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# CHEMICAL CHANGES ASSOCIATED WITH UPPER MANTLE STRUCTURE

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## SUMMARY

Several petrological models have been proposed in recent years to explain the low velocity zone in the earth's upper mantle. In addition to high thermal gradients, these models rely on chemical changes or variations in physical state, which in turn require a density minimum in the upper mantle. It is suggested in this paper that the low velocity zone coincides with a region of increasing iron content. Ultrabasic inclusions with olivine compositions close to 10% fayalite are considered representative of mantle composition at the Mohorovičić discontinuity. Both theoretical investigations of density–velocity relations and shock-wave data for dunites indicate that the intermediate region of the mantle contains rock with a total iron content equivalent to olivine with a composition in the range of 20–40% fayalite. Thus a simple model is proposed for the upper mantle in which the iron-magnesium ratio increases with depth. Consideration of velocity–density relations for compressional and shear waves leads to the conclusion that a change in fayalite content of olivine from 10 to 25% would produce decreases in seismic velocities of 0.25–0.35 km/sec and an increase in density of 0.20 g/cm$^3$.



## INTRODUCTION

During the past few years speculation regarding the nature of the upper mantle has received new impetus from investigations of ultramafic rocks and seismic velocity distributions. Two of the most important features of this region which have been established by seismological studies over the past decade are: (1) there are horizontal variations of $P_n$ and $S_n$ velocities, and (2) a low velocity zone appears to be generally present in the upper mantle. Horizontal variations in $P_n$ and $S_n$ velocities are probably the result of many factors, the most important being regional variations in mantle composition immediately below the Mohorovičić discontinuity, temperature and pressure differences which influence the velocities, and anisotropy due to preferred orientation of olivine.

Evidence for the presence of a low velocity channel in the upper mantle is obtained from travel times of body waves and studies based on surface wave dispersion and the periods of free oscillation of the earth. The distribution of regional variations in the low velocity zone has been discussed by many geophysicists (e.g., Aki and Press, 1961; Herrin and Taggart, 1962; Nuttli, 1963; and Clark and Ringwood, 1964). These studies show that there are regional variations in both the depth and width of the low velocity channel, as well as variations in the actual decrease in velocity. In general, the low velocity zone for P waves is not as continuous as that for S waves. Further, velocity distributions usually show a zone of either constant or increasing velocity between the Mohorovičić discontinuity and the region of velocity decrease.

The region of low velocity has been explained by abnormally high temperature gradients (Birch, 1952; Valle, 1956; Gutenberg, 1959) and vertical changes in chemical composition or transitions between mineral phases. It now appears that in many regions high temperature gradients are not the sole cause of the decrease in velocity with depth. Ringwood (1962a) postulated that the required temperature gradients would lead to extensive melting in a homogeneous upper mantle. Moreover, if high temperature gradients are solely responsible for the low velocity zone, velocity decreases should be most rapid immediately beneath the crust where the temperature gradient is the greatest (MacDonald and Ness, 1961; Clark and Ringwood, 1964; Ringwood, 1966). Because of this, many recent models for the upper mantle have been proposed which rely on changes in mineralogy with depth. Simply the procedure is to replace a relatively high velocity mineral assemblage with a lower velocity assemblage, thus producing a low velocity zone.

## COMPOSITION OF THE MANTLE IMMEDIATELY BELOW THE MOHOROVIČIĆ DISCONTINUITY

Considerable study has recently been given by many investigators to peridotite inclusions and their host rocks. Even though these peridotite nodules have been interpreted as primary xenoliths from the earth's crust or solid products of fractional crystallization from a mafic magma, many petrologists agree that the inclusions are most likely primary mantle material or residual mantle formed after removal of basalt. A majority of ultramafic nodules can be classified into two types: (1) peridotite inclusions in alkali olivine basalts, nephelinites, basanites, and melilite nephelinites which generally contain olivine, orthopyroxene, diopside, and spinel, and (2) garnet peridotite inclusions typically found in kimberlite diatremes which contain pyrope-rich garnet in addition to olivine, pyroxenes, and spinel. Minor hornblende, plagioclase, phlogopite, and various other accessory minerals may be present in both rock types.

