many of the rock series (e.g. Taupo, New Zealand (Grange 1937; Steiner 1958; Ewart 1965) and the Southern Californian batholiths (Larsen 1948)) are broadly similar to the calculated acid liquid fractionates from the quartz diorite at 0–9 kb (see Table IX), particularly in K_2O/Na_2O ratios.

Rare corroded plagioclase phenocrysts with albite-rich cores occur in some andesites where most of the plagioclase phenocrysts contain cores more calcic than rims (Williams 1932). These corroded albite-rich cores may represent early crystallization of the andesite at depth, where a more albite-rich plagioclase composition would be the equilibrium liquidus phase, in contrast to the more calcic composition obtained at shallower levels from the same parent.

Similarly, pyroxene phenocrysts with high-alumina contents may also indicate early crystallization at a deep level.

Conclusions

The experimental results on the anhydrous high pressure fractional crystallization of high-alumina basalt and gabbroic anorthosite effectively preclude any simple means of deriving highly aluminous magmas at depth, and it is unlikely that magmas with compositions as rich in plagioclase as gabbroic anorthosite are obtainable by hydrous fractional crystallization of a parent basaltic composition. However, the experimental results on the fractional crystallization of quartz diorite ($\approx$andesite) at 0–13.5 kb point to two possible geological models for obtaining anorthositic rocks, either by fractional crystallization or partial melting of a parent quartz diorite composition at lower crustal depths. In both cases the anorthositic rocks form as a crystalline residuum deep within the crust, and are essentially 'frozen' in their position of formation, except possibly for minor movement as a semi-solid crystal mush. This explains the association of anorthosites with charnockitic and granulitic rocks typically found in Precambrian metamorphic terrains. Anorthosites may well occur in younger rocks where these have been buried deep within the crust, but processes of orogenesis and erosion have not exposed these younger high-grade metamorphic terrains extensively at the earth's surface.

The models also explain the sodic nature of the plagioclase typically found in the massive anorthosite complexes, since the soda content of the plagioclase crystallizing from a parent quartz diorite composition increases with increasing pressure. Rock types related genetically to anorthosites and gabbroic anorthosites may range from granite to gabbro, depending on the degree and nature of the separation of the crystalline residuum from the parent intermediate composition magma. Spatial association of these varied, but genetically related, rocks need not necessarily be maintained.

Finally, it should be pointed out that there will be a range of compositions in the calc-alkaline series from which a large field of crystallization of sodic plagioclase will occur in the pressure range of 0–13.5 kb. Accordingly there will be some variation in plagioclase composition and the relative proportions of genetically related rock types, depending on the nature of the parent magma.

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BALK, R. 1931. Structural geology of the Adirondack anorthosite. Min. Pet. Mitt., **41**, pp. 308–434.

BARTH, T. F. W. 1933. The large Precambrian intrusive bodies in the southern part of Norway. Rept. XVI Session, Intern. Geol. Cong., pp. 297–309.

BERG, R. B. 1966. Petrology of anorthosites of the Bitterroot Range, Montana (Abstr.). *In* Symposium on the origin of anorthosites. State Univ. College, Plattsburgh, New York, October 1966, p. 25.

BOWEN, N. L. 1917. The problem of anorthosites. J. Geol., **25**, pp. 209–243.

BUDDINGTON, A. F. 1939. Adirondack igneous rocks and their metamorphism. Geol. Soc. Amer., Mem. 7.

——— 1961. The origin of anorthosite re-evaluated. Geol. Surv. India, Records 86, pp. 421–432.

DALY, R. A. 1933. Igneous rocks and the depths of the earth. McGraw-Hill Book Co., New York.

DE WAARD, D. 1966. The anorthosite problem: The problem of the anorthosite–charnockite suite of rocks (Abstr.). *In* Symposium on the origin of anorthosite. State Univ. College, Plattsburgh, New York, October 1966, pp. 7–8.

VON ECKERMANN, H. 1938. The anorthosite and kenningite of the Nordingra-Rodo region. Geol. Foren. Stockholm Forh., **60**, pp. 243–284.

EMSLIE, R. F. 1965. The Michikamau anorthositic intrusion, Labrador. Can. J. Earth Sci., **2**, pp. 384–399.

ENGEL, A. E. J., ENGEL, C. G., and HAVENS, R. G. 1965. Chemical characteristics of oceanic basalts and the upper mantle. Bull. Geol. Soc. Amer., **76**, pp. 719–734.

EWART, A. 1965. Mineralogy and petrogenesis of the Whakamaru ignimbrite in the Maretai area of the Taupo volcanic zone, New Zealand. N.Z. J. Geol. Geophys., **8**, pp. 611–677.

GOLDSCHMIDT, V. M. 1954. Geochemistry. (A. Muir, *Ed.*) Oxford Univ. Press, Oxford.

GRANGE, L. I. 1937. The geology of the Rotorua–Taupo sub-division. N.Z. Geol. Surv. Bull., **37**.

