

lack of definition of X-ray patterns of similar insular collophanes as resulting from low grain size and poor crystallinity. The effect may also arise from compositional variation amongst different generations of cement crystallites. While spot EDAX analyses for Ca, P and F showed a range of values (Table 1), in part this range reflects the varying amounts of organic mucilage intimately admixed with the cement and regarded as an integral part of the paragenetic association. Only analysis 3 in Table 1 is close to that of a stoichiometric, reasonably pure, carbonate hydroxyapatite. Apart from traces of Na and Cl, no significant amounts of other elements were detected in the EDAX spectrum. It can be noted that in only two cases was fluorine in excess of 0.1%.

In most samples from above the tidal range whitlockite is present although always subordinate to dahllite. The mineral occurs as drusy clusters of flattened rhomb-shaped crystals growing porewards of the main crustose cement (Fig. 1*d*). For samples from within the intertidal zone and below, whitlockite is at best a minor component although identification of small amounts of this mineral in X-ray diffraction traces is made difficult by the diffuse nature of the apatite pattern.

No other minerals which have been recorded from comparable insular phosphate occurrences (e.g. Hutchinson, 1950; McConnell, 1950) have been identified at Amatuku. Notable in some sub-aerial samples were implanted spheres *c.* 30  $\mu$  dia, partly buried in the cement crust. Whether these were organic or inorganic could not be determined.

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#### References

- Braithwaite, C. J. R. (1968) *J. Sed. Petrol.* **38**, 1194–212.  
 Cooksey, T. (1896) *Austral. Mus. Mem.* **3**, 73–8.  
 Cullis, C. G. (1904) In *The atoll of Funafuti. Borings into a coral reef and the results*. Report, Coral Reef Boring Committee, Royal Society of London. Harrison and Sons, 392–420.  
 David, T. W. E. and Sweet, G. (1904) In *The atoll of Funafuti. Borings into a coral reef and the results*. Report, Coral Reef Boring Committee, Royal Society of London. Harrison and Sons, 61–124.  
 Hutchinson, G. E. (1950) *Bull. Am. Mus. Nat. Hist.* **96**, 1–554.  
 Judd, J. W. (1904) In *The atoll of Funafuti. Borings into a coral reef and the results*. Report, Coral Reef Boring Committee, Royal Society of London. Harrison and Sons, 362–89.  
 Lennart, J., Fredholm, D., and Mattisson, B. (1985) *J. Paleo.* **59**, 952–6.  
 McConnell, D. (1950) *J. Geol.* **58**, 16–23.  
 — (1973) *Apatite: its crystal chemistry, mineralogy, utilization, and geologic and biologic occurrences*. Springer-Verlag, Wien, 111 pp.  
 Rodgers, K. A. (1987) *South Pacific J. Nat. Sci.* in press.  
 Sollas, W. J. (1904) In *The atoll of Funafuti. Borings into a coral reef and the results*. Report, Coral Reef Boring Committee, Royal Society of London. Harrison and Sons, 1–28.  
 Stoddart, D. R. and Scoffin, T. P. (1983) In *Chemical sediments and geomorphology* (Goudie, A. S. and Pye, K., eds). Academic Press, London, 369–400.

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## Low-temperature, hydrothermal garnet associated with zeolites, from basalt lavas near Beith, Ayrshire

A WORKING quarry, at Loanhead (NS363557) within the Clyde Plateau Carboniferous lavas, is

traversed by a tholeiitic Tertiary dyke some 25–30 m wide. Throughout the quarry the lavas

are extensively altered and the most prominent secondary minerals are calcite and prehnite. Adjacent to the dyke is an indefinite alteration zone within which garnet has developed in close association with analcime and thomsonite. Contact metamorphism is not apparent. Secondary minerals in the quarried lavas and from the alteration zone have been described by Meikle (1989). The most salient feature of secondary mineral formation central to this paper is that grossular and andradite occur, *in situ*, in close proximity to the dyke, and only in the amygdaloes.

Zeolitised Tertiary lavas of Antrim, Mull, Morven and Skye are characterised by a rich variation in zeolite species, even within a single hand specimen (Walker, 1951, 1960, 1971; Heddle, 1901). Although the zeolites in the Loanhead quarry are limited in species, this markedly contrasts with the wide ranging mineral assemblages encountered in such contact-zone amygdaloes. The more common contact zone amygdaloe assemblages are briefly listed below and some illustrated in Fig. 1 (*a-f*). In this context garnet (< 3 mm) includes grossular and andradite, as both frequently occur in the same amygdaloe.

