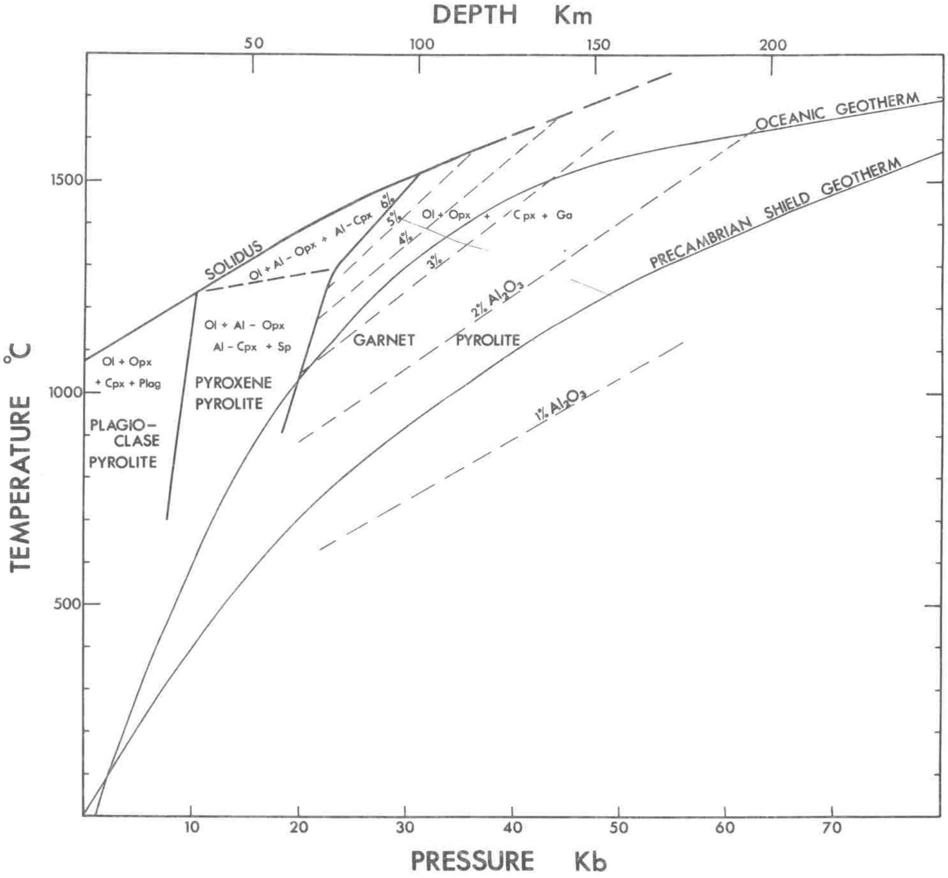

Fig. 2. Diagram illustrating the *P, T* fields of different mineral assemblages in pyrolite III composition. The figures 1%Al_2O_3, 2%Al_2O_3 etc. refer to the Al_2O_3 content of orthopyroxene in equilibrium with garnet in the garnet pyrolite field. The oceanic and Precambrian shield geotherms are those illustrated by Ringwood et al. [13].

simple 2-component systems. This effect is attributed to differences in garnet and pyroxene composition, possibly relating particularly to Ca and Cr contents and the presence of clinopyroxene, between the two component and complex systems. The persistence of spinel to around 1300°C in the pyrolite composition contrasts with its anticipated absence above 1000°C predicted by Ringwood et al. [13] and is also attributed to chemical or coupled reaction effects in the complex composition.

4. MINERALOGY IN A PYROLITE UPPER MANTLE.

In the following discussion, it is assumed that the average composition of the upper mantle beneath oceanic and geologically "young" regions is that of pyrolite. In continental regions and particularly in Precambrian shield regions, there is probably a much greater proportion of refractory residual peridotite at shallower levels and the upper mantle may be chemically zoned [3,4]. Mineralogical variation in the upper mantle is determined by the intersection of geothermal gradients with the stability fields of fig. 1. The variation of temperature in the continental and oceanic crusts and upper mantle has been discussed by Clark [15] and Clark and Ringwood [16]. It is clear from these papers that there is a large difference 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 their closeness of approach to the pyrolite solidus, depend sensitively on knowledge of the magnitude of radiative heat transfer in the upper mantle. Clark and Ringwood [16] assumed an opacity of about 5 cm^{-1} and obtained geotherms about 200°C lower at 150-200 km and 100°C lower at 100 km than those in fig. 2. Ringwood, MacGregor and Boyd [13] and Ringwood [4] assumed a higher opacity for the upper mantle and qualitatively obtained the geotherms which we illustrate in fig. 2. 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 [1,3] would limit the possible phase assemblages. If rocks of composition approaching pyrolite composition occur locally, then there may be an extremely limited zone near the base of the crust where these would crystallize to olivine + orthopyroxene (1%Al_2O_3) + clinopyroxene + spinel assemblages. Similar compositions below about 35-40 km would yield olivine + orthopyroxene (1-2% Al_2O_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 (c.f. refs. [13,14]).

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 [14]. Within this interval the amount of spinel would decrease and the Al_2O_3 content of pyroxenes would increase with increasing depth (reaction 3):

$$\text{(3)}\quad \underset{\text{spinel}}{MgAl_2O_4} + \underset{\text{enstatite}}{m\, MgSiO_3} \rightleftharpoons \underset{\text{aluminous enstatite}}{(m-2)MgSiO_3 \cdot MgAl_2SiO_6} + \underset{\text{olivine}}{Mg_2SiO_4}$$

Prior to the incoming of garnet at 60-70 km and about 1000°C, aluminous spinel would co-exist with orthopyroxene containing about 3% Al_2O_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 Al_2O_3 content (4-5% Al_2O_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% Al_2O_3) + aluminous clinopyroxene field. This is a principal point of difference between the present results and earlier conclusions [13,14,4] and stems from the persistence of spinel to higher temperatures in the complex composition than that predicted by study of the two component systems.

At depths of 60-70 km on the oceanic geotherm, garnet appears from reaction (1) and is in equilibrium with orthopyroxene containing about 3% Al_2O_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 co-existing with orthopyroxene containing about 4.5% Al_2O_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 Al_2O_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 Al_2O_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 data [10] and with the conclusions of Ito and Kennedy [17] on the stability of spinel and garnet-bearing peridotite. Although the present work does not support earlier conclusions [13, 14] 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