White (1966) and Green and Ringwood (1967a) have recently presented comprehensive discussions of the mineralogy and genesis of ultramafic inclusions from basalts. The salient features are summarized as follows:

(1) Lherzolite nodules represent the most abundant type of ultramafic inclusion. Olivine with a limited range of composition ($Fa_{8-15}$) is the most abundant mineral, generally forming 65–90% of the nodules. The remaining minerals consist primarily of aluminous enstatite, chrome diopside, and spinel.

(2) Although other interpretations are possible, the lherzolite inclusions most likely represent fragments of infusible portions of the upper

mantle or a residue produced from partial melting of primary mantle.

(3) The degree of solid solution of the pyroxenes and the low $CaO$ content of olivine suggest that the lherzolite nodules originated from relatively shallow depths in the upper mantle.

Nodules of garnet peridotite have been considered by many investigators as primary constituents of the upper mantle (e.g., O'Hara and Mercy, 1963; Nixon et al., 1963; Stueber and Murthy, 1966). This hypothesis is based on chemical considerations which are consistent with a derivation of basaltic liquids by fractional melting of mantle material of garnet peridotite or pyrolite composition. However, this interpretation has been challenged by Davidson (1967), who considers garnet peridotite inclusions found in kimberlite pipes as fragments of the deeper crust rather than the mantle.

Considerations of the mineralogy and chemistry of peridotite nodules lead to the conclusion that both garnet peridotite and lherzolite nodules in basalts can be samples of the upper mantle. Harris et al. (1967) and White (1967) have established from published chemical analyses that the range in composition of nodules in basalt overlaps the composition of garnet peridotite nodules. Thus the two types of nodules may represent phase transitions of peridotite and differ in mineralogy because they originate from different stability regions within the mantle. The garnet bearing nodules are generally considered to have originated from greater depths than the chemically similar peridotite nodules from basalts (Nixon et al., 1963; Kuno, 1967; Harris et al., 1967). Recent investigations of melting and phase relations of peridotite by Ito and Kennedy (1967) lend support to this; however, they show that garnet peridotite may be the stable assemblage in some regions immediately below the Mohorovičić discontinuity. The experimental results show that garnet peridotite is the stable assemblage below Precambrian shield areas and at depths greater than 70 km below oceanic areas and orogenic zones. In the latter areas garnet-free peridotite, similar in mineralogy to many nodules found in basalt, may be stable at shallow depths. Peridotite nodules which differ chemically from garnet peridotite, in particular those with low alkali content, seem most likely to be a residue from partial melting of "parent" rocks similar in chemical composition to garnet peridotite, or represent products of a more advanced stage of fusion than the garnet peridotites and their low pressure modifications.

Thus it appears that there is strong evidence for lateral as well as vertical heterogeneity in the upper mantle. The mantle immediately below the Mohorovičić discontinuity most likely consists of the assemblage olivine + pyroxenes + garnet (garnet peridotite), and a chemically equivalent peridotite similar to some nodules from basalt, consisting of olivine + pyroxenes + spinel (lherzolite). Within these assemblages bodies of varying shape and size occur which contain peridotite highly depleted in fusible constituents and analogous to many of the low alkali nodules found in basalt.

## PETROLOGICAL MODELS CONSISTENT WITH A LOW VELOCITY ZONE

The influence of mineralogy on compressional and shear wave velocities of ultramafic rocks can be estimated from velocities calculated from single crystal elastic constants. Voigt and Reuss velocities, which represent the upper and lower limits of ideal isotropic aggregates (Hill, 1952),

