

that the phenocrystic garnets initially crystallized directly from the magma under equilibrium conditions at an early stage of crystallization, and later became unstable in their subsequent environment.

The experimental work described in this paper has shown that almandine-rich garnets occur on and near the liquidus in calc-alkaline rocks at high pressure. These results, when considered in relation to the phenocrystic habit of the natural almandine garnets found in calc-alkaline rocks, suggest that the garnets formed from the calc-alkaline magma at an early stage of crystallization at great depth within the earth. These garnets subsequently react to a low pressure assemblage (e.g. cordierite-hypersthene) at high levels in the crust.

An investigation of the origin of these garnets has been described in an accompanying paper (T. H. GREEN and RINGWOOD, 1968). In this study almandine-rich garnets were crystallized on or near the liquidus in a natural rhyodacite composition at pressures of > 9 kb. From a comparison of the composition of the near-liquidus garnets obtained experimentally with the composition of a large number of natural garnet phenocrysts from calc-alkaline rocks of Victoria, Australia, it was concluded that the garnet phenocrysts provide relict evidence for the early crystallization of calc-alkaline magmas at depth, and consequently support the models involving the origin of the calc-alkaline series in the upper mantle or lower crust.

b) Resorbed Quartz Phenocrysts in Calc-Alkaline Rocks

As mentioned on p. 108 quartz phenocrysts showing varying degrees of resorption commonly occur in the acid members of the calc-alkaline series. This resorption has been attributed to fluctuation in water vapour pressure in the partially crystallized magma (EWART, 1965). This alters the position of the quartz-feldspar minimum (TUTTLE and BOWEN, 1958) and may cause the resorption of quartz. However in such a mechanism the release of water vapour pressure would result in a rise in liquidus temperature and consequently an increase in crystallization. This would be the major effect — any shift in the eutectic causing feldspar instead of quartz to crystallize (and hence causing resorption of quartz) would be a second order feature. The present experimental work indicates that resorption may also be due to change in load pressure. Thus at high pressure under dry conditions, quartz is the liquidus phase in the rhyodacite and dacite compositions, but at low pressure quartz is replaced by feldspar as the liquidus phase. Hence a magma rising from depth may contain early crystallized quartz phenocrysts which when carried into a low pressure environment are no longer in equilibrium with the melt and so undergo resorption. The comparative abundance of quartz phenocrysts in the acid calc-alkaline magmas and the rarity of garnet may be explained by the ease of transport of quartz phenocrysts compared with garnet, due to the small density difference between quartz and the acid magma, compared with the large density difference between garnet and the magma.

c) Trace Element Distribution and Isotope Ratios in the Calc-Alkaline Suite

At present there is a scarcity of systematic data on the trace element distribution and the isotope ratios of the various rock types comprising the calc-alkaline suite in a particular province. NOCKOLDS and ALLEN (1953) have carried out an investigation of the trace element distribution in members of the calc-alkaline

provinces of north-western North America, the Southern Californian batholiths, Lesser Antilles, and the Scottish Caledonian. TAYLOR and WHITE (1966) report the trace element content of a number of andesites from Japan and New Zealand.

In the two stage process proposed for the origin of the calc-alkaline suite, the trace element distribution will be governed by the initial distribution in the basalt pile developed as a first stage in the process, and then by the nature of the partial melting processes operating in the second stage, and finally by the subsequent rise of the magma to the earth's surface. D. H. GREEN and RINGWOOD (1967) indicated that simple crystal fractionation in a closed system could not explain the minor element chemistry of basalts. They outlined and discussed processes of wall-rock reaction and wall-rock contamination which may operate to modify the trace element distribution observed in basalts, and which may produce a considerable variation in the distribution of the trace elements and in the isotope ratios.

Similar arguments apply to the derivation of the calc-alkaline suite, but in this case the final result may be extremely variable from one calc-alkaline province to another, because of the potential duplicated interplay of processes of wall-rock reaction and contamination during the two stage genesis of the calc-alkaline series. Also there may be extensive reaction and contamination of the calc-alkaline magma where it intrudes through great thicknesses of sediments in active orogenic areas. Thus it may be very hard to determine patterns of distribution of minor elements which are characteristic of the calc-alkaline series in general.

An increasing amount of data on initial strontium isotope ratios found for the calc-alkaline series indicates that the ratio $\text{Sr}^{87}/\text{Sr}^{86}$ characteristically falls in the range from about 0.704—0.708 (HURLEY *et al.*, 1965; EWART and STIPP, 1967). This is significantly lower than expected for ratios obtained in calc-alkali rocks derived from magma generation by anatexis processes involving old crustal rocks. It is also significantly higher than the ratio typical of oceanic tholeiites, and believed to represent the mantle $\text{Sr}^{87}/\text{Sr}^{86}$ ratio, at least in oceanic areas (ENGEL, ENGEL and HAVENS, 1964). However the above range of $\text{Sr}^{87}/\text{Sr}^{86}$ for the calc-alkaline series overlaps with the range of ratios found for some continental tholeiites (GAST, 1960; FAURE and HURLEY, 1963).

The two stage models for the origin of the calc-alkaline series proposed in this work can explain the relatively low values for the initial strontium isotope ratios, since melting of a basalt pile with low strontium isotope ratios characteristic of basaltic rocks would give rise to derivative magmas with correspondingly low ratios. Conversely because of the possible variation in the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of the initial basalt pile, calc-alkaline rocks derived from such piles, according to either of the two models outlined, may have moderately high initial strontium isotope ratios (e.g. up to 0.708). Thus contamination with material enriched in radiogenic strontium is not essential to produce isotope ratios of these values in the calc-alkaline series.

From a study of the lead isotopes from western and midwestern United States, DOE (1967) suggested that one possible explanation of the data was that the rocks were derived by partial melting of basaltic-gabbroic parent material, possibly in the mantle in the western coastal regions and in the lower crust in the mid-western interior regions. The data preclude derivation of the calc-alkaline rocks