

# Pressure Effects on Phase Equilibria in Some Principal Rock-forming Minerals. — Proposal of a Model regarding the Origin of Primary Magmas\* —

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## 1. Introduction

Hitherto, the genetical relation between tholeiitic basalt magma and olivine basalt magma has been regarded as one of the most essential problems in igneous petrology and has been discussed by many authors. Recently, H. S. YODER and C. E. TILLEY have proposed an interesting idea in connection with this problem on the basis of their successful experiments under high pressure. They have shown, in Diopside-Forsterite-Quartz-Nepheline quarternary system, that the plane Diopside-Albite-Forsterite becomes thermal barrier under low pressure, the plane Diopside-Clinoenstatite-Jadeite being thermal barrier under high pressure (higher than 30 kb.).

Thus, they have concluded that the origin of the two magma types is governed by the difference in pressure, under which produced magma is differentiated in the course of solidification.

On the other hand, H. KUNO and his co-workers have proposed a different idea that the tholeiitic magma is generated under low pressure by differential melting of peridotite layer or by complete melting of the basaltic layer in the earth's crust, the olivine basalt magma being generated by differential melting of peridotite layer under high pressure.

KUNO's idea is based on the consideration that the incongruent relation between forsterite and clinoenstatite vanishes under high pressure (higher than 6 kb.). But, it would hardly be possible that tholeiitic magmas are generated in such shallow portions in the earth's crust corresponding to the pressure, under which the incongruent relation above cited is present.

At any rate, in both of the former ideas, only the origin of two magma types is discussed. In spite of their differences in opinion, all of these authors are consistent in the point that these two types of magma are essentially parental and that the diversities of igneous rocks are derived from the differentiation and/or assimilation of these parental magmas.

It will be certain that the magmatic differentiation plays an important role in petrogenesis. However, it is a grave problem not yet solved whether the origin of diversities in igneous rocks is mainly due to magmatic differentiation or due to another causes also.

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Recently, in connection with this problem, M. GORAI has shown the possibility that granitic magmas might be produced by partial melting of upper mantle on the basis of the isotopic composition of lead contained in granitic rocks. He has suggested also that calc-alkaline magmas in general could be produced primarily in upper mantle.

The present writer has been working on the Cenozoic volcanic activities in Southwest Japan. In the course of his work, he has gained the conclusions in consistent with GORAI's suggestions that the petrographic characters of volcanic series in question would be determined essentially by tectonic conditions, under which magmas were produced. This conclusion has been derived from tectogenetical and petrographical considerations.

In this paper, the writer intends to approach the problem by physical method. For this purpose, he considers especially about pressure effects on magmagenesis in the view-point of thermodynamics.

## 2. Thermodynamical calculations on the pressure effects in some principal binary systems.

Simple thermodynamical calculations are made to see the pressure effects on phase equilibria between crystalline phase and liquid phase in binary system essential for petrogenetical considerations. For this purpose, two cases must be treated separately.

### 2. 1. The case of solid solution.

In general, if we assume ideal solution, we obtain

$$\mu^l_i = \mu^l_{i0} + R \cdot T \cdot \ln N^l_i \dots \dots \dots (1) \text{ for liquid phase.}$$

$\mu^l_i$ : chemical potential of i component in binary liquid phase.

$\mu^l_{i0}$ : chemical potential of pure i component in liquid state.

$R$ : gas constant.

$T$ : temperature in KELVIN scale.

$N^l_i$ : molal fraction of i component in liquid phase.

Thus,  $d\mu^l_i = d\mu^l_{i0} + R \cdot \ln N^l_i \cdot dT + R \cdot T \cdot d(\ln N^l_i)$ , but  $d\mu^l_{i0} = v^l_{i0} dp - s^l_{i0} dT$ .

$p$ : pressure.

$v^l_{i0}$ : molal volume of pure i component in liquid state.

Then, we obtain

$$d\mu^l_i = v^l_{i0} \cdot dp - s^l_{i0} \cdot dT + R \cdot \ln N^l_i \cdot dT + R \cdot T \cdot d(\ln N^l_i) \dots \dots \dots (2)$$

In the same way, we obtain

$$d\mu^c_i = v^c_{i0} \cdot dp - s^c_{i0} \cdot dT + R \cdot \ln N^c_i \cdot dT + R \cdot T \cdot d(\ln N^c_i) \dots \dots \dots (3)$$

for crystalline phase. In this case, superscript c denotes crystalline phase.

If crystalline phase and liquid phase are in chemical equilibrium,  $d(\Delta\mu_i) = 0$ ,  $\Delta\mu_i = \mu^c_i - \mu^l_i$ .

So, we obtain from Eq. (2) & (3)

$$\Delta v_i dp - \Delta s_i \cdot dT + R \cdot \ln(N^c_i/N^l_i) dT + R \cdot T \cdot d[\ln(N^c_i/N^l_i)] = 0 \dots \dots \dots (4)$$

$$\Delta v_i = v^c_{i0} - v^l_{i0}, \Delta s_i = s^c_{i0} - s^l_{i0}.$$

For first approximation, it is assumed that  $\Delta v_i$  and  $\Delta s_i$  are constant. Then, Eq. (4) is integrated from  $(T_0, p_0, N^l_{i0}, N^c_{i0})$  to  $(T, p, N^l_i, N^c_i)$ . We obtain



$$\Delta v_i \cdot (p - p_0) - \Delta s_i \cdot (T - T_0) + R \cdot T \cdot \ln(N_i^c / N_i^l) - R \cdot T_0 \cdot \ln(N_{i0}^c / N_{i0}^l) = 0 \dots (5)$$

In this case, if we choose  $T_0$  as the melting temperature for endmember  $i$  in the binary system under the pressure of  $p_0$ , we obtain

$$\Delta v_i \cdot (p - p_0) - \Delta s_i \cdot (T - T_0) + R \cdot T \cdot \ln(N_i^c / N_i^l) = 0 \dots (6)$$

The other endmember  $j$  is represented by suffix  $j$ , then

$$N_i^l + N_j^l = 1, N_i^c + N_j^c = 1.$$

In the same way as in the case of  $i$  component, we obtain

$$\Delta v_j \cdot (p - p_0) - \Delta s_j \cdot (T - T_0^*) + R \cdot T \cdot \ln[(1 - N_i^c) / (1 - N_i^l)] = 0 \dots (7)$$

for  $j$  component.