- (a) Epidote-lined, with hematite and epidote, garnet and minor analcime.
- (b) Garnet-lined, infilled with either/or a combination of thomsonite, calcite, and analcime. Minor hematite and chalcopryrite may be present.
- (c) Garnet-lined, secondary lining of hematite, infilled with calcite and analcime.
- (d) Garnet and calcite only, filling the whole cavity.
- (e) Garnet-lined, with calcite above; cavity not filled.
- (f) Clinopyroxene, chlorite or fibrous amphibole lining cavities with calcite and garnet. Garnet usually absent from either chlorite or amphibole-lined cavities.
- (g) Chalky analcime filling many amygdaloes, some lined with this material and containing garnet in the centre.
- (h) Fissure coatings containing garnet, calcite, goethite, clinopyroxene, minor plagioclase (albite/oligoclase), prehnite, epidote, and chalky analcime.

Throughout these assemblages the garnet displays a variety of colours ranging from white, ivory, pale buff to pale brown and yellow-brown. Small cavities frequently contain hessonite. Several, large amygdaloes (up to 7–8 cm) are lined with white to ivory-coloured exceptionally fine-grained garnet and contain excellent terminated thomsonite.

From the assemblages *a-h*, garnets were selected for electron probe microanalysis and results are given in Table 1. Significantly, garnet compositions fall close to either grossular or andradite end-members. Continuous variation from a grossular-rich composition (anal. 6) to andradite (anal. 7) has been detected over 100  $\mu\text{m}$  in one garnet crystal. Also noted was an andradite core (anal. 15) followed by a sharp transition to a broad grossular-rich rim (anal. 14). Examination of the infrared spectra of some garnets from these cavities yielded no evidence for the hydrogrossular molecule being present.

*Discussion.* Formation of garnet at very low temperatures is rarely documented in the literature. Easton *et al.* (1977) gave an account of low-temperature (*c.* 170 °C) metasomatic hydrothermal garnet formation in deep-sea sediments, and also from the Bone Bed of the Rhaetic at Larne, Antrim. The association garnet-zeolite is rare and the only other Scottish record known to the author is that on Mull, where garnet (grossular) is a primary amygdaloe mineral associated with scolecite and rarely chabazite and thomsonite (McLintock, 1915). In the Mull occurrence garnet may be found 'in the centre of the zeolite' though is commonly located at the epidote and prehnite/scolecite junction.

Assemblages in the amygdaloes indicate that the garnet may pre-date, be contemporaneous with, or post-date zeolite formation. Thus, it seems highly improbable that large temperature differences over short distances could be held responsible for vastly dissimilar mineralogy even within a single hand specimen. Kristmannsdottir and Tomasson (1978) detailed zeolite formation in high- and low-temperature geothermal areas in Iceland noting that in the former zeolites formed up to 230 °C and up to 190 °C in the latter. In the Reykjavik geothermal field zeolite occurrence is closely related to the primary rock temperature. For development of the thomsonite zone Kristmannsdottir and Tomasson (1978) estimated a range of approximately 45 °C, from close on 65 to 110 °C. In Yellowstone Park drill cores the most important factor controlling zeolite formation is the thermal water chemistry and the rocks through which they flow rather than temperature (Bargar *et al.*, 1981).

Within the garnet-bearing zone at Loanhead quarry diverse amygdaloe mineralogy strongly suggests an influx of chemically different solutions. A single pulse may conceivably have been chemically inhomogeneous and changing dramatically as it migrated further from the dyke. Although the lavas adjacent to the dyke are not thermally metamorphosed the latter probably provided the