TABLE I

Aggregate velocities (km/sec) calculated from single crystal elastic constants (Birch, 1961a; Christensen, 1965, 1966a; Simmons, 1965; Soga, 1967)

| | $V_p$ | | $V_s$ | |
|---|---|---|---|---|
| | Voigt | Reuss | Voigt | Reuss |
| Spinel | 10.08 | 9.77 | 5.86 | 5.46 |
| Olivine | 8.56 | 8.40 | 4.98 | 4.88 |
| Garnet 3 | 8.53 | 8.53 | 4.76 | 4.76 |
| Garnet 2 | 8.52 | 8.52 | 4.77 | 4.77 |
| Garnet 1 | 8.47 | 8.47 | 4.77 | 4.77 |
| Diopside | 7.88 | 7.52 | 4.46 | 4.31 |
| Aegirite 1 | 7.41 | 7.24 | 4.15 | 4.04 |
| Augite | 7.39 | 7.05 | 4.25 | 4.11 |
| Aegirite 2 | 7.37 | 7.21 | 4.10 | 4.01 |
| Magnetite | 7.39 | 7.39 | 4.20 | 4.19 |
| Diallage | 7.12 | 6.94 | 4.32 | 4.21 |
| Aegirite-augite | 7.04 | 6.65 | 3.73 | 3.59 |
| Hornblende 1 | 6.93 | 6.68 | 3.79 | 3.64 |
| Hornblende 2 | 7.26 | 6.83 | 4.03 | 3.60 |
| Labradorite | 6.82 | 6.58 | 3.70 | 3.40 |
| Oligoclase | 6.54 | 5.90 | 3.48 | 2.98 |
| Phlogopite 1 | 6.43 | 4.67 | 3.71 | 2.05 |
| Phlogopite 2 | 6.32 | 4.57 | 3.79 | 2.19 |
| Biotite | 6.17 | 4.35 | 3.73 | 2.02 |



TABLE II

Velocities (km/sec) at 4 kbar for monomineralic rocks and mineral aggregates

| Rock | $V_p$ | $V_s$ | Reference |
|---|---|---|---|
| Jadeite, Burma | 8.72 | | Birch (1960) |
| Grossularite garnet, Conn. | 8.72 | | Birch (1960) |
| Dunite, Wash. | 8.55 | 4.66 | Christensen (1966b) |
| Dunite, Wash. | 8.32 | 4.77 | Birch (1960), Simmons (1964) |
| Jadeite, Japan | 8.23 | 4.78 | Birch (1960), Simmons (1964) |
| Almandite-pyrope garnet | 7.99 | | Birch (1960) |
| Pyroxenite, Cal. | 7.88 | | Birch (1960) |
| Bronzitite, Bushveld | 7.75 | | Birch (1960) |
| Bronzitite, Stillwater | 7.72 | 4.62 | Birch (1960), Simmons (1964) |
| Actinolite, Vermont | 7.41 | | Birch (1960) |
| Anorthosite, Bushveld | 7.13 | | Birch (1960) |
| Magnetite, N.Y. | 7.11 | | Birch (1960) |
| Anorthosite, Mont. | 7.05 | 3.76 | Birch (1960), Simmons (1964) |
| Anorthosite, N.Y. | 6.82 | | Birch (1961a) |
| Anorthosite, Quebec | 6.78 | | Birch (1961a) |

are given in Table I for minerals which may be important constituents of the upper mantle. Though of limited use because of the unknown effects of variable chemical composition on velocities for many of the minerals, the single crystal data give a reasonable estimate for the relative velocities of minerals generally found in ultramafic rocks. For comparison, recent laboratory measured velocities at 4 kbar for some monomineralic rocks are summarized in Table II.

Ringwood (1962a,b) and Clark and Ringwood (1964) constructed several petrological models for the upper mantle on the basis of possible stability fields of various pyrolite mineral assemblages. Regional differences in upper mantle velocity distributions were explained by the intersection of regional geotherms with the pyrolite stability fields. In addition to high temperature gradients, low velocity zones were related to the stability of plagioclase pyrolite or an increase in the percentage of pyroxene at the expense of olivine.

