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23. *A Model for the Upper Mantle, with Special Reference to the Origin of Rock Magma.*

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Abstract

A sharp increase of Poisson's ratio in the upper mantle has been attributed to the large increase of actual temperature. Possible temperature distribution was calculated on assuming that the upper mantle is mainly composed of eclogite. In the subcontinental upper mantle, actual temperature is believed to be close to the melting point of eclogite between a depth of 120 and 250 km which coincides with the depth of the low velocity zone. The author proposed that the low velocity zone is starred with oblate spheroidal molten pockets. The elastic ratio at normal temperature and pressure, ϕ_{00}, has been calculated for the upper mantle, in which the elastic ratio increases from 40 (km/s)^2 to 50 (km/s)^2 implying a gradual variation of constituent mineral assemblage with depth. From the considerations of mean atomic weight, density, velocity as well as elastic ratio, the author suggests that the upper mantle is mainly composed of olivine, pyroxene, garnet (pyrope) or even jadeite. Hence, eclogite or garnet peridotite will be the most favourable material in the upper mantle, the basaltic magma being the product of partial melting of these materials originating from the low velocity zone.

1. Introduction

In recent papers, the present author[1),2),3)] calculated the possible temperaure distribution in the upper mantle on assuming that the upper mantle is mainly composed of forsterite. The results show that the

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1) D. SHIMOZURU, "Temperature distribution and the possibility of the existence of magma pockets in the upper mantle of the earth," *J. Seis. Soc. Japan*, **14** (1961), 227.

2) D. SHIMOZURU, "Geophysical evidences for suggesting the existence of molten pockets in the earth's upper mantle," *Bull. Volcanol.*, **26** (1963), 181.

3) D. SHIMOZURU, "The low velocity zone and the temperature distribution in the upper mantle of the earth," *J. Phys. Earth*, **11** (1963), 19.

temperature increases steeply at the upper part of the upper mantle and reaches very close to the melting temperature of forsterite at a depth of 150–250 km. He suggested the existence of scattered oblate molten pockets in this region which might be the origin of rock magma in the subcontinental upper mantle. These molten pockets would account for the low velocity zone.

Alternatively, in his recent papers, Ringwood[4),5)] proposed a model for the upper mantle from mainly petrological grounds. He considered that the mantle immediately below the Mohorovičić discontinuity consisted mainly of dunite and peridotite. This passed downwards into more primitive material, "pyrolite" as he called it, which is chemically equivalent to a mixture of 1 part of basalt and 4 parts of dunite. He suggested that the low velocity zone is caused by downward transition from the sub-Mohorovičić dunite-peridotite zone into transitional pyrolite and then into garnet pyrolite. This model can, according to him, account for the low velocity zone as a consequence of the low velocity of the relatively abundant complex pyroxene in the transitional pyrolite compared with olivine and garnet.

From petrological grounds, the constituent material of the upper mantle is not likely to be forsterite, as assumed previously by the present author, but the assemblage of olivine, pyroxene and garnet should be considered at least.

Recently, Yoder and Tilley[6)] obtained the melting curve of eclogite and they maintain that the basaltic magma is derived from the partial melting of a more primitive rock (e. g. garnet peridotite).

In this paper, (1) the temperature distribution in the upper mantle is revised by using the melting curve of eclogite and (2) a constituent mineral assemblage is suggested in the upper mantle from seismological data.

2. Temperature distribution in the upper mantle

The principle of estimating the temperature in the upper mantle is the same as those stated in the earlier papers.[7),8)] A sharp increase in

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4) A. E. RINGWOOD, "A model for the upper mantle," *J, Geophys. Res.*, **67** (1962), 857.

5) A. E. RINGWOOD, "A model for the upper mantle, 2," *J. Geophys. Res.*, **67** (1962), 4473.

6) H. S. YODER, Jr. and C. E. TILLEY, "Origin of basalt magmas; An experimental study of natural and synthetic rock systems," *J. Petrology*, **3** (1962), 342.