From Eq. (6) & (7),  $T$  is eliminated, then we obtain in atm. scale

$$\begin{aligned} & R \left\{ \frac{\Delta v_j \cdot (p - p_0)}{41.27} + \Delta s_j \cdot T_0^* \right\} \ln N_i^l - R \left\{ \frac{\Delta v_i \cdot (p - p_0)}{41.27} + \Delta s_i \cdot T_0 \right\} \ln(1 - N_i^l) \\ & = R \left\{ \frac{\Delta v_j \cdot (p - p_0)}{41.27} + \Delta s_j \cdot T_0^* \right\} \ln N_i^c - R \left\{ \frac{\Delta v_i \cdot (p - p_0)}{41.27} + \Delta s_i \cdot T_0 \right\} \ln(1 - N_i^c) \\ & + \frac{(\Delta v_i \cdot \Delta s_j - \Delta v_j \cdot \Delta s_i) \cdot (p - p_0)}{41.27} + \Delta s_i \cdot \Delta s_j \cdot (T - T_0^*) \dots (8) \end{aligned}$$

By using Eq. (8), we can estimate roughly how the solidus and liquidus curves should be deviated due to increasing pressure.

Thus, the case of plagioclase, which is one of the most principal rock forming minerals, will be examined.

According to KELLEY (1936),

$$\begin{array}{ll} \Delta s_{An} = -16.13 \text{ cal/mol} & \Delta s_{Ab} = -9.53 \text{ cal/mol} \\ T_0 = 1823^\circ \text{k} & T_0^* = 1380^\circ \text{k} \quad \text{under 1 atm.} \end{array}$$

Under 1 atm., parameter  $(p - p_0)$  vanishes in Eq. (8), so we can solve Eq. (8) about  $N_i^l$  for a certain value of  $N_i^c$ . When  $N_i^l$  is determined,  $T$  is determined using Eq. (6) or (7).

The result obtained by such procedure is in good agreement with the experimental result obtained by N. L. Bowen, who has already performed thermodynamical calculation under 1 atm..

In order to examine pressure effects on the solidus and liquidus curves, we need the values  $dT_m/dp$  for albite and anorthite. According to BIRCH,  $dT_m/dp$  for albite is some 11.5 °c/kb., which corresponds to  $\Delta v_{Ab} = -4.325$  c.c/mol.

The value  $dT_m/dp$  for anorthite is not yet determined strictly.

But, according to YODER and VERHOOGEN, this value is said to be safely of the

Table 1. (% in mol)

Press.	1 atm.		5 × 10 <sup>3</sup> atm.	
An % in solid	An % in liquid	Temp. °k	An % in liquid	Temp. °k
100	100	1823	100	1848
90	64.5	1748	86	1830
80	43	1683.8	61.5	1790
70	30	1633	44.2	1755
60	20	1577	33.1	1725
50	14	1536	27.6	1700



same order with that of forsterite.

Then,  $dT_m/dp$  for anorthite is assumed as 5 °c/kb., which corresponds to  $\Delta v_{An} = -3.13$  c.c/mol. Using these values, phase relations under 5 kb. is determined, as shown in Table 1.

In table 1, it is clearly shown that composition of liquid in equilibrium with solid phase of a certain composition becomes richer in anorthite component as much as some ten percent under 5 kb. than under 1 bar.

In general, in Eq. (8), the condition  $(\Delta v_i/\Delta s_i) \cdot (T_o^*/T_o) < \Delta v_j/\Delta s_j$ ; namely  $(dT_m/dp)_j > (dT_m/dp)_i \cdot (T_o^*/T_o)$ , means that  $\eta$  and  $a$  in the equation of following form

$$(N^l_i)^\eta + a \cdot N^l_i - a = 0 \dots\dots\dots (9)$$

becomes larger due to increasing pressure, if  $T_o$  is larger than  $T_o^*$ . If  $\eta$  and  $a$  becomes larger, value of  $N^l_i$  should become larger for  $0 < N^l_i < 1$ .

Then, the condition that  $(dT_m/dp)_j > (dT_m/dp)_i \cdot (T_o^*/T_o)$  means that the composition of liquid phase in equilibrium with crystalline phase of a certain composition becomes richer in  $i$  component due to increasing pressure. It is clear that this condition is fulfilled in the case of Plagioclase system.

In binary solid solution, which is composed of  $i$  component and  $j$  component, if endmember  $i$  has higher melting temperature than  $j$  component under 1 atm., it would be most probable that  $(dT_m/dp)_j$  is larger than  $(dT_m/dp)_i$ , because that  $i$  component has higher melting temperature than  $j$  component would mean that  $i$  component is more hardly bonded than  $j$  component, pressure effects on melting temperature being larger in  $j$  component. Thus, in spite of nonperfect solid solution, it might be expected, in Enstatite-Ferrosilite binary system, that the composition of melt in equilibrium with solid phase of a certain composition becomes richer in enstatite component with increasing pressure. This assumption has an important meaning on mamagenesis subsequently refered to.

2. 2. The case of binary system of pure substances.

In general, for binary system of pure substances, we obtain

$$d\mu^l_i = v^l_{i0} \cdot dp - s^l_{i0} \cdot dT + R \cdot d(T \cdot \ln N^l_i) \dots\dots\dots (1)'$$

$$\text{and } d\mu^c_i = v^c_{i0} \cdot dp - s^c_{i0} \cdot dT \dots\dots\dots (2)'$$

In the same way as in the case of 2.1, we obtain

$$R \cdot T \cdot \ln N^l_i = \{ \Delta v_i \cdot (p - p_0) / 41.27 \} - \Delta s_i \cdot (T - T_o) \dots\dots\dots (3)'$$

$$R \cdot T \cdot \ln(1 - N^l_i) = \{ \Delta v_j \cdot (p - p_0) / 41.27 \} - \Delta s_j \cdot (T - T_o^*) \dots\dots\dots (4)'$$

In Eq. (3)' & (4)',  $T$  means the temperature of eutectic point and  $N^l_i$  means the molal fraction of component  $i$  in liquid phase at the temperature of eutectic point. From Eq. (3)' & (4)'  $T$  is eliminated, we obtain

$$\left\{ \frac{\Delta v_j \cdot (p - p_0)}{41.27} + \Delta s_j \cdot T_o^* \right\} \cdot R \cdot \ln N^l_i - \left\{ \frac{\Delta v_i \cdot (p - p_0)}{41.27} + \Delta s_i \cdot T_o \right\} \cdot R \cdot \ln(1 - N^l_i) = \frac{(\Delta v_i \cdot \Delta s_j - \Delta v_j \cdot \Delta s_i) \cdot (p - p_0)}{41.27} + \Delta s_i \cdot \Delta s_j \cdot (T_o - T_o^*) \dots\dots\dots (5)'$$

By solving Eq. (5)' about  $N^l_i$ , we can estimate how the eutectic point should shift with increasing pressure.