Oxburgh (1964) has also proposed a petrological model for the upper mantle based on compositional change with depth. Inclusions of olivine nodules in basalts consisting of olivine, pyroxenes, and spinel are believed to represent fragments of residual mantle which has at an earlier date become depleted of liquid of basaltic composition. This residual layer passes downward into parent mantle composed of olivine, pyroxenes, amphibole, garnet, and spinel, which on fractional melting produces basaltic liquids. It is argued that the ratio of $K_2O/Na_2O$ in primary basalts is consistent with a source rock which contains 5–20% amphibole. The presence of amphibole below the residual peridotite would cause a reduction of seismic velocities coinciding with the low velocity channel.

From the available experimental data in the system $CaO–MgO–Al_2O_3–SiO_2$, MacGregor (1967) has constructed possible stability limits for peridotite facies at upper mantle temperatures and pressures. Geothermal gradients for oceanic and Precambrian shield areas when compared with these stability fields indicate that at pressures above a few kilobars the stable mineral assemblage in the upper mantle consists of forsterite + enstatite solid solution + diopside solid solution + garnet (i.e., garnet peridotite). Using this mineral assemblage and data on the solid solution of $Al_2O_3$ in enstatite (as given by Boyd and England, 1964), MacGregor related the decrease in seismic velocity in the upper mantle to the disappearance of garnet as the result of increased solid solution of $Al_2O_3$ in pyroxene.

Green and Ringwood (1967b) recently have proposed a petrologic model for the upper mantle beneath oceanic areas which would produce two low velocity channels for shear waves at depths of about 65 km and 100–150 km. The upper decrease in velocity is predicted from phase relationships which suggest decreasing spinel content in this region, the idealized reaction being:

$$(1)\ \underset{\text{spinel}}{MgAl_2O_4} + \underset{\text{enstatite}}{m\,MgSiO_3} \rightleftharpoons \underset{\text{aluminous enstatite}}{(m\text{-}2)\,MgSiO_3 \cdot MgAl_2SiO_6} + \underset{\text{olivine}}{Mg_2SiO_4}$$

This lowering of velocity is further augmented by a rapid increase in temperature with depth. Passing below this low velocity region, a velocity increase is expected due to the reaction of spinel and pyroxene to yield garnet and olivine. The velocity increase produced by this reaction overcomes a decrease in velocity resulting from increasing temperature. The second region of velocity decrease is essentially produced by the same mechanisms postulated by MacGregor (1967), that is the temperature effect and a decrease in garnet content accompanied by an increase in aluminous pyroxene:

$$(2)\ \underset{\text{pyrope}}{Mg_3Al_3Si_3O_{12}} + \underset{\text{enstatite solid solution}}{(m\text{-}2)\,MgSiO_3 \cdot (n\text{-}1)\,MgAl_2SiO_6} \rightleftharpoons \underset{\text{aluminous enstatite solid solution}}{m\,MgSiO_3 \cdot n\,MgAl_2SiO_6}$$

The experimental data in Tables I and II are consistent with the different mineralogical changes postulated to produce a region or regions of low velocity. Plagioclase, amphibole, and most pyroxenes have lower velocities than olivine, garnet, or spinel. The velocity decreases resulting from reaction (2) can be estimated from recent measurements of the elastic properties of garnet and enstatite. Single crystal data for an almandite-pyrope garnet (Soga, 1967) extrapolated to 10 kbar give a shear velocity of 4.78 km/sec, whereas an enstatite aggregate shear velocity at 10 kbar is approximately 4.65 km/sec (Christensen, 1966b). Similar values for compressional waves are 8.61 km/sec for garnet and 7.93 km/sec for enstatite. Green and Ringwood (1967b) estimate that reaction (2) produces about a 1% decrease in garnet under oceanic areas. The available data suggests that the actual decreases in compressional and shear wave velocities produced by this reaction are thus probably less than 0.01 km/sec, an amount presently undetectable by seismic methods.

All of these petrologic models require a density minimum coinciding with the low velocity zone, which, in turn, imply gravitational instability in the upper mantle (Clark and Ringwood, 1964; Anderson, 1965). In the following sections a model will be proposed for the upper mantle based on increasing iron content with depth, which contributes to the low velocity zone and does not produce a density minimum.