7) D. SHIMOZURU, *loc. cit.*, 1).

8) D. SHIMOZURU, *loc. cit.*, 3).

Poisson's ratio in the upper part of the upper mantle in Gutenberg's continental model[9] has been attributed to the large temperature gradient in the corresponding depth. Instead of the forsterite melting curve as used in the previous papers, the eclogite melting curve determined by

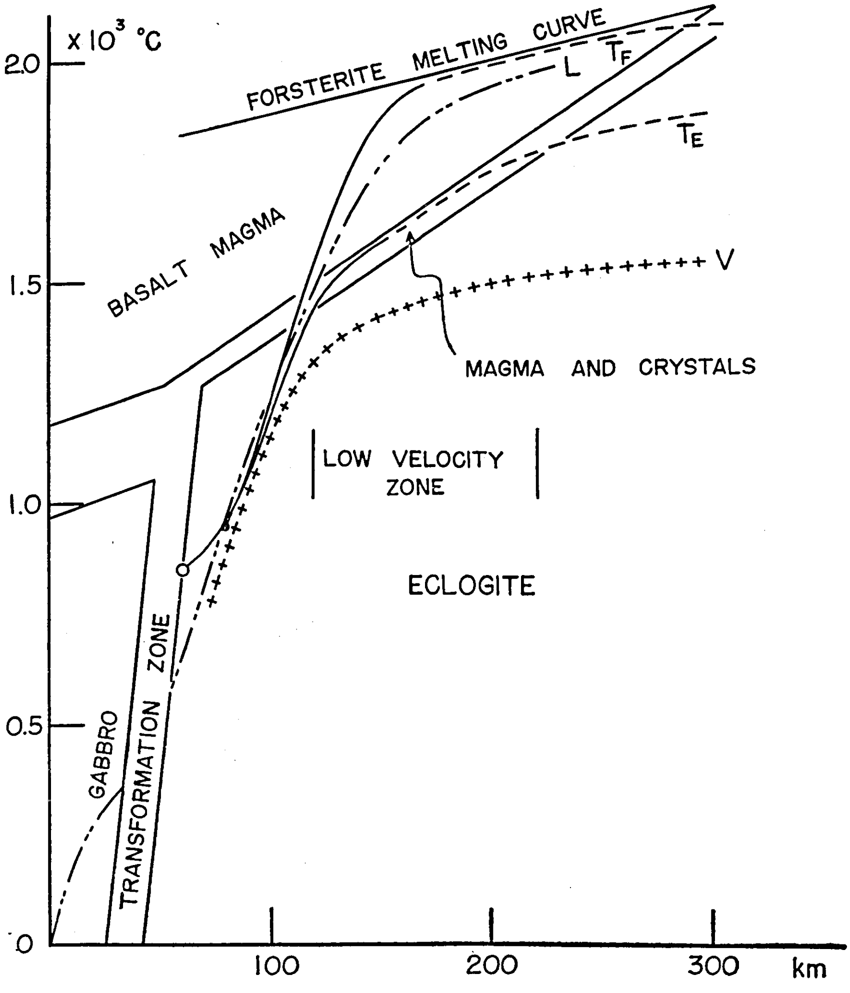

Fig. 1. Temperature within the upper mantle. T_F and T_E are the temperatures based on a forsterite and eclogite model. Curves of L and V are the temperatures obtained by Lubimova and Verhoogen. The stability curve of eclogite is due to Yoder and Tilley.

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9) B. GUTENBERG, "The asthenosphere low velocity layers." *Ann. di Geofisica,* **12** (1959), 439.

Yoder and Tilley,[10] was boldly extrapolated beyond the experimental limit. The starting temperature was taken as 850°C at 60 km. The temperature, thus calculated, is illustrated in Fig. 1 (T_E). In the figure, previous temperature obtained by the author (T_F) and those obtained by Lubimova[11] and Verhoogen[12] are also shown. The region of transformation zone between eclogite and gabbro and the region of co-existence of magma and crystal are determined by Yoder and Tilley.