In general, for the condition  $(\Delta v_j/\Delta s_j) < (\Delta v_i/\Delta s_i) \cdot (T_o^*/T_o)$ ; namely  $(dT_m/dp)_j < (dT_m/dp)_i \cdot (T_o^*/T_o)$ ,  $\eta$  and  $a$  in the equation of the form of Eq. (9) becomes smaller with increasing pressure, if  $T_o^* > T_o$ . This means that the eutectic point



should shift toward j component side, as pressure increases.

In Diopside-Anorthite system,  $(dT_m/dp)_{\text{Diopside}} = 13^\circ\text{C}/\text{kb.}$ ,  $(dT_m/dp)_{\text{Anorthite}} = 5^\circ\text{C}/\text{kb.}$ ,  $T_o^* = 1823^\circ\text{K}$  for anorthite and  $T_o = 1665^\circ\text{K}$  for diopside, then eutectic point must shift toward anorthite side with increasing pressure. In fact, by solving Eq. (5)', we can confirm that eutectic point shifts toward anorthite side some ten percent of anorthite component under 5 kb..

In this case, the amount of shifting is not strict quantitatively, because, in this binary system, activity coefficient is not equal to unity. But, in qualitative sense, it is expected safely that the eutectic point should shift toward anorthite side.

In the same way, in Diopside-Quartz system, eutectic point must shift toward diopside side with increasing pressure, because  $(dT_m/dp)_{\text{quartz}} \times (1665/1743) > (dT_m/dp)_{\text{Diopside}}$ . In this case, it is noted that, in spite of  $T_o > T_o^*$ , the absolute value of the first term is greatly larger than that of the second term in the right hand side of Eq. (5)' under high pressure. Then parameter a becomes large with increasing pressure.

In Diopside-Forsterite system, eutectic point must shift toward forsterite side with increasing pressure [ $(dT_m/dp)_{\text{Forsterite}} = 4.7^\circ\text{C}/\text{kb.}$ ].

The system Forsterite-Quartz is very important in considering magma genesis, as stressed by YODER, TILLEY and KUNO.

Then, we will examine tentatively the changes of phase relations in this system with increasing pressure.

According to BOYD and ENGLAND, the incongruent relation between forsterite and clinoenstatite vanishes at the pressure of 6 kb., then, under some higher pressure than 6 kb., the join diopside-clinoenstatite would become thermal barrier.

This is natural result from theoretical considerations, because  $(dT_m/dp)_{\text{Enstatite}} = 9.5^\circ\text{C}/\text{kb.}$ ,  $(dT_m/dp)_{\text{Forsterite}} = 4.5^\circ\text{C}/\text{kb.}$ ,  $T_o = 1797^\circ\text{K}$  for clinoenstatite  $T_o^* = 2163^\circ\text{K}$  for forsterite, which means that  $(dT_m/dp)_{\text{Enstatite}} \times (T_o^*/T_o) > (dT_m/dp)_{\text{Forsterite}}$ , eutectic point between forsterite and clinoenstatite appearing at some high pressure.

When the incongruent relation between forsterite and clinoenstatite vanishes

$$\left\{ \begin{aligned} R \cdot T \cdot \ln 0.5 &= \frac{\Delta v_{Fo} \cdot (p - p_o)}{41.27} - \Delta s_{Fo} \cdot (T - T_o^*) \dots\dots\dots (9)' \end{aligned} \right.$$

$$\left\{ \begin{aligned} \frac{\Delta v_{En} \cdot (p - p_o)}{41.27} &= \Delta s_{En} \cdot (T - T_o) \dots\dots\dots (10)' \end{aligned} \right.$$

must be fulfilled. From (9)' & (10)', we obtain

$$p = - \left[ \frac{\Delta s_{Fo} \cdot (T_o^* - T_o) - R \cdot T_o \cdot \ln 0.5}{\Delta v_{Fo} - \Delta v_{En} \cdot \{ (\Delta s_{Fo} / \Delta s_{En}) + (R / \Delta s_{En}) \cdot \ln 0.5 \}} \right] \times 41.27 + p_o \dots\dots (11)'$$

Using Eq. (11)', we can gain the pressure, at which the incongruent relation between forsterite and clinoenstatite vanishes.

For the following values ;

$$\begin{array}{lll} T_o = 1797^\circ\text{K}, & \Delta s_{En} = -8.18 \text{ cal/mol}, & \Delta v_{En} = -3.2 \text{ c.c/mol} \\ T_o^* = 2163^\circ\text{K} & \Delta s_{Fo} = -7.07 \text{ cal/mol}, & \Delta v_{Fo} = -1.43 \text{ c.c/mol}, \end{array}$$

we obtain  $p = 6.5 \times 10^3 \text{ atm.}$

In spite of nonideality of the system, this value is in rather good agreement with the experimental result after BOYD and ENGLAND.

In the same way, we can expect that the incongruent relation between quartz



and clinoenstatite will appear newly at some high pressure, because the eutectic point between quartz and clinoenstatite would shift toward clinoenstatite side with increasing pressure for the condition  $(dT_m/dp)_{\text{quartz}} \times (T_o^*/T_o) \doteq 50/1000 > (dT_m/dp)_{\text{Enstatite}} = 9.5/1000$ .

Then, using the following values and Eq. (11)''

$$\begin{aligned} \Delta v_{En} &= -3.2 \text{ c.c./mol}, & \Delta s_{En} &= -8.18 \text{ cal/mol}, & T_o &= 1797^\circ \text{ k}, \\ \Delta v_q &= -4.6 \text{ c.c./mol}, & \Delta s_q &= -1.95 \text{ cal/mol}, & T_o^* &= 1743^\circ \text{ k}, \\ p &= - \left[ \frac{\Delta s_q \cdot (T_o^* - T_o) - R \cdot T_o \cdot \ln 0.5}{\Delta v_q - \Delta v_{En} \left\{ (\Delta s_q / \Delta s_{En}) + (R / \Delta s_{En}) \cdot \ln 0.5 \right\}} \right] 41.27 + p_o \dots \dots \dots (11)'' \end{aligned}$$

we obtain  $p = 2.6 \times 10^4 \text{ atm.}$

Namely, it is expected that, at the pressure of about 26 kb., incongruent relation between quartz and clinoenstatite appears.

Further, using Eq. (3)' and (4)' we can obtain the phase diagram under 30 kb. (Fig. 1), which shows that the incongruent relation between quartz and clinoenstatite is present.