## CHANGES IN CHEMICAL COMPOSITION WITH DEPTH IN THE UPPER MANTLE

Recent studies of compressional wave velocities in rocks (Birch, 1960, 1961a; Christensen, 1965, 1966b, 1968) show that at pressures above a few kilobars velocities are simply related to density and mean atomic weight. Most iron-poor rocks, such as granites, common sedimentary and metamorphic rocks, and high magnesium dunites, have mean atomic weights close to 21, even though they may differ considerably from one another in bulk chemistry. The common basic igneous and meta-igneous rocks, basalt, amphibolite, and ecologite have mean atomic weights near 22. Higher mean atomic weights are possible in rocks such as dunite and peridotite with fayalite-rich olivine, and rocks containing abundant almandite or andradite-rich garnet or magnetite. These differences in mean atomic weight are primarily related to the percentages of iron in the rocks (Birch, 1961a). Thus seismic velocities appear to be strongly related to the amount of iron present in the mineral phases in the mantle. Little can be learned from seismic velocities on the abundance and distribution of the alkali metals. Magnesium, on the other hand, generally substitutes for iron in equivalent lattice positions in olivine, pyroxenes, and garnets. It follows that, at best, an estimate of the iron–magnesium ratio in mantle minerals may be obtained from seismic velocities.

Values of mean atomic weight calculated from chemical analyses for peridotite nodules in basalt and garnet peridotite are close to 21 (Table III). As olivine is the most abundant mineral in these rocks and contains a large proportion of the iron reported in the chemical analyses, the mean atomic weights of olivine from the nodules are also approximately 21 (Table III). For comparison, pure forsterite and fayalite have mean atomic weights of 20.1 and 29.1, respectively.

TABLE III

Mean atomic weights for ultramafic nodules and olivine

| Specimen | m | Reference |
|---|---|---|
| Olivine from peridotite nodules in basalt: | | |
| 1 | 20.9 | Ross et al. (1954) |
| 2 | 21.1 | Ross et al. (1954) |
| 3 | 21.0 | Ross et al. (1954) |
| 4 | 21.0 | Ross et al. (1954) |
| 5 | 21.0 | Ross et al. (1954) |
| 6 | 21.0 | Ross et al. (1954) |
| 7 | 21.0 | Ross et al. (1954) |
| 8 | 21.0 | Ross et al. (1954) |
| 9 | 20.9 | Ross et al. (1954) |
| Olivine from garnet peridotites: | | |
| E8 | 20.9 | Nixon et al. (1963) |
| E9 | 20.8 | Nixon et al. (1963) |
| Peridotite nodules in basalt: | | |
| HK63111602a | 20.7 | Kuno (1967) |
| HK61082601a | 21.1 | Kuno (1967) |
| HK57101204d | 21.1 | Kuno (1967) |
| HK61030402 | 20.8 | Kuno (1967) |
| Average peridotite nodule in basalt | 21.1 | Ito and Kennedy (1967) |
| Garnet peridotite: | | |
| HK50061804 | 21.0 | Kuno (1967) |
| N.69-(10316) | 21.3 | O'Hara and Mercy (1963) |
| E3 | 20.9 | Nixon et al. (1963) |
| E11 | 20.8 | Nixon et al. (1963) |
| KA64-16 | 20.9 | Ito and Kennedy (1967) |
| Average lherzolite nodule in kimberlite | 21.0 | Ito and Kennedy (1967) |

Composition of the transition region and lower mantle is subject to more speculation than that of the upper mantle, as ultramafics now in the earth's crust which have originated in the mantle most likely have come from relatively shallow depths. Because of this, any speculation regarding composition in the lower regions of the mantle must rely on seismological studies and related laboratory investigations at high pressures.