The curve of the present temperature (T_E) penetrates the zone of the co-existence of magma and crystal between a depth of 120–220 km which coincides with the range of the low velocity zone of Lehmann's continental case.

Thus, the author suggests, as in the previous paper, that the low velocity zone is caused by the scattered molten pockets which seem to be the origin of rock magma.

The present procedure for obtaining the temperature distribution in the upper mantle yields the ratio of actual temperature to the melting temperature of the material (T/T_m) at various depths. Therefore, the actual temperature depends on the melting temperature at respective depths, i. e., the actual temperature depends on the constituent material at those depths. The present temperature was calculated based on the assumption that the upper mantle is composed of eclogite. Hence, in order to obtain a consistent model of the upper mantle we must examine the constituent material of the upper mantle, which will be done mainly from seismological data.

3. ϕ in the upper mantle

According to Bullen,[13] the quantity ϕ, elastic ratio, is defined as

$$\alpha^2-\frac{4}{3}\beta^2=K_s/\rho\equiv\phi\ , \qquad (1)$$

where α, β are P- and S- seismic velocities and K_s is adiabatic bulk modulus. Thus, ϕ is observable throughout the earth's interior. On adopting Jeffrey's velocity distribution, Birch[14] calculated ϕ in the mantle.

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[10] H. S. YODER, Jr. and C. E. TILLEY, *loc. cit.*, 6).

[11] H. A. LUBIMOVA, "On the temperature gradient in the earth's upper layers and possibility of explanation of low velocity," *Izvestia, ser. Geophys.*, **12** (1959), 1861.

[12] J. VERHOOGEN, "Temperature within the earth," *Amer. Scientist*, **48** (1960), 134.

[13] K. E. BULLEN, "The variation of density and the ellipticities of strata of equal density within the earth," *Mon. Not. Roy. Astr. Soc. Geophys. Suppl.*, **3** (1936), 395.

[14] F. BIRCH, "Elasticity and constitution of earth's interior," *J. Geophys. Res.*, **57** (1952), 227.

By virtue of the theory of finite strain, he obtained ϕ at hydrostatic strain zero, ϕ_0, at various depths. He discussed the chemical composition and structural form of the material in the mantle by comparing ϕ_0 at various depths with those of silicates and oxides determined by laboratory experiments.

He did not take account of the temperature in the upper mantle, however, with a conservative allowance for the effect of temperature, Birch's concept of the B-layer is "an assemblage of olivines, pyroxenes, such as jadeite and its potassium equivalent, and garnets can evidently have the required ϕ."

In order to obtain a more quantitative idea of the constituent material of the upper mantle, we next evaluate ϕ on taking account of the effect of both pressures and temperatures by adopting Gutenberg's velocity model and the temperature distribution obtained at present.

Disregarding the temperature effect, and by the use of the Gutenberg-Bullen model A, ϕ and ϕ_0 are calculated as listed in Table 1 and also as plotted in Fig. 2. ϕ_0 shows a slight increase in the upper mantle and, on an average, it takes 32–33 (km/s)^2.

Next, we may evaluate the effect of temperature on ϕ. From the the thermodynamical identities, the following relations are derived,

Table 1. The values of strain (f), P and S seismic wave velocities (α km/s and β km/s), density, elastic ratio (ϕ) at various depths. ϕ_0 is the elastic ratio at ordinary pressure.