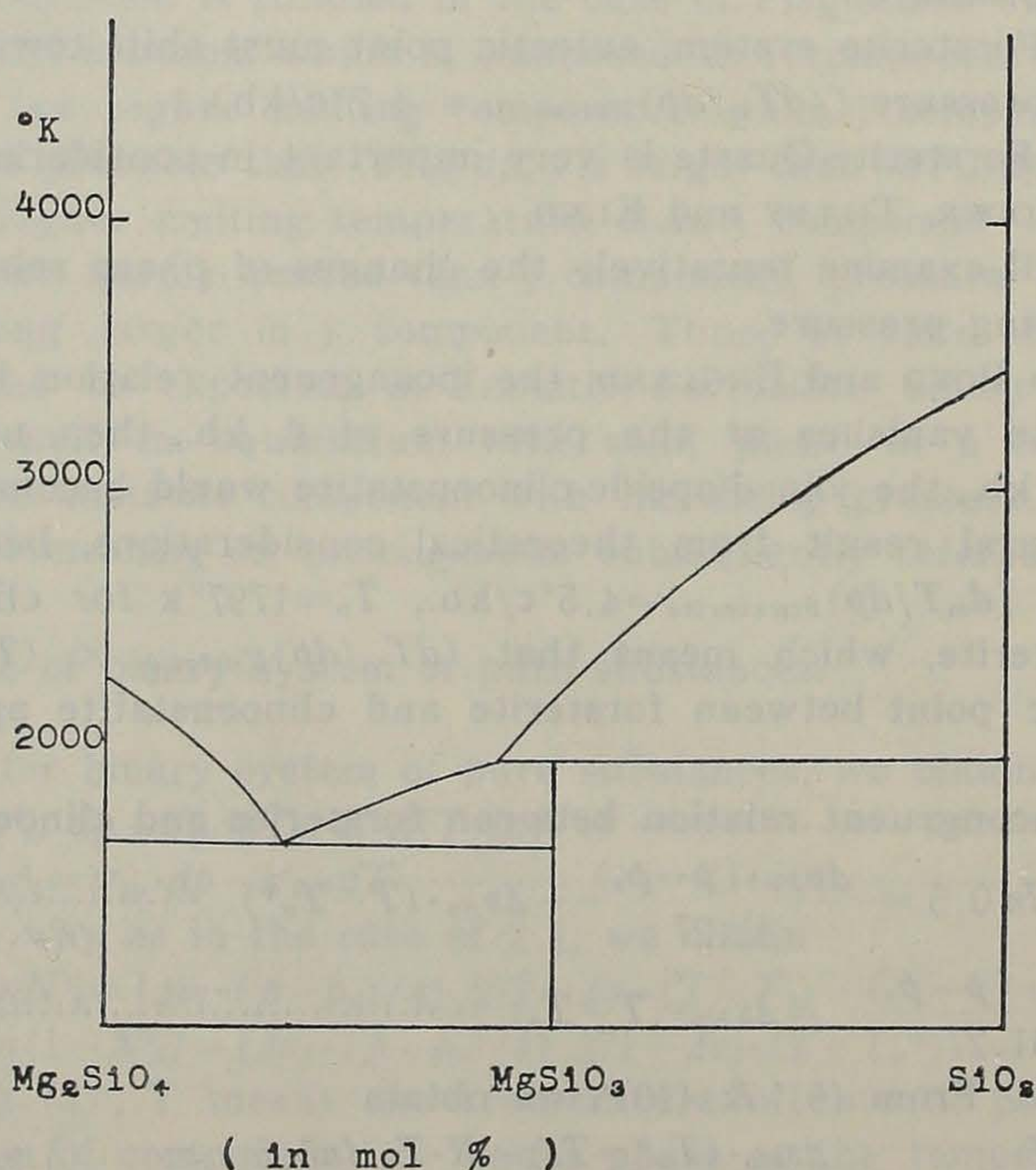


Fig. 1. Forsterite-Quartz System.  $p=30\text{kb.}$

Under such high pressure as 31kb  $\sim$  40kb., we must take into account the abrupt decrease of molal volume of silica glass in order to estimate the phase relations in Forsterite-Quartz system.

In 1953, BRIDGMAN and SIMON have found that, under the pressure higher than 31 kb., silica glass is abruptly compressed and becomes to have remarkably high density ( $\rho=2.61$ ), which is the value very near to that of crystalline quartz (quoted from YOSHIKI 1959). This highly dense silica glass is called suprapiezo glass (S. P. glass). Under this condition,  $\Delta v_q = -0.3 \text{ c.c./mol.}$



If we assume that the entropy difference between normal glass and S.P. glass is at most of the order of 1 cal/mol, it would be expected that  $3.68^{\circ}\text{C}/\text{kb} < (dT_m/dp)_q < 7.17^{\circ}\text{C}/\text{kb}$ . For the condition that  $\Delta s_q = -1$  cal/mol under the pressure higher than 31 kb.,  $p-T$  curve for silica and silica melt is estimated roughly (Fig. 2).