Using his velocity–density relationship and assuming uniform mean atomic weight throughout the mantle, Birch (1961b) found the average mean atomic weight of the mantle to be roughly 22.5, which corresponds to dunite with a fayalite content of 33%. Birch (1964) later calculated two new density distributions for the mantle. Extrapolated surface pressure and temperature densities of the lower mantle were found to be 4.10 and 4.16 g/cm$^3$. These densities are consistent with mixtures of high-pressure oxides derived from olivine with compositions in the range of 22–28% fayalite, which are considerably higher than fayalite compositions from ultramafic inclusions.

Anderson (1967), using an estimated phase diagram for the system $Mg_2SiO_4$–$Fe_2SiO_4$ and assumed densities of the phases in this system, calculated the variation in density throughout the mantle for different compositions ranging from $Mg_2SiO_4$ to $Fe_2SiO_4$. These densities along with the appropriate mean atomic weights were used by Anderson to obtain velocities as a function of depth for various compositions from the velocity–density relationship of Birch (1961b). Compressional wave velocities for the mantle model of Johnson (as given by Anderson, 1967) compared with the calculated velocities were found to be consistent with a fayalite content between 20 and 40% in region C. These results, in agreement with the earlier conclusion by Birch (1961b, 1964), imply that the iron content of the intermediate region of the earth's mantle is higher than that of ultramafic nodules.

The existence of a relatively high iron–magnesium ratio for the intermediate and inner regions of the mantle is supported by recent shock-wave experiments (McQueen et al., 1967). In this extremely important study, equations of state were determined from shock-wave data for two dunites with olivine compositions of 12% fayalite (Twin Sisters Peaks, Wash.) and 55% fayalite (Mooihoek Mine, Transvaal). A comparison of the equations of state for these two dunites with similar data for the earth's mantle supports the assumption that the earth's mantle has an iron content intermediate between the compositions of the Twin Sisters dunite and the Transvaal dunite. Linear interpolation of the data suggests a mean atomic weight of approximately 22 for the mantle (McQueen et al., 1967, p.5032), which corresponds to an olivine composition of 26% fayalite.

## DISCUSSION

From the evidence discussed earlier, it appears that ultrabasic rocks occurring in the upper regions of the mantle have mean atomic weights close to 21. This corresponds closely to an olivine-rich rock with a fayalite content of approximately 12%. Further, both theory and experiment suggest that the mean atomic weight increases with depth in the upper mantle to 22 or

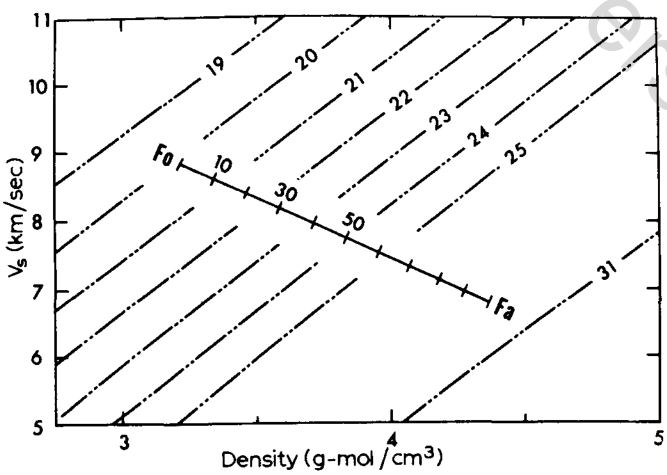


Fig.1. Compressional wave velocity at 10 kbar versus density for olivine aggregates ranging from forsterite to fayalite. Dashed lines represent lines of constant mean atomic weight.

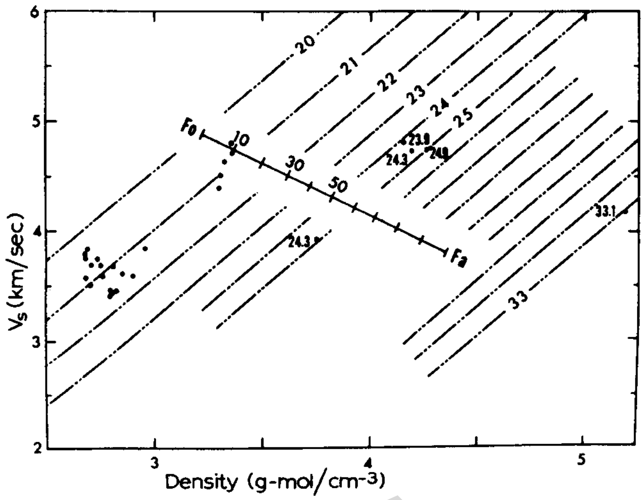


Fig.2. Shear wave velocity at 10 kbar versus density for olivine aggregates.