Depth km	f (strain)	α km/s	β km/s	Density	ϕ(km/s)^2	ϕ_0(km/s)^2
60	0.0054	7.87	4.51	3.34	34.8	33.2
80	0.0071	7.80	4.45	3.36	34.4	32.3
100	0.0090	7.83	4.42	3.38	35.3	32.6
120	0.0107	7.89	4.40	3.40	36.4	33.2
140	0.0124	7.94	4.39	3.42	37.3	33.5
160	0.0141	8.00	4.40	3.43	38.2	33.8
180	0.0158	8.06	4.42	3.45	38.9	34.0
200	0.0175	8.12	4.45	3.47	39.5	34.0
250	0.0215	8.30	4.54	3.51	41.4	34.5
300	0.0254	8.51	4.66	3.55	43.5	35.1
350	0.0288	8.75	4.81	3.59	45.7	36.0
400	0.0323	9.00	4.95	3.63	48.3	37.0

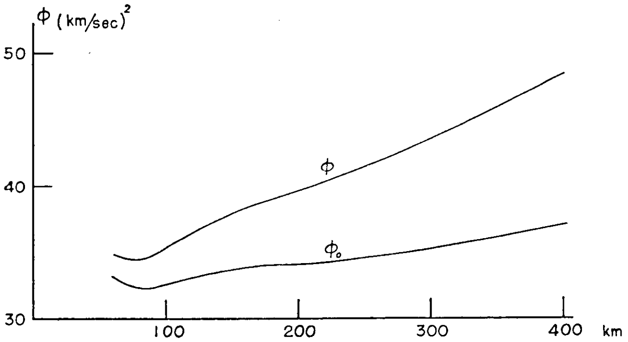

Fig. 2. Distribution of elastic ratio ϕ and that eliminating the pressure effect, ϕ_0, based on Gutenberg-Bullen Model A.

$$\left(\frac{\partial\phi}{\partial T}\right)_p=\frac{1}{\rho}\left[\left(\frac{\partial K_s}{\partial T}\right)_p+\alpha K_s\right], \tag{2}$$

$$\left(\frac{\partial K_s}{\partial T}\right)_p=\alpha K_s\gamma_G+\frac{K_s}{K_T}\left(\frac{\partial K_T}{\partial T}\right)_p, \tag{3}$$

$$\frac{1}{K_T}\left(\frac{\partial K_T}{\partial T}\right)_p=-\frac{1}{\beta_T}\left(\frac{\partial\beta_T}{\partial T}\right)_p, \tag{4}$$

where

α ······coefficient of thermal expansion,
γ_G ······Grüneisen's parameter,
K_T······isothermal bulk modulus,
β_T ······isothermal compressibility.

The experimental values of (4) for MgO, α-quartz and olivine are listed in Table 10 of Birch's paper.[15] Taking a mean value, we have 3×10^{-4}/deg. Putting $\gamma_G=1.5$, $\alpha=3\times10^{-5}$/deg., and $K_s=1.3\times10^{12}$ dynes/cm,² we have

$$\left(\frac{\partial K_s}{\partial T}\right)_p=-3.3\times10^{8}\ \text{dynes/cm}^2\ \text{deg}\,. \tag{5}$$

Experimental determination of thermal dependence of adiabatic bulk modulus are due to the measurements of stiffness constants or the elastic wave velocities at various temperatures. $\left(\frac{\partial K_s}{\partial T}\right)_p$ for single crystals and for some basic rocks are listed in Table 2. Values for rocks

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[15] F. BIRCH, *loc. cit.*, 14), page 255.

were calculated from Hughes' measurements of ultrasonic wave velocities at 5000 atm.[16] Those for single crystals were calculated from the measured stiffness constants of the elastic wave velocities at various temperatures. Table 2 shows a considerable scattering of values for single crystals and for basic rocks.

Table 2. Thermal dependence of adiabatic bulk modulus for single crystals and rocks.

