

between oceanic and stable shield geotherms and that this difference takes the form illustrated in fig. 2. Nevertheless, the specific form of the curves, particularly their "convexity" and closeness of approach to the pyrolite solidus, depend sensitively on knowledge of the magnitude of radiative heat transfer in the upper mantle. No unique solution for geothermal gradients is currently possible but a general evaluation of the role of mineralogical zoning in the upper mantle can best be obtained by consideration of the two examples in fig. 2.

Along the Precambrian shield geotherm, the probability of chemical zoning would limit the possible phase assemblages. If rocks of composition approaching pyrolite occur locally, then there may be an extremely limited zone near the base of the crust where these would crystallize to olivine + orthopyroxene (1%  $\text{Al}_2\text{O}_3$ ) + clinopyroxene + spinel assemblages. Similar compositions below about 35–40 km would yield olivine + orthopyroxene (1–2%  $\text{Al}_2\text{O}_3$ ) + clinopyroxene + garnet assemblages and it may be noted that the garnet content would be relatively high (e.g. 12% garnet in pyrolite III composition). No regular change in mineralogy would occur for rocks of pyrolite composition along the Precambrian shield geotherm.

The picture is very different along the oceanic geotherm. The olivine + orthopyroxene + clinopyroxene + spinel assemblage is stable in pyrolite composition to depths of 60–70 km. Within this interval the amount of spinel would decrease and the  $\text{Al}_2\text{O}_3$  content of pyroxenes would increase with increasing depth (reaction (2)). Prior to the incoming of garnet at 60–70 km and about 1000 °C, aluminous spinel would coexist with orthopyroxene containing about 3%  $\text{Al}_2\text{O}_3$ . An intersection of the geotherm with the phase boundary at a higher temperature than that illustrated in fig. 2 would yield assemblages with less spinel and with orthopyroxene of higher  $\text{Al}_2\text{O}_3$  content (4–5%  $\text{Al}_2\text{O}_3$ ).

An extremely steep geothermal gradient, possibly realized only in regions actively producing basaltic magmas, would be required to enter the olivine + aluminous enstatite (6%  $\text{Al}_2\text{O}_3$ ) + aluminous clinopyroxene field. In regions of partial melting and magma generation, such gradients must be attained and it may be noted that garnet does not appear on the pyrolite III (anhydrous) solidus until depths > 100 kms are reached.

At depths of 60–70 km on the oceanic geotherm,

garnet appears from reaction (1) and is in equilibrium with orthopyroxene containing about 3%  $\text{Al}_2\text{O}_3$ . It is estimated that about 6% garnet would appear in pyrolite III composition at 60–70 km on the geothermal gradient illustrated. If the geothermal gradient intersected the boundary at a higher temperature, the amount of garnet appearing would be correspondingly less, e.g. about 3–4% garnet coexisting with orthopyroxene containing about 4.5%  $\text{Al}_2\text{O}_3$ .

The incoming of garnet due to reaction (1) at about 60–70 km in the oceanic mantle probably occurs over a relatively small depth interval (5–15 km). With further penetration along the geotherm into the garnet pyrolite field the amount of garnet may actually *decrease* – this will occur for temperature gradients steeper than the lines of constant  $\text{Al}_2\text{O}_3$  content of orthopyroxene shown in fig. 2. For the gradient shown, pyrolite III will contain about 5% garnet at depths between 90 and 120 km and the mineralogy will remain constant over this interval. At depths greater than 120 km the geothermal gradient becomes increasingly transgressive to the lines of constant  $\text{Al}_2\text{O}_3$  content for orthopyroxene. Thus, along this part of the geothermal gradient, the aluminous pyroxenes will gradually break down to yield an increasing garnet content and low-alumina pyroxenes. At depths of 200–250 km the assemblage of pyrolite III will probably contain 11–12% of garnet.

The transition from aluminous pyroxenes + spinel pyrolite to garnet pyrolite at depths of 60–70 km in the oceanic mantle is in agreement with MACGREGOR'S (1964) data and with the conclusions of ITO and KENNEDY (1967) on the stability of spinel and garnet-bearing peridotite. Although the present work does not support earlier conclusions (RINGWOOD *et al.*, 1964; MACGREGOR and BOYD, 1964) that garnet pyrolite would not in general be stable until depths of 120–150 km, it provides excellent confirmation of the importance at this depth interval of the breakdown of aluminous pyroxenes to garnet + low alumina pyroxenes, the reactions on which these earlier conclusions were based. It should be pointed out that for pyrolite-like compositions with higher pyroxene/(Al, Cr) $_2\text{O}_3$  ratios than pyrolites I, II and III, the field of garnet pyrolite may not be entered until depths in excess of 120 km are reached – this is particularly relevant for mantle regions from which basaltic fractions have been removed (cf. MACGREGOR, 1967). Geothermal gradients steeper than that

Fig. 3. Dis along the o

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