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/$(Al,Cr)_2O_3$ 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. Geothermal gradients steeper than that illustrated will have a similar effect in diminishing the amount of garnet produced at 60-70 km depth by reaction (1) and increasing the amount of garnet produced at deeper levels from reaction (2).

This brief discussion serves to illustrate the application of our experimental data to a more flexible range of mantle compositions and geothermal gradients than implied in fig. 2.

5. VARIATION OF SEISMIC VELOCITY WITH DEPTH IN THE UPPER MANTLE

Seismic velocity distributions in the upper mantle will be principally determined by

1. The effects of pressure and temperature changes along the geothermal gradient. Previous authors [18-21] have discussed the opposing effects of temperature increase (causing seismic velocity to decrease) and pressure increase (causing seismic velocity to increase) along a geothermal gradient and concluded that, in homogeneous upper mantle material, seismic velocities V_s and V_p should initially decrease to a minimum and then increase with increasing depth in the upper mantle.
2. The effects of mineralogical variation in the upper mantle. Although later data on the solidus curves for basalts and peridotite have removed some of the reasons for Ringwood's [1] postulate of mineralogical zoning in the upper mantle, experimental evidence on mineral reactions in peridotitic compositions has confirmed the high probability of such effects in the upper mantle.
3. The effects of vertical chemical fractionation of the upper mantle such that some regions may be mainly residual, refractory dunite and peridotite, depleted of low melting components now residing in overlying crustal levels. These effects have been discussed elsewhere [1,3,16] and are probably of greatest significance in mantle regions beneath stable continental shields.

From the data presented in previous sections it is possible to examine qualitatively the effects of the first and second factors in determining seismic velocity along the oceanic geotherm illustrated in fig. 2. It is emphasized that this exercise is of an illustrative nature and no special significance is claimed for the geotherm assumed for fig. 2 or the absolute values of seismic velocities (V_s) estimated in fig. 3.

Fig. 3a is a quantitative expression of the change in mineralogy along the oceanic geotherm, as discussed in the previous section. At depths less than 30 km it is assumed that amphibole may be an important phase in the oceanic upper mantle [2,4]. The effects of these assemblages on density (room T and P) and seismic velocity (V_s) are qualitatively estimated in figs. 3b and 3c. A principal reason for suggesting an amphibolite zone (U_1) at the top of the oceanic mantle is the seismological evidence for an initial *increase* in seismic velocity with depth just below M [18, 22].

In estimating seismic velocity variation with depth it is necessary to know the critical temperature gradient $(\partial T/\partial P)_{V_s}$ for which the seismic velocity V_s remains constant, the opposing pressure and temperature effects just cancelling each other. In the past, critical gradients for V_s of around 6-10°C/km have been predicted on theoretical grounds but Schreiber and Anderson [23] have recently measured critical gradients for V_s in MgO of 2.7°C/km and in Al_2O_3 of 2.1°C/km, values which are considerably lower than those previously assumed for the silicate minerals of the upper mantle. It is possible that the critical gradient for olivine may be somewhat higher than these values. In fig. 3c, a critical gradient for V_s of 4.5°C/km has been assumed, this being the value which would produce a velocity minimum in homogeneous material at a depth of about 130 km along the oceanic geothermal gradient of fig. 2. The assumption of a smaller critical gradient would have the effect of increasing the depth of the velocity minimum. The superimposition of the mineralogical zoning effects and the P,T effects on V_s suggest a "fine structure" in the oceanic upper mantle seismic velocity distribution as follows:

a) *Zone U_1.* A zone in which the mineralogical variation due to decreasing amphibole content produces