GREEN, D. H. and RINGWOOD, A. E. 1967. An experimental investigation of the gabbro to eclogite transformation and its petrological applications. Geochim. Cosmochim. Acta, **31**, pp. 767–833.

GREEN, T. H. 1967*a*. An experimental investigation of sub-solidus assemblages formed at high pressure in high-alumina basalt, kyanite eclogite and grosspydite compositions. Contr. Mineral. Petrol., **16**, pp. 84–114.

——— 1967*b*. High pressure experimental investigations on the origin of high-alumina basalt, andesite and anorthosite. Unpublished PhD. thesis, Australian Natl. Univ., Canberra, Australia.

——— 1969. Experimental fractional crystallization of quartz diorite and its application to the problem of anorthosite origin. *In* Symposium on the origin of anorthosite (Y. Isachsen, *Ed.*) (in press).

GREEN, T. H., GREEN, D. H., and RINGWOOD, A. E. 1967. The origin of high-alumina basalts and their relationships to quartz tholeiites and alkali basalts. Earth Planetary Sci. Lett., **2**, pp. 41–51.

GREEN, T. H. and RINGWOOD, A. E. 1968. Genesis of the calc-alkaline igneous rock suite. Contr. Mineral. Petrol., **18**, pp. 105–162.

GREEN, T. H., RINGWOOD, A. E., and MAJOR, A. 1966. Friction effects and pressure calibration in a piston-cylinder apparatus at high pressure and temperature. J. Geophys. Res., **71**, pp. 3589–3594.

HARGRAVES, R. B. 1962. Petrology of the Allard Lake anorthosite suite, Quebec. *In* Petrologic studies (A. E. J. Engel, H. L. James, and B. F. Leonard, *Eds.*). Geol. Soc. Amer., Buddington Vol., pp. 163–189.

HIGGS, D. V. 1954. Anorthosite and related rocks of the western San Gabriel Mountains Southern California. Univ. Calif. Dept. Geol. Sci. Bull., **30**, pp. 171–222.

KRANCK, E. H. 1961. The tectonic position of the anorthosites of eastern Canada. Compt. Rend. Soc. Geol. Finlande, **33**, pp. 299–320.

LARSEN, E. S. 1948. Batholith and associated rocks of Corona, Elsinore and San Luis Rey quadrangles, Southern California. Geol. Soc. Amer., Mem. 29.

LETTENEY, C. D. 1966. Petrology, chemistry, and field relationships of the Thirteenth Lake anorthosite–metanorite–charnockite series, south-central Adirondack highlands, New York (Abstr.). *In* Symposium on the origin of anorthosite. State Univ. College, Plattsburgh, New York, October 1966, pp. 12–13.

MORSE, S. A. 1966. Layered intrusions and anorthosite genesis (Abstr.). *In* Symposium on the origin of anorthosite. State Univ. College, Plattsburgh, New York, October 1966, pp. 16–17.

NOCKOLDS, S. R. 1954. Average chemical composition of some igneous rocks. Bull. Geol. Soc. Amer., **65**, pp. 1007–1032.

OLMSTED, J. F. 1966. Petrology of a Keeweenawan anorthositic intrusion in northwestern Wisconsin (Abstr.). *In* Symposium on the origin of anorthosite. State Univ. College, Plattsburgh, New York, October 1966, p. 23.

PETTIJOHN, F. J. 1957. Sedimentary rocks (2nd edn.). Harper and Bros., New York.

PHILPOTTS, A. R. 1966. Origin of the anorthosite–mangerite rocks in southern Quebec. J. Petrol., **7**, pp. 1–64.

STEINER, A. 1958. Petrogenetic implications of the 1954 Ngaurahoe lava and its xenoliths. N.Z. J. Geol. Geophys., **1**, pp. 325–363.

SUBRAMANIAM, A. P. 1956. Petrology of the anorthosite–gabbro mass at Kadavur, Madras, India. Geol. Mag., **93**, pp. 287–300.

TAYLOR, S. R. and WHITE, A. J. R. 1965. Geochemistry of andesites and the growth of continents. Nature, **208**, pp. 271–273.

TURNER, F. J. and VERHOOGEN, J. 1960. Igneous and metamorphic petrology (2nd edn.). McGraw-Hill Book Co., New York.

WHEELER, E. P. 1942. Anorthosite and associated rocks about Nain, Labrador. J. Geol., **50**, pp. 611–641.

——— 1960. Anorthosite–adamellite complex of Nain, Labrador. Bull. Geol. Soc. Amer., **71**, pp. 1755–1762.

——— 1966. Minor intrusives associated with the Nain anorthosite (Abstr.). *In* Symposium on the origin of anorthosite. State Univ. College, Plattsburgh, New York, October 1966, p. 21.

WILLIAMS, H. 1932. Geology of the Lassen Peak National Park, California. Univ. Calif. Dept. Geol. Sci. Bull., **21**, pp. 195–385.

WINKLER, H. G. F. and VON PLATEN, H. 1960. Experimentelle gesteinsmetamorphose—III Anatektische ultrametamorphose kalkhaltiger tone. Geochim. Cosmochim. Acta, **18**, pp. 294–316.