Single crystal	Temperature °C	$-\left(\frac{\partial K_s}{\delta T}\right)_p \times 10^{-8}$ c. g. s.
Al		4.5
MgO		1.54
Rocksalt		0.80
NaCl		0.13
NaCl		0.95
KCl		1.21
Cu_3Au		0.62
Sodium		0.33
$NaClO_3$		0.02
FeS_2		0.05
Rocks		
Gabbro	0—300	0.35
(San Marco)	300—400	13.6
Dunite	0—200	1.2
(Twin Sisters Mount.)	200—300	3.5
Dunite	100—200	7.9
(Jackson County)		
Bytownite Gabbro	0—100	2.0
	100—300	6.2
Hornblend Basalt	0—300	−0.16

Due to the difficulty of experimental technique and poor accumulation of data, thermal dependence of adiabatic bulk modulus for important minerals and rocks are not well known.

However, within the degree of accuracy of the present paper, we adopt the value of (5) as a representative value for most basic rocks.

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16) D. S. HUGHES, "Determination des vitesses d'onde elastique dans diverses roches en fonction de la pression et de la temperature," *Rev. Inst. Franc. Petrole,* **12** (1957), 730.

Table 3. T_F and T_E are the temperatures based on the assumption that the constituent material is forsterite and eclogite respectively. ϕ_{00} and ϕ'_{00} correspond to the said temperatures, T_F and T_E.

Depth km	Temperature °C		ϕ_{00}(km/s)^2	ϕ'_{00}(km/s)^2
	T_F	T_E		
60	850	850	40.8	40.8
80	930	941	40.5	40.6
100	1220	1190	43.3	43.0
120	1550	1425	46.6	45.5
140	1780	1540	48.8	46.7
160	1930	1620	50.2	47.6
180	2000	1680	50.9	48.2
200	2050	1790	51.2	49.0
250	2110		51.8	
300	2150	1900	52.4	50.4

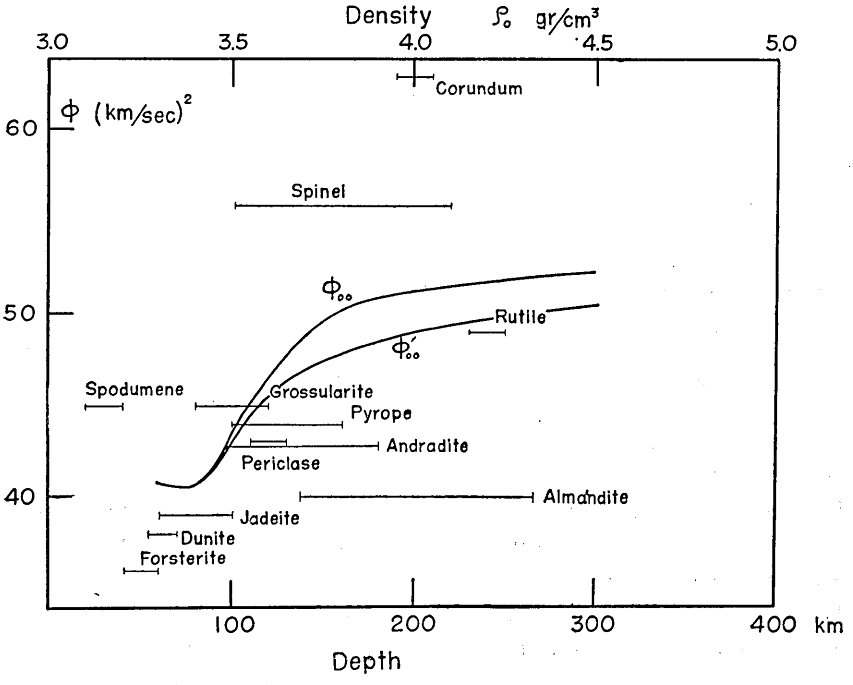

Fig. 3. Distribution of elastic ratio at normal pressures and temperatures. ϕ_{00} ϕ'_{00} are based on a forsterite and eclogite model. There is no identification between density and depth scales.

By means of (2), we obtain $(\partial\phi/\partial T)$ at various depths.