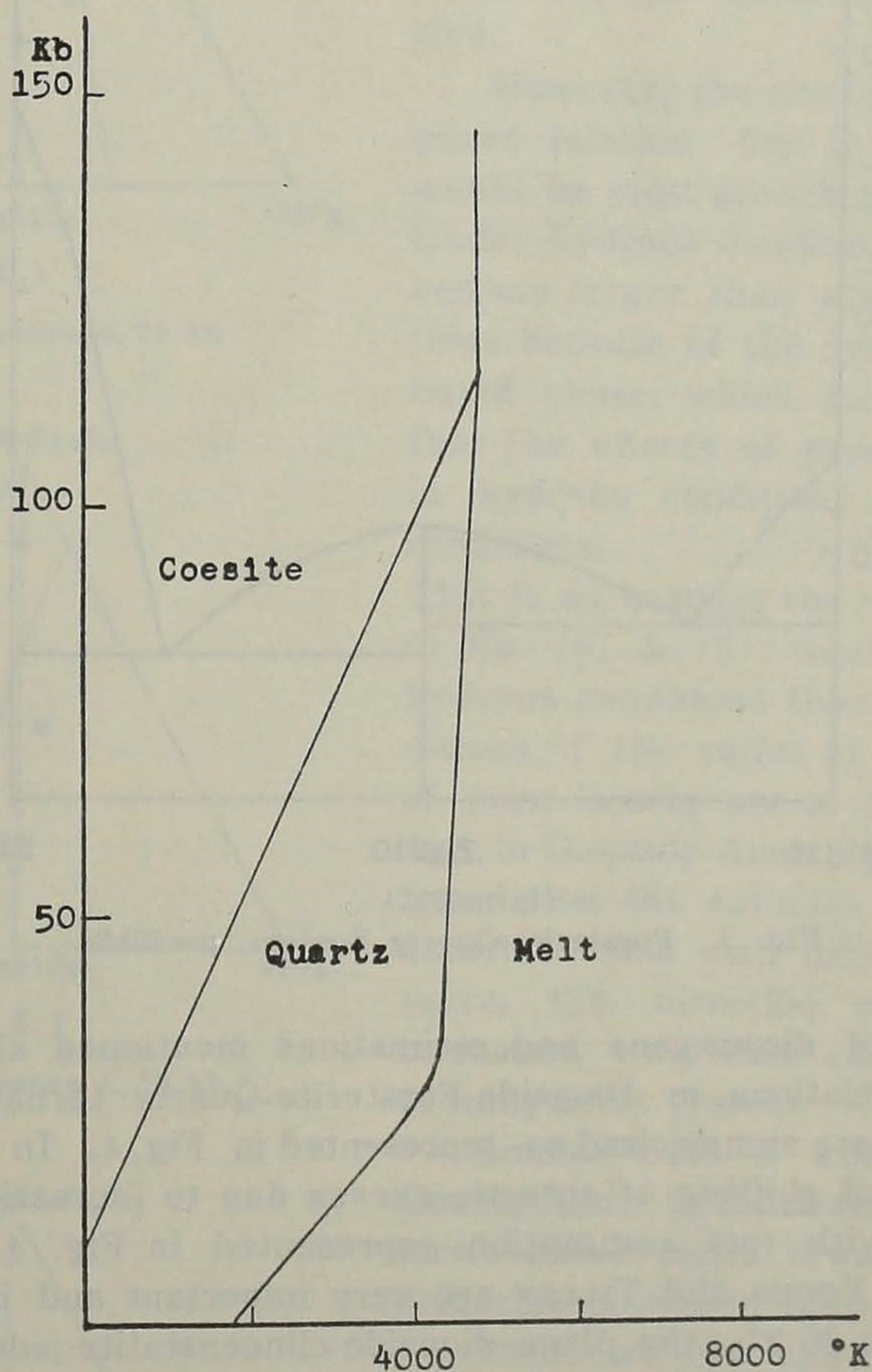


Fig. 2. P-T diagram for Silica (calculated roughly)

At the same time, using Eq. (3)' & (4)', we obtain phase diagram for Forsterite-Quartz system under 40 kb. (Fig. 3).

In this diagram, it is noted that clinoenstatite makes again thermal barrier as under the pressure between 6 kb. and 26 kb.

Further, the following two points are noted also; the first point is that the composition of eutectic point between clinoenstatite and quartz is of 37% in term of clinoenstatite component, which corresponds to 82% in term of silica component, the second point being that the eutectic point should shift toward clinoenstatite side with increasing pressure. In fact, it is confirmed by calculation that, under 50 kb., the composition of the eutectic point becomes 42% in term of clinoenstatite component.



Even if the entropy difference between normal silica glass and S.P. glass is large, say 1.6 cal/mol ( $(dT_m/dp)_q = 20/\text{kb.}$ ), the composition of the eutectic point is as acid as the former case, the direction of shifting due to increasing pressure being the same with the former case.

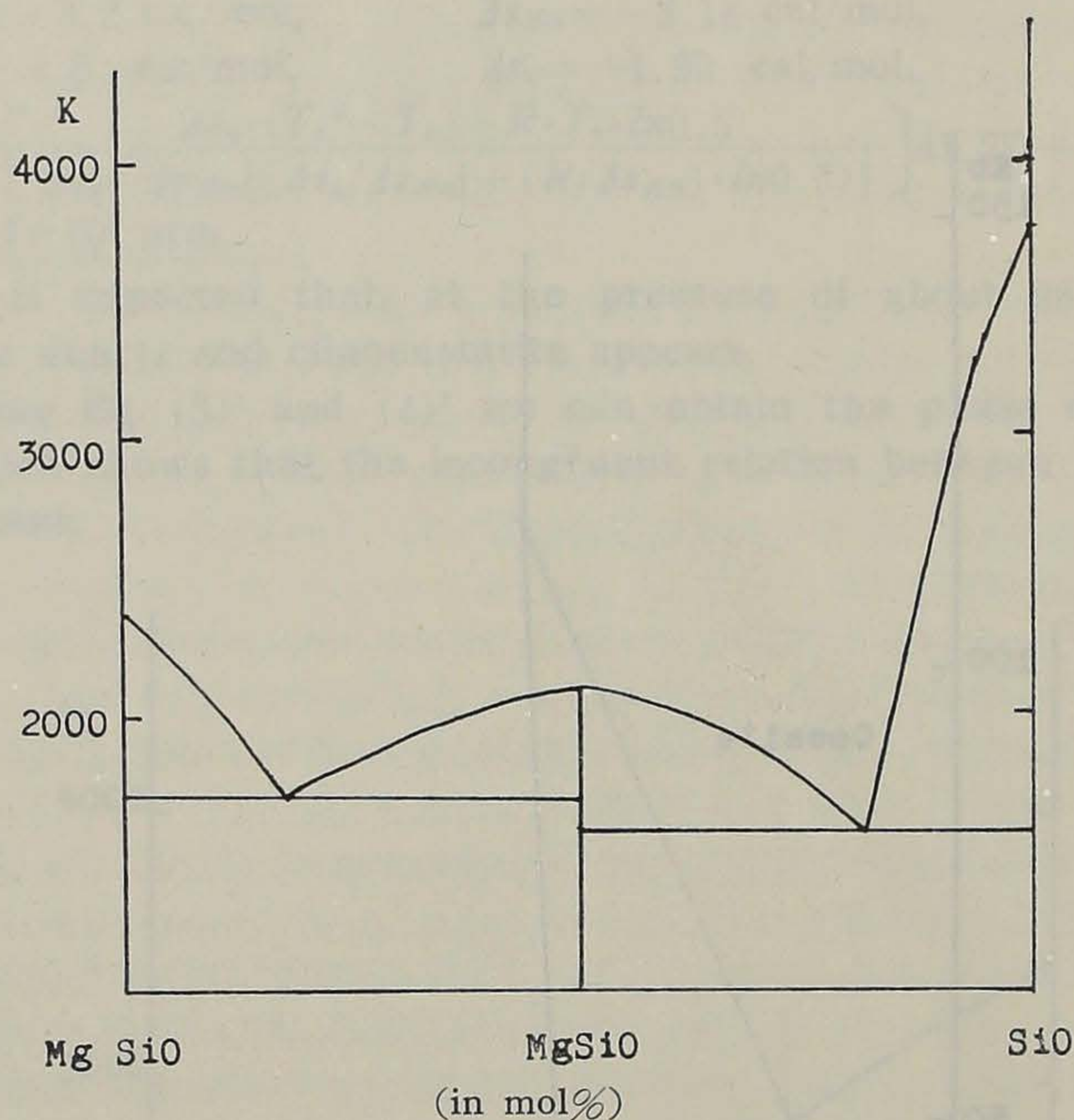


Fig. 3. Forsterite-Quartz System.  $p=40\text{kb.}$

On the basis of discussions and estimations mentioned above, the possible changes in phase relations in Diopside-Forsterite-Quartz ternary system due to increasing pressure are summarized as represented in Fig. 4. In this figure, arrows show the direction of shifting of eutectic curves due to increasing pressure.

