

Table 3
Electron microprobe analyses of amphiboles from selected wet runs on the high-alumina quartz tholeiite composition.

| Conditions of run | 10 kb | 10 kb | 9 kb | 9 kb | 10 kb | 10 kb | 10 kb | 10 kb |
|--|-------------------------------------|------------|--------------|---------------------------------|------------|--------------------|-------------------------------------|--------------|
| | 920°C | 960°C | 1040°C | 1040°C | 960°C | 920°C | 940°C | 920°C |
| | 7½ hr | 4 hr | 4 hr | 4 hr | 4 hr | 7½ hr | 6 hr | 5½ hr |
| | WET | WET | WET | WET | WET | WET | WET | WET |
| | Runs conducted in platinum capsules | | | Analyses adjusted for iron loss | | | Runs conducted in graphite capsules | |
| Co-existing phases | cpx *, opx, plag * | cpx *, opx | cpx *, opx * | cpx *, opx * | cpx *, opx | cpx *, opx, plag * | cpx *, opx, mt | cpx, opx, mt |
| SiO ₂ | 40.5 | 40.8 | 39.8 | 39.3 | 40.2 | 39.9 | 40.0 | 40.2 |
| TiO ₂ | 2.9 | 2.8 | 3.9 | 3.8 | 2.8 | 2.9 | 3.0 | 3.1 |
| Al ₂ O ₃ | 15.8 | 14.4 | 15.8 | 15.6 | 14.2 | 15.6 | 14.8 | 15.4 |
| FeO | 10.0 | 8.2 | 7.6 | 9.8 | 10.6 | 12.6 | 9.4 | 9.8 |
| MgO | 13.1 | 14.9 | 14.9 | 13.7 | 13.6 | 11.6 | 12.9 | 12.1 |
| CaO | 12.4 | 11.7 | 12.0 | 11.8 | 11.5 | 12.2 | 11.6 | 11.8 |
| Na ₂ O | 2.5 | 2.7 | 2.9 | 2.9 | 2.7 | 2.5 | 2.0 | 1.8 |
| K ₂ O | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.4 | 0.3 | 0.3 |
| | 97.6 | 95.9 | 97.1 | 91.7 | 96.0 | 97.7 | 94.0 | 94.5 |
| $\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}}$ | 70.3 | 76.4 | 77.8 | 71.4 | 69.6 | 62.1 | 71.0 | 68.8 |

Structural formulae – calculated on 'dry' basis of 23 [0] since H₂O content could not be determined

| | | | | | | | | | |
|---|------|-------|-------|-------|-------|-------|-------|-------|-------|
| z | { Si | 5.932 | 6.025 | 5.802 | 5.790 | 6.002 | 5.909 | 6.288 | 6.039 |
| | { Al | 2.068 | 1.975 | 2.198 | 2.210 | 1.998 | 2.091 | 1.712 | 1.961 |
| y | { Al | 0.659 | 0.531 | 0.516 | 0.498 | 0.500 | 0.631 | 1.029 | 0.766 |
| | { Ti | 0.320 | 0.311 | 0.427 | 0.422 | 0.314 | 0.323 | 0.354 | 0.350 |
| | { Fe | 1.209 | 1.013 | 0.927 | 1.208 | 1.324 | 1.561 | 1.236 | 1.231 |
| | { Mg | 2.862 | 3.281 | 3.239 | 3.011 | 3.029 | 2.561 | 3.024 | 2.710 |
| z | { Ca | 1.945 | 1.851 | 1.874 | 1.862 | 1.840 | 1.936 | 1.954 | 1.899 |
| | { Na | 0.709 | 0.861 | 0.820 | 0.829 | 0.781 | 0.717 | 0.610 | 0.524 |
| | { K | 0.074 | 0.075 | 0.037 | 0.037 | 0.075 | 0.075 | 0.060 | 0.058 |
| z | | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| y | | 5.05 | 5.14 | 5.11 | 5.14 | 5.17 | 5.08 | 5.64 | 5.06 |
| z | | 2.73 | 2.79 | 2.73 | 2.73 | 2.70 | 2.79 | 2.62 | 2.48 |

* Denotes co-existing phase analyzed.

enrichment of iron relative to magnesium would have been decreased if the experiments had not been carried out under such reducing conditions, since under more oxidising conditions a significant amount of iron in the trivalent state may be taken into the amphibole and pyroxene structures. For example amphiboles and pyroxenes from plutonic and effusive members of the calc-alkaline series contain a significant amount of ferric iron ($[(100 \text{ Fe}_2\text{O}_3)/(\text{FeO} + \text{Fe}_2\text{O}_3)]$ ranges from 15.7–48.6 for amphiboles and from 19.1–32.8 for clinopyroxenes [13–16]).

