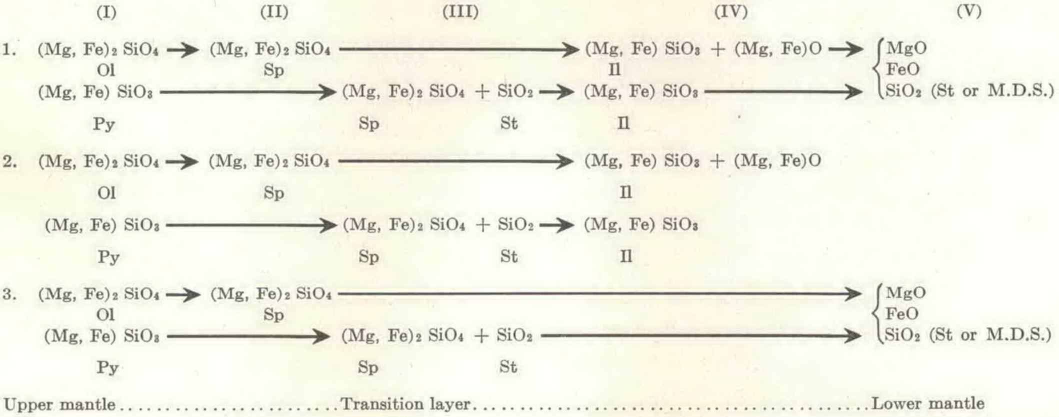
in a narrow range. Most of the values of the [Fe × 100/(Mg + Fe)] ratio of this kind of olivine fall short of 15 and are concentrated around 10 [e.g., *Ross et al.*, 1954; *O'Hara and Mercy*, 1963; *White*, 1966]. The histogram of the values of this ratio for this kind of olivine in inclusions at some localities is shown, for example, in Figure 3.

We therefore use the Fe/Mg ratio of 1:9 for olivine in the upper mantle throughout the following discussions.

POLYMORPHIC CHANGE AND DISCONTINUITIES IN THE TRANSITION LAYER

Results of high-pressure, high-temperature experiments. We will now consider the sequence of polymorphic transitions, which appear likely to occur in the mantle under pressures and temperatures prevailing in the transition layer. In the light of the recent progress in high-pressure research, three probable types of sequences can be written:



where Ol, Py, Sp, Il, St, and M.D.S. denote, respectively, olivine, pyroxene, spinel, ilmenite, stishovite, and the most dense form of silica [see *Akimoto and Fujisawa*, 1967; *Akimoto and Ida*, 1966; *Birch*, 1952; *Ida et al.*, 1967; *Ringwood and Major*, 1966*a, b, c, d; Ringwood and Seabrook*, 1962*a, b*, 1963; *Syono and Akimoto*, 1968].

It is very important that in the $MgSiO_3$-$FeSiO_3$ system pyroxenes remain stable without exception at pressures higher than are required for olivine-spinel transition in olivines having similar Fe/Mg ratios [*Ringwood and Major*, 1966*c, d*]. *Ringwood and Major* [1966*d*] also reported that under the maximum available pressure of their apparatus, $(Mg_{0.75}Fe_{0.25})SiO_3$ pyroxene breaks down partially to spinel plus stishovite at about 900°C. At the same period they succeeded in synthesizing $(Mg_{0.85}Fe_{0.15})_2SiO_4$ spinel at about 900°C with the same apparatus [*Ringwood and Major*, 1966*c*]; for this synthesis pressures greater than about 130 kb are required, in view of the phase diagrams of olivine-spinel transition in the Mg_2SiO_4-Fe_2SiO_4 system [*Akimoto and Fujisawa*, 1967]. Thus, the maximum pressure of their apparatus at that time should have reached up to 130 kb. Accordingly, it seems likely that pyroxenes with a composition around $(Mg_{0.9}Fe_{0.1})SiO_3$ will break down, at least partially, to spinel plus stishovite at about 150 kb and 900°C.

$FeSiO_3$ pyroxene, which once broke down to spinel plus stishovite, recrystallizes to the denser structure (probably ilmenite) under pressures that are considerably higher than the pressure required for the first breakdown (S. Akimoto and Y. Ida, private communication, 1966). It could safely be said, therefore, that among three probable types of sequences of polymorphic transitions mentioned above either of the first two sequences, which have the mineral assemblage of case IV, appears likely to occur. There are two possible cases (IV and V) of the final mineral assemblage for the lower mantle, but there would be little difference in the physical properties between them. Therefore, we adopted only case V for the lower mantle minerals in the density calculation above.

