ing from the Fe-Mg side to the alkali apex (Fig. 13 and TILLEY, 1950). There is a little iron enrichment relative to magnesium with increasing total alkali content (i.e. with increasing silica content). This contrasts with the typical tholeiitic fractionation trend which shows marked iron enrichment in the early and middle stages of fractionation (e.g. WAGER, 1960; CARMICHAEL, 1964). The calc-alkaline band is most pronounced for compositions ranging from basaltic andesite to rhyolite. The more basic compositions scatter from a distinct band and indicate some iron enrichment relative to magnesia (see Fig. 13). Some of the scatter of these points may also be due to analyses of rocks which are in part accumulative, and do not represent a true liquid line of descent. Although there is little variation in the Mg/Fe ratio of a calc-alkaline sequence as a whole, there is evidence for iron enrichment in individual lava flows as crystallization proceeds under surface or near surface conditions (WILLIAMS, 1932).

The calc-alkaline rock suite is often characterized by high-alumina content ($\sim 17\%$ Al_2O_3) in basaltic to andesitic members. There may be considerable variations in the alkali/lime index between different provinces. In particular lime is high in the Marianas and Japanese provinces and potash is generally low (SCHMIDT, 1957; KUNO, 1950) compared with the Western North American province where potash is generally high and where there are two distinct zones of differing lime contents — a western zone of more calcic volcanic rocks contrasted with an eastern zone of less calcic rocks (WILLIAMS, 1932, 1935; THAYER, 1937; COOMBS, 1939).

It is important to note that chemical analyses of the groundmass of calc-alkaline rocks or groundmass compositions calculated from known bulk compositions and known phenocryst mineralogy and composition, demonstrate that liquids from basaltic andesite to rhyolite in composition exist in some calc-alkaline provinces. Thus WILLIAMS (1934) showd that the glassy groundmass of a hypersthene andesite approached rhyolite in composition, while WILCOX (1954) indicated that the groundmass composition of the Paricutin lavas varied from basaltic andesite to andesite. This is approximately similar to the variation observed in the bulk rock compositions. Similarly KUNO (1950) demonstrated that the groundmass compositions of representatives of the calc-alkaline rocks of Japan varied from basaltic andesite to rhyodacite in composition. This evidence is critical in explaining the origin of this type of calc-alkaline sequence, since any hypothesis of origin must allow the derivation of such a range of liquid compositions (basic to acid) of appropriate chemistry.

In contrast to the evidence for a line of liquid descent in some localities, it has also been demonstrated that some members of the calc-alkaline suite have been derived by hybridization of an acid magma by basic igneous rocks e.g. WILKINSON (1966) and WILKINSON *et al.* (1964) describe and discuss the formation of an adamellite porphyrite by such a mechanism, thus illustrating a case where no continuous line of liquid descent occurs.

Mineralogy of the Calc-Alkaline Suite

The mineralogy and petrography of the calc-alkaline series are characterised by non-equilibrium assemblages and markedly porphyritic texture. The members of the series display large phenocrysts with varying degrees of zonation and resorption set in a glassy or fine grained groundmass. In the more basic members (basalts to some andesites) the groundmass is usually crystalline, while in the acid members (dacites to rhyolites) it is usually glassy.

The phenocryst minerals include mainly plagioclase, clinopyroxene, orthopyroxene, hornblende and quartz, with occasional biotite, opaque minerals, olivine and garnet. In the glassy acid representatives of the calc-alkaline suite quartz and plagioclase are the most common phenocrysts, often showing signs of resorption. Biotite and almandine-rich garnet occur rarely. In the more basic compositions (basaltic andesite, andesite), plagioclase is by far the most abundant phenocryst and groundmass mineral comprising 50—70% of the rock. Phenocrysts are typically zoned, with either normal, oscillatory or reversed zones, often with resorbed margins to some of the zones. The zoning may range from bytownite to oligoclase.

Phenocrysts of both hypersthene and augite are common. They sometimes show evidence of resorption (e.g. SCHMIDT, 1957). Hypersthene is the most common groundmass ferromagnesian mineral (TAYLOR and WHITE, 1965) but clinopyroxene has also been recorded (VERHOOGEN, 1937; COOMBS, 1939). Hornblende is the characteristic ferromagnesian phenocryst in some provinces e.g. Japan and the Aleutians but is relatively uncommon in the Marianas Islands, New Zealand and western North America. It usually shows marked resorption. Minor olivine phenocrysts occur in some basaltic andesites and less frequently in andesites where they are usually surrounded by hypersthene coronas (COATS, 1952; COOMBS, 1939; WILCOX, 1954; WILLIAMS, 1932, 1934). Opaque mineral phenocrysts (magnetite or ilmenite) are not common and if they occur comprise $< 5\%$ of the rock. Minute opaque crystals are sometimes scattered through the glassy groundmass, reflecting late-stage sub-aerial oxidation of the rocks during eruption.

Hypotheses of Origin of the Calc-Alkaline Igneous Rock Suite

The calc-alkaline suite consists of a complex association of rock types exhibiting a complex history of crystallization. These features have made it difficult for petrologists to interpret the origin of these rocks, and accordingly several different hypotheses of origin have arisen. There is convincing evidence for a polygenetic origin of the calc-alkaline suite, and it is improbable that a single hypothesis of origin will satisfy all the features of the suite from different localities.

a) Fractional Crystallization of Basaltic Magma

BOWEN (1928) considered that the calc-alkaline rock series was derived by simple fractional crystallization of a basaltic magma. However this is not an efficient mechanism for enrichment in silica because of the moderate silica content of the crystal extract (low-alumina pyroxene, olivine and plagioclase). Thus an initially immense volume of basalt would be required to produce the large volumes of intermediate to acid calc-alkaline compositions observed, and basalt is often not an abundant member of the calc-alkaline series. Also the end product of the fractional crystallization of a tholeiitic basalt magma is tholeiitic andesite (icelandite)