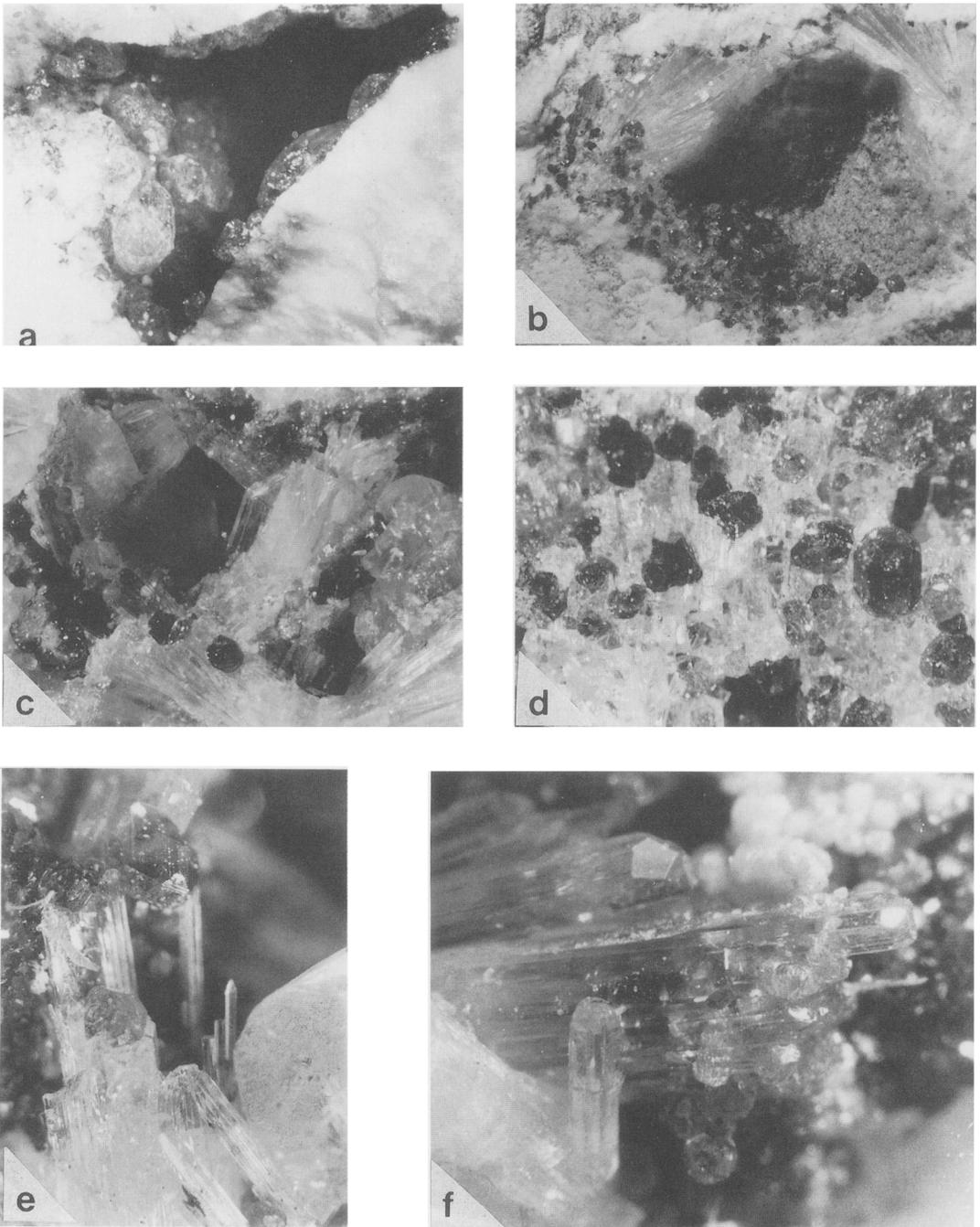


FIG. 1. (a) Triangular cavity in chalky alcime lined with garnet. (b) Cavity with thomsonite sprays (upper half) and garnet (dark) lower half. (c) and (d) Simultaneous crystallization of garnet and thomsonite. (e) Garnet crystallization after thomsonite, garnet sitting on end of thomsonite prisms. (f) Garnet after thomsonite.