In connection with this assumption represented in Fig. 4, the experimental results obtained by YODER and TILLEY are very important and interesting. They have shown that, at 30 kb., the plane diopside-clinoenstatite-jadeite becomes thermal barrier in Diopside-Forsterite-Quartz-Nepheline tetrahedral system, which would suggest that the assumption made by the present writer, that the incongruent relation between quartz and clinoenstatite vanishes, clinoenstatite becoming thermal barrier under the pressure higher than 31 kb., is reasonable. Furthermore, their experimental result would suggest that the incongruent relation between quartz and clinoenstatite is present under high pressure, because, according to them, thermal barrier is the plane diopside-forsterite-albite under the pressure lower than 30kb., although the plane diopside-clinoenstatite-albite would be expected to become thermal barrier under the pressure higher than 6kb. as already suggested.

In this way, in Fig. 5, the assumed transpositions of thermal barrier in Diopside-Forsterite-Quartz-Nepheline tetrahedral system are shown.

The discussions mentioned above are carried out on the premises that the systems concerned are anhydrous and activity coefficient of phases are all equiva-



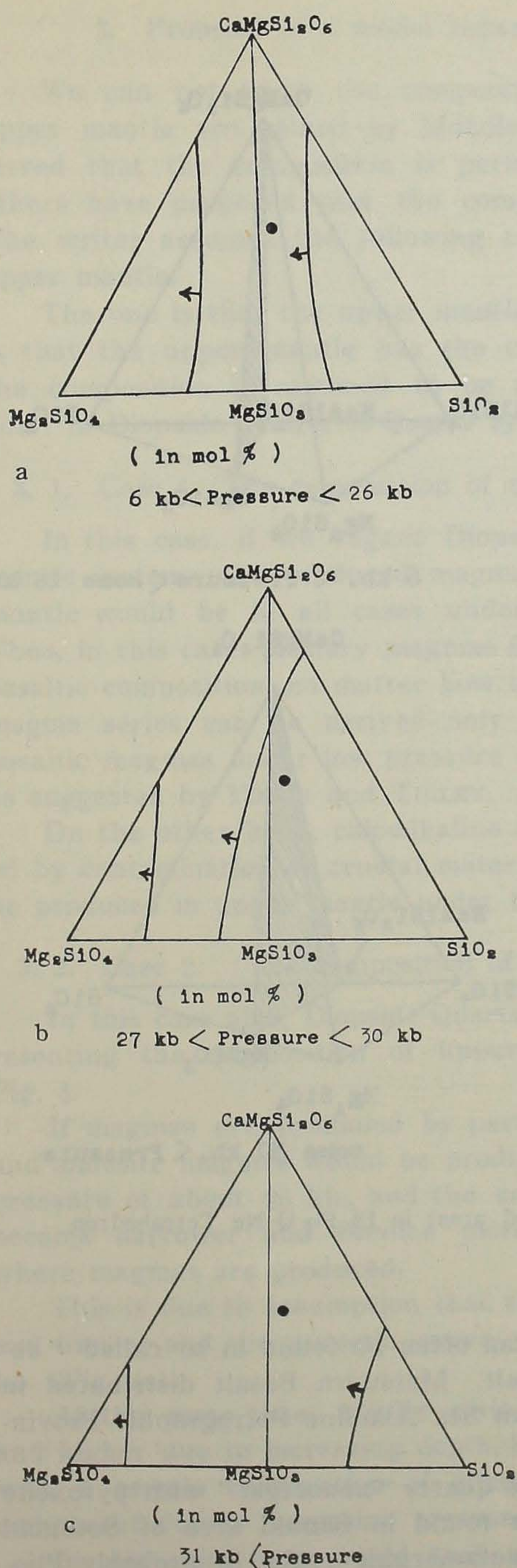


Fig. 4. Schematic diagrams showing the changes of phase relations in Diopside-Forsterite-Silica system by increasing pressure.

lent to unity. In fact, such premises are not real, for the real conditions of systems concerned are not ideal and the real conditions of earth's crust and of upper mantle would be not anhydrous. Because of non-ideality of the systems, the discussions mentioned above are not quantitative but are qualitative.

However, the tendencies of changes of phase relation due to increasing pressure would be most probable in qualitative sense. Under hydrous conditions,  $\Delta s$  and  $\Delta v$  would become larger than under anhydrous conditions because of the increase in entropy of liquid phase, which mean, in many cases, that the effects of pressure become larger in hydrous conditions than in anhydrous conditions.

This is so, because the parameter of  $(p-p_0)$  in Eq. (8) & (5)' would become larger in hydrous conditions than in anhydrous conditions, if the ratios of increase in entropy of pure liquids are of the same order. In fact, in Diopside-Anorthite system, Yoder has found that the eutectic point shift toward anorthite side with increasing vapour pressure, the direction of shifting being in consistent with that expected in the case of anhydrous system.

Similar case is known in the system Quartz-Albite-Orthoclase, in which the eutectic curve shifts toward the join albite-orthoclase due to increasing vapour pressure.

Thus, we are allowed to expect that the tendencies of changes in phase relations assumed in this chapter hold good under the real conditions of earth's crust and upper mantle.

Now, if the incongruent relation between quartz and clinoenstatite appears under high pressure, it is expected that quartz phenocryst having pyroxene corona can be found in basic volcanic rocks, especially in alkaline basaltic rocks.

In fact, such phenomena have been known in many instances.