Hence, we can calculate ϕ at ordinary pressure and temperature, ϕ_{00}, for various depths in the upper mantle as listed in Table 3. ϕ_{00}, thus calculated, is shown in Fig. 3. In this figure, ϕ_{00} is based on a forsterite model and ϕ'_{00} based on a eclogite model. In the same figure, ϕ_0 for various minerals are also plotted against density. ϕ_{00} and ϕ'_{00} increase sharply in the upper mantle from almost 40 $(\text{km/s})^2$ to 50 $(\text{km/s})^2$. Then they gradually increase with depth. This implies that constituent materials vary with depth in the upper part of the upper mantle; an abundance of materials having a high elastic ratio increase with depth.

4. Discussion on the constituent materials

From Fig. 3, it is clear that forsterite and dunite have a lower elastic ratio less than 40 $(\text{km/s})^2$, than that of the material of the upper mantle. Most of the minerals of geological importance have an elastic ratio less than 40 $(\text{km/s})^2$ or even less than 30 $(\text{km/s})^2$ with the exception of garnet, beryl and spodumen. Oxides, on the other hand, such as corundum, spinel and rutile have a high elastic ratio.

Considerable increase of ϕ'_{00} in the upper mantle, therefore, implies the possibility of the existence of a considerable amount of garnet. As for garnet, ϕ_{00}, mean atomic weights and packing indices are listed in Table 4.

In view of the high degree of ion packing, pyrope, almandite and spessartite are considered to be formed at considerable depth. From field observations, geologists believe that the garnet formed at the highest pressures are the most rich in magnesium. Fig. 4 shows the stability curves of two end members of garnet[17] as well as the present temperature curve. From this figure, it is well understood that the

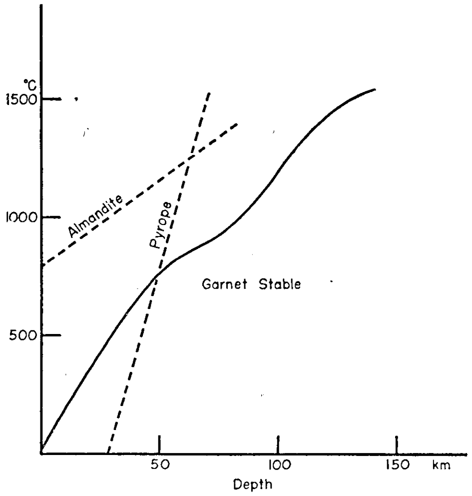

Fig. 4. Stability curve of garnet. The solid line indicates the temperature curve based on a eclogite model.

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[17] H. S. YODER, Jr. and G. A. CHINNER, "Almandite-pyrope-water system at 10,000 bars," *Carnegie Inst. Annual Report*, (1959), 81.

Table 4. Parameters for garnet.

		ϕ_{00}	Mean atomic weight	Packing index
pyrope	$Mg_3Al_2Si_3O_{12}$	44	20.15	6.5
almandite	$Fe_3Al_2Si_3O_{12}$	40	24.88	6.6
spessartite	$Mn_3Al_2Si_3O_{12}$	—	24.74	6.5
grossularite	$Ca_3Al_2Si_3O_{12}$	45	22.52	6.4
andradite	$Ca_3Fe_2Si_3O_{12}$	43	25.40	6.1

pyrope-almandite system is stable in the upper mantle. It should be noted that pyrope breaks down at a depth of 50 km which almost coincides with the depth of subcontinental Moho.

On the other hand, materials having a high elastic ratio have high compressional wave velocities. If we assume Poisson's relation, $K=5/3\,\mu$, we have

$$\alpha=1.265\sqrt{\phi}\,, \tag{6}$$

where α represents the compressional wave velocities.