The most significant feature of this experimental investigation at 9–10 kb under hydrous conditions where $P_{\text{H}_2\text{O}} < P_{\text{load}}$, is that the amphiboles and pyroxenes are subsilic, so that extraction of these phases provides a very efficient means of enriching liquid fractionates in silica. Thus the residuum in equilibrium with a liquid of basaltic andesite composition will consist of approximately equal proportions of pyroxene and amphibole. However, amphibole and subordinate pyroxene will form the residuum in equilibrium with a liquid of andesite composition (the

Table 4
Electron microprobe analysis of plagioclase from a wet run
on the high-alumina quartz tholeiite composition.

| Conditions of run | 10 kb 920°C 7½ hr |
|--------------------------------|-------------------------|
| Co-existing phases | cpx *, opx, amph * |
| SiO ₂ | 52.9 ** |
| Al ₂ O ₃ | 30.0 |
| CaO | 13.9 |
| Na ₂ O | 3.9 |
| K ₂ O | 0.1 |
| | 100.8 |
| Mol. Prop. | |
| Or | 0.6 |
| Ab | 33.4 |
| An | 66.0 |

* Denotes co-existing phase analyzed.

** Denotes calculated content.

residuum will be approximately 45% by weight of the initial basalt). Finally amphibole, pyroxene, plagioclase and possibly minor garnet will constitute the residuum when dacitic and rhyodacitic liquids are extracted.

The alumina content of the liquids is high when compared with the content normally found in members of the calc-alkaline series. This is attributed to the fact that the experiments have been conducted on a high-alumina basaltic composition. If a basalt with an alumina content of about 14% had been used then the alumina enrichment in the early stages, caused by the separation of pyroxenes and amphibole, would probably have resulted in compositions corresponding to basaltic andesite and andesite with alumina contents of 16–17%. Continued fractionation would involve plagioclase so that the alumina content of the liquid would then decrease.

7. APPLICATION OF RESULTS TO THE ORIGIN OF THE CALC-ALKALINE IGNEOUS ROCK SUITE

These experimental results and calculated fractionation trends suggest that the calc-alkaline igneous rock suite may be derived by the fractional crystalli-

zation of a hydrous basalt at 30–40 km depth under conditions of $P_{H_2O} < P_{load}$, or alternatively by the partial melting of an amphibolitic lower crust at similar depths and water pressure conditions. In both cases the crystalline residuum will consist dominantly of amphibole, with subordinate clinopyroxene and orthopyroxene, and possibly calcic plagioclase and garnet, depending on the extent of fractional crystallization or partial melting.

In the first case the required P_{H_2O} conditions may be obtained in a basalt magma at 30–40 km depth in such areas as continental margins and island arcs. It might be postulated that the ultimate source of the water was the hydrosphere, and that it was introduced into the mantle by a sinking limb of a convection cell containing some hydrated rocks, as in the hypothesis of 'sea-floor spreading' [17]. This, in turn, might explain the association of calc-alkaline rocks with a particular tectonic environment. The basalt magma may be derived by direct partial melting of the mantle at 30–40 km depth (in which case a high-alumina basalt would be expected [18]), or it may have been derived at greater depth and subsequently rose to a depth of 30–40 km before being contaminated with water and undergoing fractional crystallization under hydrous conditions (in this case the parent basalt may be an olivine tholeiite or an alkali basalt type [19]). The overall composition of the calc-alkaline suite resulting from such fractional crystallization will vary to some extent, depending on the parent basaltic composition and on the depth at which the process takes place.

The crystalline residuum will be comparatively poor in alkalis and similar to an alkali-poor olivine tholeiite. Under appropriate P - T conditions subsequent to the fractional crystallization, the residuum may lose its water content and over a long period of time transform to eclogite [20, 10]. The work of Ringwood and D. H. Green demonstrated that such a composition transformed to eclogite more readily than other basalts. If the transformation takes place then the residuum may subsequently sink into the mantle because of its high density ($\sim 3.6 \text{ g/cm}^3$). In this way no volume problem arises regarding the crystalline residuum resulting from the derivation of the calc-alkaline series from the fractional crystallization of a parent basalt.

In the second case it is envisaged that the calc-