

mina 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. However it is significant to note that although some alumina enrichment occurs in the early stages of fractionation, derivation of liquids of highly aluminous compositions such as anorthosite or gabbroic anorthosite by the fractionation of basalt under wet conditions is not likely (c.f. suggestion of YODER and TILLEY, 1962; YODER, 1966; BUDDINGTON, 1961). The liquids obtained are too enriched in silica and depleted in lime to correspond to gabbroic anorthosite. Also alumina enrichment is not sufficiently high before crystallization of plagioclase begins. The problem of the derivation of anorthositic compositions is dealt with in greater detail elsewhere (T. H. GREEN, 1966, 1967b).

### Comparison of Experimental Fractionation Trends with Natural Calc-Alkaline Trends

The general fractionation trends under dry conditions for the two basalts, basaltic andesite and andesite compositions at 27–36 kb are plotted in Fig. 13. For

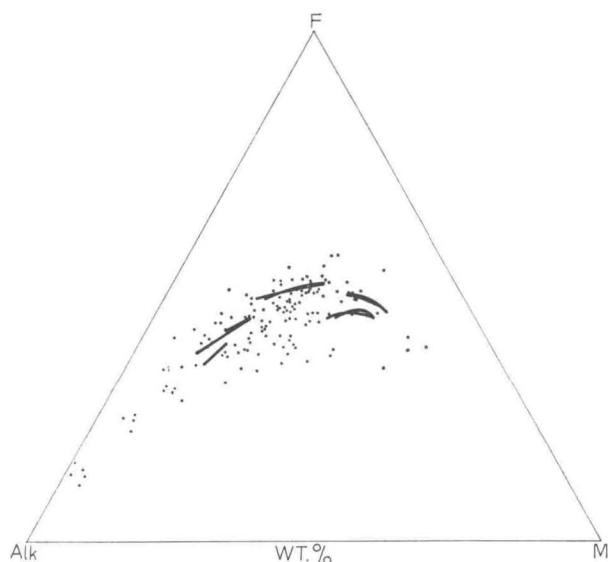


Fig. 13. FMA plot for the Aleutian Islands calc-alkaline province. The experimentally determined fractionation trends at 27–36 kb are superimposed on this plot as solid lines for comparison between the natural and experimental fractionation trends

comparison, a plot of analyses of calc-alkaline rocks from the Aleutian island arc calc-alkaline province is also given. The similarity of the trends is apparent. Minor iron enrichment relative to magnesium occurs in the more basic compositions, but there is no marked iron enrichment as characterized by tholeiitic series (e.g. SKAERGAARD, WAGER, 1960; THINGMULI, CARMICHAEL, 1964; KUNO's pigeonitic series of Japan, KUNO, 1965). The fractionation trends observed

experimentally at 18 kb (Fig. 9) do show marked iron enrichment, and at this pressure (and lower pressures as well, since similar phases dominate the crystallization under dry conditions from 0—18 kb) the trends are similar to the typical tholeiitic fractionation trends.

A feature frequently exhibited by basalt to andesite members of the natural calc-alkaline series is the uniform increase in soda and potash contents with increasing silica content of the rocks (also the  $K_2O/Na_2O$  ratio increases uniformly but stays less than unity) until the silica content reaches about 60—65%. For more acid members of the series, the potash content continues to increase but soda begins to decrease, and consequently the  $K_2O/Na_2O$  ratio increases sharply to greater than unity. It is explained by the present experimental work since fractionation trends for members of the suite ranging from basalt to andesite are dominated by pyroxene and garnet (model I — dry melting at 27—36 kb) or by pyroxene and amphibole (model II wet melting at about 10 kb). Of these phases garnet contains no detectable soda or potash, pyroxenes contain minor soda (e.g. 0.6—3.0%) but no detectable potash, and amphibole contains minor soda (e.g. 2.0—2.9%) and subordinate potash (e.g. 0.2—0.4%). Thus extraction of garnet + pyroxene or amphibole + pyroxene results in an increase in both soda and potash in the liquid fractionates, together with a slight increase in the  $K_2O/Na_2O$  ratio (due to the small but significant content of  $Na_2O$  and the absence of  $K_2O$  in the pyroxenes).

However compositions more acid than andesite may only be derived under dry conditions in model I by fractionation at crustal pressures. At these pressures the crystallization is dominated by plagioclase with the result that the more acid liquids obtained are depleted in soda relative to potash. Similarly in model II in compositions more acid than andesite, crystallization becomes dominated by plagioclase. Thus a sharp increase in  $K_2O/Na_2O$  ratio in acid members of the calc-alkaline series result. Alternatively in model I if wet conditions ( $P_{H_2O} < P_{LOAD}$ ) prevail at 27—36 kb more silica-rich compositions than andesite such as dacite or granodiorite may be derived, but in these cases the  $K_2O/Na_2O$  ratio will remain less than unity, unless subsequent fractional crystallization occurs at crustal pressures. The silica-rich but potash-poor dacites of Saipan, Marianas Islands (SCHMIDT, 1957) with low  $K_2O/Na_2O$  ratios may have originated by wet partial melting at mantle depths.

## Geological Evidence

### a) Garnet Phenocrysts in Calc-Alkaline Rocks

Almandine-rich garnet phenocrysts have been recorded in rocks of the calc-alkaline suite from Australia (EDWARDS, 1936; RINGWOOD, 1955), New Zealand (COX, 1926), Japan (MIYASHIRO, 1955), England (OLIVER, 1956), and Russia (MAKAROV and SUPRYCHEV, 1964). They are most common in dacites, rhyodacites and granodiorites, but may also occur in andesites and rhyolites. MIYASHIRO (1955) emphasized the compositional differences between garnets occurring as phenocrysts in calc-alkaline lavas and plutonic rocks (almandine-rich with some pyrope, spessartine poor), and those occurring either in cavities in calc-alkaline lavas, or in pegmatites associated with calc-alkaline plutonic rocks (almandine-spessartine-rich, pyrope poor). EDWARDS (1936) and OLIVER (1956) concluded