The solid line in Fig. 5 shows equation (6) as well as the relations for minerals of geological importance. It seems that Poisson's relation

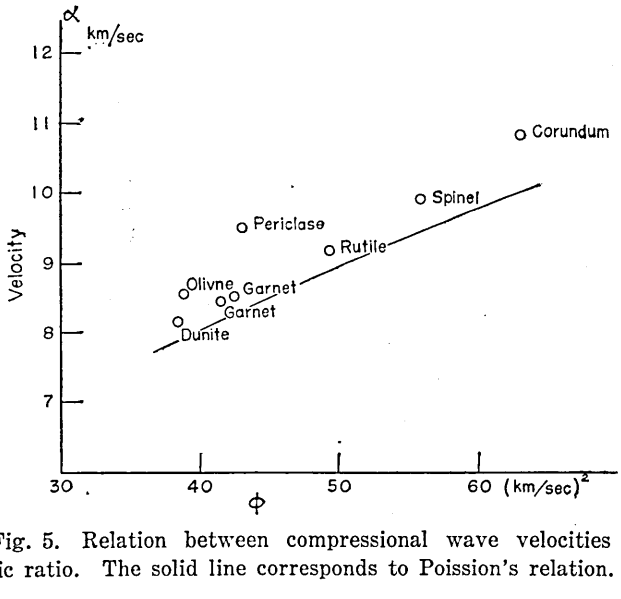

Fig. 5. Relation between compressional wave velocities and elastic ratio. The solid line corresponds to Poission's relation.

indicates the minimum boundary of velocities for these minerals.

According to Birch,[18] there is an empirical relation between velocity (α) and density (ρ), such as

$$\alpha = a(m) + 3.31\rho\,, \tag{7}$$

where $a(m)$ is an empirical constant related to the atomic weight of material concerned.

Combining (6) with (7), we obtain,

$$a(m) = 1.265\sqrt{\phi} - 3.31\rho\,, \tag{8}$$

Equation (8) was calculated for various densities as shown in Fig. 6. The density distributions of Bullen and Gutenberg imply that density of materials of the upper mantle at normal pressures and temperatures is almost 3.3 gr/cm^3. Therefore, from this figure, $a(m)$ in the upper mantle in which ϕ varies from 40 to 50 (km/s)^2 seems to exist between -2 and -3. This means, from Birch's empirical relation, that the mean atomic weight decreases in the upper mantle from about 21.5 to about 20 with increasing depth. The mean atomic weight of peridotite is 21.6 on an average[19]. Hence, for the material immediately below the Moho, it seems to be reasonable, and is widely recognized, to consider "peridotite".

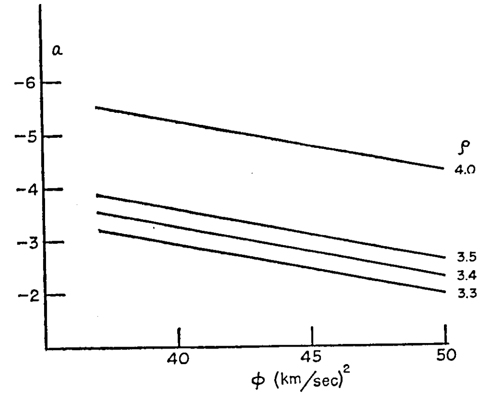

Fig. 6. Relation between Birch's empirical constant a and elastic ratio based on equation (8).

However, peridotite cannot account for the increasing elastic ratio or the decreasing mean atomic weight. Then, referring to Table 4, among garnet group, pyrope has the lowest mean atomic weight and high packing index and is stable in the mantle.

Thus, there is a possibility of an increasing abundance of pyrope with increasing depth, or, in other words, pyrope-peridotite may be the

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[18] F. Birch, "Composition of the earth's mantle," *Geophys. J.*, **4** (1961), 295.

[19] S. R. Nockolds, "Average chemical compositipns of some igneous rocks," *Bull. Geol. Soc. Amer.*, **65** (1954), 1007.

most probable constituent material for the upper part of the upper mantle. If allowed to use "eclogite" in a wide sense, the use of the eclogite model seems to be possible for the upper part of the upper mantle on reserving its compositional change with depth.