Table 1. Electronprobe-microanalyses of garnets

	1	2	3	4	5	6	7	8
SiO <sub>2</sub>	35.66	35.57	36.04	35.83	35.59	39.45	35.71	35.64
TiO <sub>2</sub>	0.04	0.01	0.02	0.02	0.02	0.04	0.01	0.03
Al <sub>2</sub> O <sub>3</sub>	0.03	0.03	0.43	0.02	0.02	18.65	0.16	-
Fe <sub>2</sub> O <sub>3</sub>	30.52	30.12	29.87	30.27	29.69	5.49	29.46	30.28
MnO	0.06	0.18	0.18	0.20	0.07	0.22	0.11	0.47
MgO	0.06	0.06	0.17	0.07	0.20	0.79	0.13	0.10
CaO	33.56	33.77	33.65	33.67	33.89	36.15	34.11	33.32
Na <sub>2</sub> O	0.03	-	0.02	0.03	-	0.01	-	0.02
	99.96	99.74	100.38	100.11	99.48	100.80	99.69	99.86

	9	10	11	12	13	14	15
SiO <sub>2</sub>	35.84	35.89	36.96	39.82	35.91	39.37	35.38
TiO <sub>2</sub>	0.02	0.01	0.01	0.02	0.02	0.12	0.03
Al <sub>2</sub> O <sub>3</sub>	0.01	0.02	3.82	21.20	-	17.97	0.27
Fe <sub>2</sub> O <sub>3</sub>	29.85	30.19	25.46	2.31	30.43	6.20	30.55
MnO	0.46	0.18	0.13	0.17	0.31	0.36	0.85
MgO	0.09	0.02	0.01	0.19	0.15	0.22	0.03
CaO	33.26	33.68	34.49	37.27	33.35	36.50	32.54
Na <sub>2</sub> O	0.03	0.02	0.02	-	0.01	0.02	0.03
	99.56	100.01	100.90	100.98	100.18	100.76	99.68

1. Brown garnet from cavity, garnet on top of epidote and hematite.
2. Yellow garnet from tip of thomsonite spray, calcite present in cavity which is lined with clinopyroxene.
3. Second grain, as for 2.
4. Brown garnet from a fissure containing yellow and cream garnet, calcite, goethite, clinopyroxene, albite/oligoclase and epidote.
5. Yellow garnet, as for 4.
- 6.7. Cream garnet, as for 4, two spots 100 $\mu$ m apart.
8. Yellow garnet from a filled amygdale containing only calcite and garnet, latter disseminated throughout the former.
9. Second grain, as for 8.
10. Pale brown from large cavity (6 cm) lined with chalky analcime and containing clear, terminated thomsonite up to 1 cm. Garnet crystallised simultaneously with, and post, thomsonite.
11. Pale brown, as for 10.
12. White garnet lining large 6-7 cm amygdale containing clear thomsonite.
13. Brown garnet associated with hematite, magnetite and calcite.
14. Clear, broad zone around a yellow core in garnet from garnet-lined cavity.
15. Yellow core, as for 14.

heat for generation of a secondary, localised hydrothermal system with its accompanying characteristic mineralogical overprint. Heating studies on thomsonite suggest that the zeolite loses eight H<sub>2</sub>O molecules up to 350 °C (van Reeuwijk, 1972). It seems reasonable to assume that garnet formed from a Na-Al-Si-Ca-Fe-rich fluid, from which excess Ca and/or Fe developed to generate calcite

or hematite respectively at temperatures probably considerably below 300 °C.

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### References

- Bargar, K. E., Beeson, M. H., and Keith, T. E. C. (1981) *Mineral. Rec.* **12**, 29–38.
- Easton, A. J., Hamilton, D., Kempe, D. R. C., and Sheppard, S. M. F. (1977) *Mineralogy Towards the Twenty-first Century*, Phil. Trans. R. Soc. London, A., 253–71.
- Hedde, M. F. (1901) *The Mineralogy of Scotland* (ed. J. G. Goodchild). **1** and **2**, David Douglas.
- Kristmannsdottir, H., and Tomasson, J. (1978) In

*Natural Zeolites* (Sand, L. B. and Mumpton, F. A., eds). Pergamon Press Ltd.

McLintock, W. F. P. (1915) *Trans. R. Soc. Edinb.* **51**, 1, 1–33.

Meikle, T. K. (1989) *J. Russ. Soc.* (in press).

van Reeuwijk, L. P. (1972) *Am. Mineral.* **57**, 499–510.

Walker, G. P. L. (1951) *Mineral. Mag.* **29**, 773–91.

— (1960) *Ibid.* **32**, 503–27.

— (1971) *West Commem. Vol.* (Univ. Saugar, India).

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