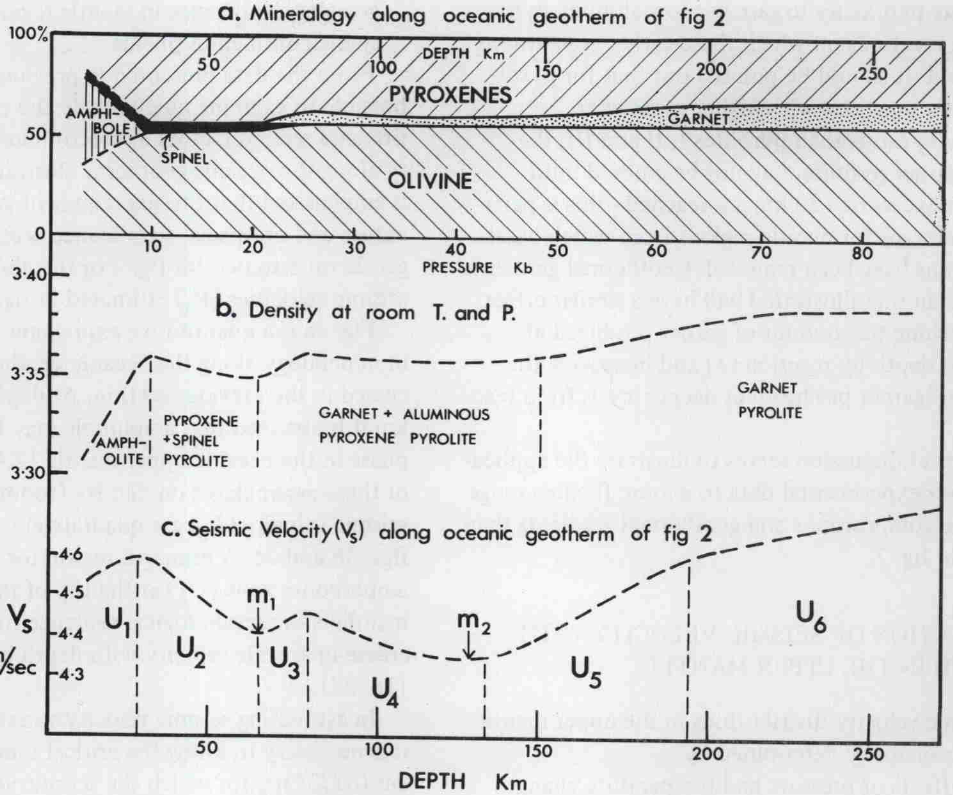

Fig. 3. Diagram illustrating the changes in mineralogy, density (room T and P) and the relative changes in seismic velocity (V_S) along the oceanic geotherm. The mantle is assumed to be of pyrolite III composition and the critical gradient $(\partial T/\partial P)_{V_S} = 4.5^{\circ}$C/km.

an increase in seismic velocity. This is sufficiently large to overcome the temperature effect tending to produce a decrease in seismic velocity.

b) *Zone U_2.* The mineralogical effect of decreasing spinel content produces a density decrease which *augments* the temperature effect, leading to relatively rapid decrease in V_s with depth.

c) *Zone U_3.* A velocity increase is caused by the relatively large density change over a small depth interval caused by the reaction of spinel and pyroxene to yield garnet and olivine. This is sufficient to cancel the temperature effect in decreasing V_s and leads to the narrow but rather sharply defined velocity minimum (M_1) between zones U_2 and U_3.

d) *Zone U_4.* The temperature effect on V_s is dominant but is augmented by slight decrease in garnet content and increase in aluminous pyroxene content (a density decrease). V_s thus decreases to a minimum value with the location of this determined by the critical temperature gradient $(\partial P/\partial T)_{V_S}$ for the upper mantle. If this is 4.5°C/km or thereabouts then the minimum lies above the zone of increasing garnet content (U_5).

e) *Zone U_5.* This is below the critical depth for the geotherm illustrated and increasing depth leads to increase in seismic velocity, even in a homogeneous medium. This is augmented by the mineralogical change in U_5 giving increased garnet content. Thus the rate of increase in seismic velocity with depth is more rapid, leading to a more sharply defined "floor" to the low velocity minimum between U_4 and U_5.

f) *Zone U_6.* This is homogeneous in mineralogy and the seismic velocity increase is that determined by the P,T effect on V_s alone. Zone U_6 extends to about 350 km where a more rapid increase in seismic velocity marks the beginning of the Transition Zone of the mantle and may be attributed to increase of garnet at the expense of pyroxene by solid solution of pyroxene in garnet [24].