independently of the refractory residuum with which it was formerly associated. The degree of fractional melting which is required before the magma separates from residual crystals doubtless varies according to physical conditions, but perhaps ranges mostly between 20 and 40 percent (by volume).

Many processes of magma generation have been advocated in the past, e.g. melting by relief of pressure, localised melting caused by liberation of energy during earthquakes, melting caused by accumulation of heat in regions characterised by a high concentration of radioactivity, and melting connected with rising "convection" cells or "advective movement" in the mantle. After an examination of possibilities, the authors are of the opinion that the only generally satisfactory mechanism for producing basalt magmas and their observed distribution over the face of the earth and through geologic time, is some process connected with "convection" or "advection" in the mantle. Such processes have been advocated by many authors (e.g. Holmes, 1926, 1927; Verhoogen, 1954). Accordingly we will base our discussion of magma generation on this type of process. Nevertheless it should be pointed out that much of the following discussion is of a general nature and could be applied to some other models of magma generation.

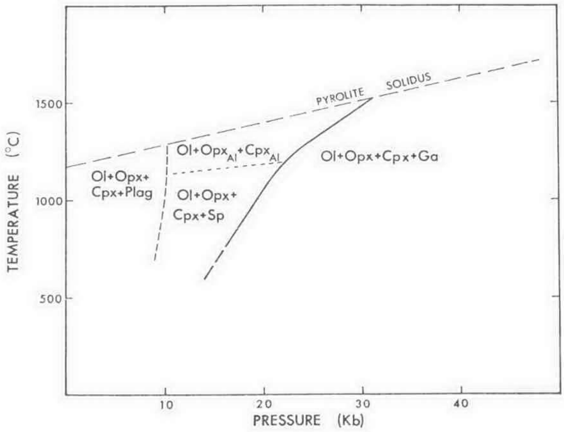

Fig. 11. Preliminary experimental determination of the stability fields of different mineral assemblages in the pyrolite composition of Table 20. The data are for an anhydrous composition and do not include the "ampholite" (olivine + amphibole ± enstatite) assemblage

The condition for gravitational instability in the mantle is that the actual temperature gradient should exceed the adiabatic gradient. This condition is therefore most favourable in the upper few hundred kilometers of the mantle, where the geothermal gradient is greatly in excess of the adiabatic gradient. Indeed, as shown by Clark and Ringwood (1964) it is probable that the density of the mantle actually decreases with depth down to 100 km or so in many regions. Although the outermost mantle many be potentially gravitationally unstable, the triggering-off of an actual instability leading to some form of mass-transfer requires other favourable conditions controlled particularly by rheological properties and by the presence of horizontal inhomogeneities in density, caused either by temperature or chemical differences. Because of the close approach of the actual temperature gradient to the melting point gradient in the uppermost mantle, this region will constitute a zone of low strength and high mobility as previously pointed out by numerous authors. Also, horizontal inhomogeneities are most pronounced in the upper mantle. All these factors contribute towards the occurrence of mass transfer processes in the upper mantle, and their essential restriction to this region.

Processes of mass transfer in the upper mantle are commonly referred to as "convection" a term which characteristically applies to quasiregular, thermally generated motions in a viscous fluid. The analogy has frequently been applied to the earth and it has been argued e.g. VENING MEINESZ (1952, 1962), RUNCORN (1962) that the mantle is characterised by regular arrays of convection cells, extending as deep as the core. Such schemes appear unrealistic and implausible for many reasons. ELSASSER (1963) has provided a stimulating discussion of the subject, and argued convincingly for restriction of mass transport processes to the upper mantle. Furthermore he emphasizes the probable extreme irregularity both in time and configuration, of the processes to be expected in the upper mantle. An additional complication in the models which we shall discuss is that mass motions are accompanied by partial melting and chemical differentiation, and are hence irreversible. Clearly, "convection" in the conventional sense is not an ideal term[5] to apply to such complex processes.

The model for magma generation which we have in mind is given in Fig. 12. It is characterised by a highly specific relationship between the actual temperature distribution and the pyrolite solidus, as shown in the diagram. Gravitational instability in the upper mantle combined with a suitable combination of horizontal inhomogeneity and rheological properties causes a source-mass (S) of solid pyrolite to rise diapirically (in the manner of a salt dome) from the low-velocity zone. It is possible that the initial triggering-off was connected with stresses associated with seismic activity, i.e. the diapir may be derived from an earthquake source-region; however this is not essential. The rising diapir is sufficiently large and hence possesses sufficient thermal inertia in relation to its velocity, so that it cools adiabatically and does not interact by thermal conduction with the surrounding mantle. The adiabatic gradient, of the order of 0.3° C/km (BIRCH, 1952) is much smaller than the gradient of the pyrolite solidus. Accordingly partial melting in the rising diapir will occur as the temperature of the diapir, following the adiabat from S, intersects the solidus at F (Fig. 12). This causes an increase of the density contrast between rising diapir and surrounding mantle and accordingly, an increase in its rate of upward movement. We assume that the partially melted diapir remains adiabatic. As it rises, and the pressure decreases further, the degree of partial melting increases. The absorption of latent heat accordingly steepens the effective adiabatic gradient, and the temperature of

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[5] In a previous paper (RINGWOOD and GREEN, 1966) we adopted the term "advection" for the process, following ELSASSER (1963). Although this term adequately specifies the complexity of the mass transport envisaged, it also carries the implication that the horizontal dimensions of the motions greatly exceed the vertical dimensions. This may not necessarily apply in the upper mantle.