The temperature curve based on the melting curve of eclogite was obtained on assuming that the upper mantle is homogeneously composed of eclogite and that there is no compositional change within it.

Contrary to this, the present result suggests an increasing amount of pyrope with increasing depth. The present temperature curve (T_E), and hence ϕ'_{00}, were obtained based on the change of Poisson's ratio with depth assuming the upper mantle as being uniform. Strictly speaking, however, T_E and ϕ'_{00} are not consistent with the actual structure. The Poisson's ratio of garnet is 0.268-0.272[20) which is very close to the Poisson's ratio of dunite or peridotite. Therefore, annexation of garnet to peridotite would affect little influence on Poisson's ratio as a whole.

However, unfortunately, we have no laboratory data on the change of melting curve of eclogite with garnet content. On taking account for this, the temperature curve and the ϕ'_{00} curve would be slightly varied. Even so, the feature of a relatively large increase of ϕ'_{00} with depth requires a considerable amount of garnet in the upper part of the upper mantle. Still we have a slight discrepancy between the elastic ratio of pyrope and that of the upper mantle. A silicate structure can no more than account for the increasing elastic ratio. It would not be unreasonable to expect a little amount of spinel ($MgOAl_2O_3$) or corundum (Al_2O_3) at a depth below 100 km.

Transformation to a high pressure phase, such as Mg_2SiO_4-spinel, occurs at a deeper interior, i.e., the layer C.

Anyhow, for the interpretation of a relatively large increase of elastic ratio in the upper mantle, the present author anticipates a small amount of increase of material having a high elastic ratio as well as an increasing abundance of garnet.

5. Conclusion

The results can be summarized as follows:

1) Temperature distribution was obtained on assuming the upper mantle being composed of eclogite.

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20) R. K. VERMA, "Elasticity of some high-density crystals," *J. Geophys. Res.*, **2** (1960), 757.

2) Temperature reaches very close to the melting point of eclogite between a depth of 120 and 220 km.

3) This region coincides with the low velocity zone of the subcontinental upper mantle.

4) Oblate spheroidal molten pockets have been proposed in this zone which implies the origin of rock magma.

5) Garnet (pyrope) peridotite was found to be the most probable material for the upper part of the upper mantle from which basalt magma is produced by partial melting at a depth corresponding to the low velocity zone.

6) Even considering the increasing amount of garnet, the increasingly high elastic ratio still requires the addittion of unknown materials (spinel or corundum?) having a high elastic ratio.

7) The upper mantle is not uniform but has a character of gradual compositional change.

6. Acknowlegement

I am indebted to Dr. M. Yamaguchi of Kyushu Univesrity who offered much petrological advice.

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23. Upper Mantle のモデル—特に岩漿の起源に関する考察

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Upper mantle における Poisson 比の増加率から, eclogite の melting curve をもとにして温度分布を計算しなおした. ϕ に圧力と温度の補正を行つて, 各深さについて常温常圧における値を計算し, 種々の珪酸塩および酸化物のそれと比較した. 更に縦波速度, 平均原子量などを考慮して次の結論を得た.

1) elogite モデルによる温度は深さ 120-220 km で eclogite の融点に近接する.

2) この領域は大陸下の低速度層の存在する深さと一致する.

3) この低速度層にパッチ状に横に長い熔融ポケットがあると推定され, これが岩漿の起源であると考えられる.

4) Moho の下では peridotite でよいが, 次第に garnet (pyrope) が増加しなければならない.

5) より深くなると, 一般に考えられる silicate では計算された ϕ_{00} を説明できない. そのためには spinel や corundum のような大きい ϕ_0 を持つた酸化物の存在を仮定しなければならない.

6) 以上のように B 層は上部では garnet peridotite または eclogite であり, 深くなるに従つて ϕ_0 の大きい物質が増えてくるらしい.