and Judd, 1988). In the quantitative expression of the model, water was used as an example of a volatile with a high solubility such that a large amount of fluid is exsolved during crystallization of the intercumulus liquid and hence