Increase of density at zero pressure ($\Delta\rho_0$) in each transition is shown in Table 2. Strictly

TABLE 2. Rate of Increase of Zero-Pressure Density in High-Pressure Phase Transitions

Reaction	Rate of Density Increase, %
$\underset{Ol}{Mg_2SiO_4} \rightarrow \underset{Sp}{Mg_2SiO_4}$	10
$2\underset{Py}{MgSiO_3} \rightarrow \underset{Sp}{Mg_2SiO_4} + \underset{St}{SiO_2}$	17
$\underset{Sp}{Mg_2SiO_4} \rightarrow \underset{Il}{MgSiO_3}{}^* + MgO$	7.4
$\underset{Sp}{Mg_2SiO_4} + \underset{St}{SiO_2} \rightarrow \underset{Il}{2MgSiO_3}$	4.6
$\underset{Sp}{Mg_2SiO_4} \rightarrow 2MgO + \underset{St}{SiO_2}$	8.5
$\underset{Sp}{Mg_2SiO_4} + \underset{St}{SiO_2} \rightarrow 2MgO + \underset{St}{2SiO_2}$	6.2
$\underset{Il}{MgSiO_3} + MgO \rightarrow 2MgO + \underset{St}{SiO_2}$	1.0
$\underset{Il}{MgSiO_3} \rightarrow MgO + \underset{St}{SiO_2}$	1.5

Notes

Ol denotes olivine; Sp, spinel; Py, pyroxene; St, stishovite; Il, ilmenite.

* The density estimated by Ringwood [1966, pp. 385 and 389] is used.

speaking the density increase ($\Delta\rho$) at the depth of transition is less than the density increase at zero pressure ($\Delta\rho_0$), because high-pressure minerals are generally less compressible, but $\Delta\rho$ would be approximately proportional to $\Delta\rho_0$. The jump of physical properties associated with each transition would be directly related to the density increase $\Delta\rho$ and so related to $\Delta\rho_0$.

As was previously assumed, if the mantle materials are composed mainly of olivine, the breakdown of pyroxene has little influence and makes a minor step or no step in the velocity-depth curve. Thus, there should exist two main steps in the velocity-depth curve, which correspond to olivine-spinel transition and successive breakdown of spinel, provided that a moderate temperature gradient is considered in the transition region (see Table 2).

On the other hand, if the content of coexisting pyroxene increases in the upper mantle, another seismic discontinuity corresponding to the pyroxene breakdown may become apparent at the depth between the olivine-spinel and the post-spinel transitions. At the same time, as the increase in the amount of coexisting minerals (mainly pyroxene) other than olivine becomes greater, the average rate of increase in the density of the mantle materials as a whole in the region of the olivine-spinel transition becomes smaller. If the ratio of olivine to pyroxene is 1:1 in the upper mantle, approximate calculation shows that the average rates of the increase in the density of mantle materials are about 6 and 7% at the olivine-spinel transition and at the breakdown of pyroxene, respectively. Accordingly, three discontinuities, which correspond to the olivine-spinel transition, the pyroxene breakdown, and the post-spinel transition, could possibly be observed in the velocity-depth curve. There remains the possibility, however, that the transition region of the pyroxene breakdown would occur immediately after the region of the olivine-spinel transition. In this case, the first two steps might become combined, and the first steep rise in the velocity-depth curve would, under an adequate temperature distribution, be succeeded by the wide high-velocity gradient zone.

Ringwood and Major [1966*d*] and *Ringwood* [1967] suggested that the newly discovered garnet-pyroxene (e.g., $Mg_3Al_2SiO_3O_{12}$-$MgSiO_3$) solid solutions would occur first at a depth of about 350 km and would cause the recently observed strong velocity gradient. Because in the present model the contents of pyroxene and garnet in the upper mantle materials are assumed to be very small, we will not discuss this problem further. Even if this phenomenon actually occurs, the depth of its occurrence will nearly coincide with the depth of the olivine-spinel transition, judging from their stability relations.

Observed discontinuities. It is very interesting that the recently observed seismic discontinuities are concentrated in two regions around the depths of 350 and 650 km. Some examples are listed below. (This list is not complete; for a more complete list see *Anderson* [1967*a*] and *Johnson* [1967].)

360 and 700 km (CIT 11) [*Anderson and Toksöz*, 1963].
360 ~ 440 km (CIT 11A) [*Kovach and Anderson*, 1964].
350 and 700 km (CIT 12) [*Toksöz and Anderson*, 1966].
350 and 680 km [*Golenetskii and Medvedeva*, 1965].
320 and 640 km (CIT 11CS3) [*Niazi and Anderson*, 1965].
340 km [*Archambeau et al.*, 1966].