slightly higher. The effect of this chemical change on compressional wave velocity and density can be evaluated with the use of Birch's (1960, 1961a) laboratory data. The velocity–density relations derived by Birch (1961a) are given in Fig.1 for values of constant mean atomic weight. Corresponding values of mean atomic weight and density for the olivine solid solution series are also plotted on the velocity–density diagram.

If we assume, as a first approximation, that the changes of mean atomic weight are associated with variations in fayalite content, Fig.1 may be used to estimate a velocity–density distribution for the upper mantle. A change in fayalite content from 10 to 25% (corresponding to mean atomic weights of 20.8 and 21.9) would produce a decrease in compressional wave velocity of 0.3 km/sec and an *increase* in density of 0.2 g/cm$^3$. It is emphasized that increasing mean atomic weight in the upper mantle is probably accompanied by an increase of iron content in pyroxene and garnet as well as olivine. Therefore the actual fayalite content of olivine in the upper mantle may increase to a value somewhat lower than 25%. The velocity–density changes would nevertheless be similar to those predicted for an olivine-rich aggregate with all of the iron existing as the fayalite component of olivine.

A similar relationship is found for shear wave velocities (Fig.2). The shear velocity–density line for $m$ = 21 is based on the measurements by Simmons (1964), Kanamori and Mizutani (1965), and Christensen (1966a,b) for 22 rocks with mean atomic weights between 20.6 and 21.3. Mean atomic weights for these rocks were calculated from chemical analyses and modal analyses. The equation of least squares for this line is $V_s = 1.63\rho - 0.88$, where $V_s$ is in km/sec and $\rho$ in g/cm$^3$. The positions of the lines with $m$ = 24 and 25 were estimated from data by Verma (1960) and Soga (1967) for three garnets ($m$ = 23.9, 24.3, and 24.9) and measurements by Simmons

(1964) for a hortonolite dunite ($m$ = 24.3). The approximate position of the line for $m$ = 33 was obtained from elastic data for a single crystal of magnetite (Doraiswami, 1947). Positions of the lines of constant mean atomic weight in Fig.2 were located on the assumption that they have the same slope as the line for $m$ = 21.

The shear velocity–density relationships in Fig.2 again show that an increase in fayalite content in olivine produces a velocity decrease. In particular, a change in fayalite content from 10 to 25% in the upper mantle would result in a decrease in shear velocity of 0.25 km/sec and an accompanying *increase* in density of 0.2 g/cm$^3$.

## CONCLUSIONS

According to the proposed model, the large scale structure of the upper mantle may be simply rationalized in terms of a change in iron content with depth. The seismic velocity distribution in this region is explained as follows:

(1) In the uppermost portion of the mantle we would expect to find rocks similar in composition to many of the ultrabasic nodules in basalts and kimberlite diatremes. Variations in mineralogy of these nodules are due to phase transformations and compositional differences resulting from various stages of depletion of low melting components. Rocks in this region have mean atomic weights close to 21 and olivine compositions of approximately 10% fayalite.

(2) Decreasing velocity is accompanied by an increase in mean atomic weight and density. This is interpreted as primarily resulting from an increase in fayalite content of olivine from 10 to 25%. It is likely that some variation of mean atomic weight in the upper mantle is also associated with chemical changes in pyroxene and garnet. These velocity decreases are generally augmented by a rapid increase in temperature.

(3) Below the low velocity zone is a region homogeneous in mineralogy which is interpreted as primary mantle. Velocity increases in this region are determined by temperature and pressure effects.

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