For example, according to Y. MATSUMO-



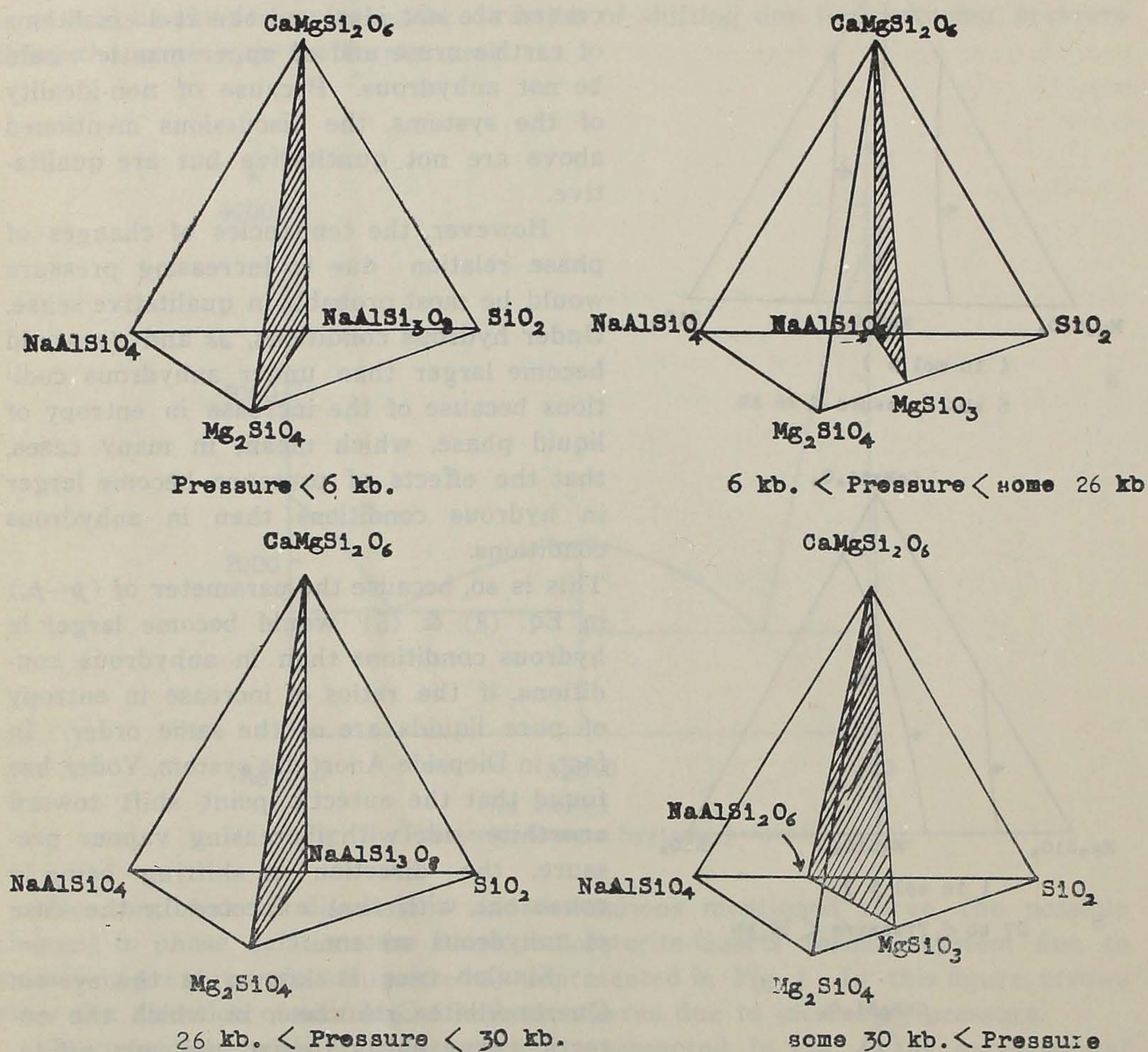


Fig. 5.

The transpositions of thermal barrier (hatched area) in Di-Fo-Q-Ne Tetrahedron due to increasing pressure

TO, such quartz phenocryst or "xenocryst" can often be found in so called "abnormal" olivine basalt named Matsuura Basalt. Matsuura Basalt distributed in Northwest Kyusyu belongs to the circum Japan Sea Alkaline Petrographic Province after T. Tomita.

The present writer also described that the quartz "xenocryst" with pyroxene corona was often found in olivine basalt cones found in Sanuki area of Setouchi Province, which were intruded into Ryoke metamorphic rocks in probably Plio-Pleistocene age. Although the writer once believed all of these "xenocryst" to be truly xenocryst derived from basemental granites or granitic gneisses, now, he infers that some of these "xenocryst" may be relict of quartz phenocryst crystallized out in upper mantle.



### 3. Proposal of a model regarding the origin of primary magmas

We can not know the composition of upper mantle, until boring cores of upper mantle are gained by Mohole or other projects. Many authors have preferred that the composition is peridotitic. However, J. F. LOVERING and some others have proposed that the composition of upper mantle is rather eclogitic. The writer assumes the following two extreme cases about the composition of upper mantle.

The one is that the upper mantle has composition of peridotite, and the other is that the upper mantle has the composition of eclogite. In the second case, the composition is assumed to be saturated a little in silica, as shown by the point in Diopside-Forsterite-Quartz system (Fig. 4).

#### 3. 1. Case 1 (The composition of upper mantle is undersaturated in silica.)

In this case, if we regard Diopside-Quartz-Forsterite system as representing mantle system, the produced magmas by partial or complete melting of upper mantle would be in all cases undersaturated in silica, as is clear from Fig. 4. Thus, in this case, primary magmas formed by partial melting must have olivine basaltic composition, no matter how is the condition of pressure. Then, tholeiitic magma series can be derived only by crystallization differentiation of alkaline basaltic magmas under low pressure up to 6 kb. —namely in the earth's crust—, as suggested by YODER and TILLEY.

On the other hand, calc-alkaline magmas including granitic one may be derived by contamination of crustal materials. The granitic primary magmas may not be produced in upper mantle under these conditions.

#### 3. 2. Case 2. (The composition of upper mantle is saturated a little in silica.)

In this case also, Diopside-Quartz-Forsterite system may be regarded as representing the composition of upper mantle, which corresponds to the point in Fig. 4.

If magmas are produced by partial melting in upper mantle, tholeiitic basalt and andesite magmas would be produced down to the depth corresponding to the pressure of about 26 kb., and the composition range of produced magmas would become narrower and become more and more basic due to increasing depth, where magmas are produced.

This is due to assumption that the join clinoenstatite-diopside would be thermal barrier and the eutectic curve would shift toward thermal barrier up to 26 kb. (Fig. 4a).

At the same time, Mg/Fe ratio in produced magmas would become higher and higher due to increasing depth, because the composition of melt in equilibrium with a certain composition of clinopyroxene would become richer in enstatite component due to increasing pressure (see Chap. 2. 1.).

In this case, it is noted that alumina content in produced magmas would become higher due to increasing pressure because of the pressure effects on plagioclase solid solution (Chap. 2. 1.) and on Diopside-Anorthite binary system (Chap. 2. 2.).

However, binary relations between anorthite and albite can not be present



under the pressure higher than 25 kb. as shown by the experimental result after ENGLAND. Under the pressure higher than this value, anorthite would be perfectly decomposed and pyrope garnet would play an essential role in mantle minerals in place of plagioclase. However,  $(dT_m/dp)$  for pyrope is higher than those for enstatite and diopside ( $(dT_m/dp)_{\text{pyrope}} \doteq 14^\circ\text{C}/\text{kb.}$ ). Thus, under the pressure higher than 25kb., the eutectic point between pyrope and pyroxenes might shift toward pyroxene side due to increasing pressure. Then, under the pressure higher than this value, magmas formed by partial melting might become poorer in Al content, as pressure increases.

It would be probable that basaltic magmas high in Al content might be formed under the pressure near 25 kb., which might mean that high alumina basalt after Kuno could be formed under such pressure.

Under the pressure near 26 kb., the composition range of formed magmas would be greatly limited, because the eutectic curve between clinoenstatite and quartz would come extremely near the thermal barrier.

Then, under this condition, the formed magmas would become high in Mg content and low in silica, although the composition is saturated in silica a little. This would mean the production of plateau basalt characterized by olivine tholeiitic composition, uniformity in bulk chemical compositions and enormous volume found in tholeiitic plateau basalt being due to the narrowness in composition range of formed magmas.

Under the pressure higher than 26 kb., thermal barrier in Diopside-Forsterite-Quartz system vanishes and the incongruent relation between quartz and clinoenstatite would appear, then plateau basalt characterized by olivine basaltic composition could be formed by partial melting of mantle saturated a little in silica.

In this way, it may be considered that the average of bulk chemical compositions of two types of plateau basalt (tholeiitic one and olivine basaltic one) represents approximate composition of upper mantle.

Then, down to the depth corresponding to the pressure, at which the thermal barrier appears again, primary basic magmas undersaturated in silica could be formed.

Under the pressure higher than some 30kb., the thermal barrier would appear again, the composition of eutectic point between clinoenstatite and quartz being high in silica content (see Chap. 2. 2)

Under this condition, the composition range of formed magmas would highly expand, which would mean the possibility that acid and intermediate calc-alkaline magmas could be formed by partial melting of upper mantle.

In this depth, under hydrous conditions, vapour pressure in formed magmas would be high, and it would be expected that hydrous minerals can be formed more easily than in the case of tholeiitic magmas and that minerals of low temperature type (e.g. rhombic pyroxenes) could be formed in the course of solidification because of high entropy of liquid phase due to high content of volatile matters. This would mean that calc-alkaline magmas, from which are derived granitic, dioritic and noritic rocks, would be produced in upper mantle under such high pressure.

Summing up these assumptions and discussions, the assumed depths where



primary magmas are produced are shown in Fig. 6. It is needless to say that such figure is schematic and is only a possible model regarding the origin of primary magmas.

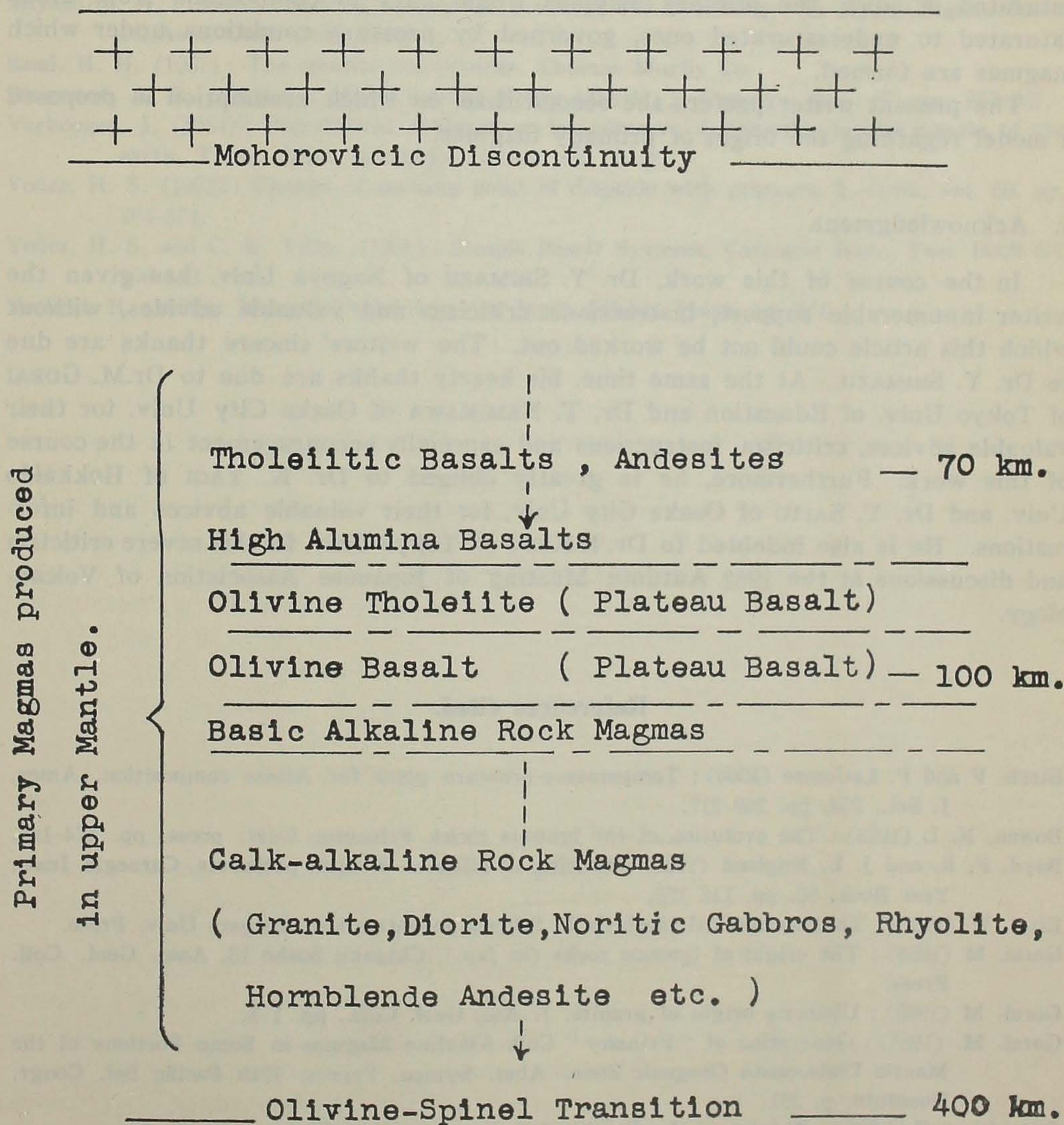


Fig. 6. Schematic figure showing relative positions of primary magmas produced in upper mantle.

#### 4. Summary.

The present writer prefers the view that parental magmas are generated in the upper mantle, based on geophysical and thermodynamical considerations. On this assumption, two cases are considered separately. In the first case, assuming that the composition of upper mantle is of peridotitic one, the primary magmas would be basaltic undersaturated in silica, from which tholeiitic and calk-alkaline



magmas are derived in earth's crust in the course of magmatic differentiation and/or assimilation.

In the second case, assuming that the composition of mantle is of eclogite saturated in silica, the primary magmas would vary in composition from much saturated to undersaturated ones, governed by pressure conditions under which magmas are formed.

The present writer prefers the second case, on which assumption is proposed a model regarding the origin of primary magmas.

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