

Table 14. *Fractionation of the olivine tholeiite at 9 kb*

P, T conditions (kb) (°C)	9 1,290	9 1,250	9 1,230	
Nature and estimated percentage of crystals	11% Olivine	12% Olivine 3% Ortho- pyroxene	12% Olivine 4% Orthopyroxene 14% Clinopyroxene	
<i>Composition of Crystal Extract</i>				
SiO <sub>2</sub>	40.3	42.5	45.9	
Al <sub>2</sub> O <sub>3</sub>	—	1.4	6.2	
FeO	12.3	13.0	11.3	
MgO	47.1	42.3	31.6	
CaO	0.3	0.8	5.0	
<i>Composition of Liquid Phase</i>				
	(Initial liquid)			
SiO <sub>2</sub>	46.95	47.6	47.6	47.3
TiO <sub>2</sub>	2.02	2.3	2.4	2.9
Al <sub>2</sub> O <sub>3</sub>	13.10	14.8	15.2	16.1
Fe <sub>2</sub> O <sub>3</sub>	1.02	1.1	1.2	1.5
FeO	10.07	9.8	9.6	9.5
MnO	0.15	0.2	0.2	0.2
MgO	14.55	10.5	9.5	7.2
CaO	10.16	11.4	11.8	12.4
Na <sub>2</sub> O	1.73	2.0	2.0	2.5
K <sub>2</sub> O	0.08	0.1	0.1	0.1
P <sub>2</sub> O <sub>5</sub>	0.21	0.2	0.2	0.3
<i>CIPW norm of Liquid Phase</i>				
Or	0.67	0.7	0.7	0.8
Ab	14.7	16.5	16.8	21.0
An	27.6	31.1	32.1	32.4
Di	17.0	19.2	20.2	22.5
Hy	12.3	13.8	12.9	5.2
Ol	21.9	12.2	10.5	10.1
Ilm	3.8	4.3	4.6	5.5
Mt	1.4	1.6	1.8	2.1
Ap	0.5	0.5	0.5	0.6
100 Mg	72.1	65.5	64.3	57.2
Mg + Fe <sup>++</sup>				

If the Al<sub>2</sub>O<sub>3</sub> content of the clinopyroxene is lower than the value used (cf. the clinopyroxene from the alkali basalt at 9 kb, 1,220°C) the resulting liquid will have higher Al<sub>2</sub>O<sub>3</sub> and higher normative anorthite content.

The calculated compositions of Table 14 illustrate the fractionation trend of the olivine tholeiite assuming quite low degrees of crystallization at pressures around 9 kb, i.e. depths of 30–35 kms. The derivative liquids are very distinctive in showing very little change in SiO<sub>2</sub> content and in normative olivine content once fractionation has proceeded to the stage of separation of both pyroxene and olivine (Fig. 8). In contrast, Al<sub>2</sub>O<sub>3</sub>, CaO and Na<sub>2</sub>O are steadily enriched in the residual liquid as fractionation proceeds (Figs. 8, 9) and the resulting compositions have high normative plagioclase contents. The derivative liquids are classifiable as high-alumina olivine tholeiites and closely resemble analyses of high

alumina olivine tholeiites, "oceanic tholeiites" or "high-alumina basalts" given by YODER and TILLEY (1962), ENGEL, ENGEL and HAVENS (1965) and KUNO (1960). It must be emphasized that the enrichment in CaO,  $\text{Al}_2\text{O}_3$  and  $\text{Na}_2\text{O}$  is caused by the absence of plagioclase as an early-crystallizing phase and by the co-precipitation of olivine and orthopyroxene, maintaining an olivine normative character and essentially constant  $\text{SiO}_2$  content. The appearance of clinopyroxene does not greatly modify this trend *provided* that the clinopyroxene is sub-calcic (i.e. co-existing with orthopyroxene) and of low or moderate  $\text{Al}_2\text{O}_3$  content. The increasing proportion of low-calcium pyroxenes extracted as fractionation proceeds results in decreasing normative hypersthene — in terms of the basalt tetrahedron (YODER and TILLEY, 1962), residual liquids from the olivine tholeiite fractionate rapidly towards the plagioclase apex of the olivine tholeiite volume and also fractionate slightly towards the Cpx-Ol-Plag plane of critical undersaturation (Fig. 1).

In the alkali olivine basalt composition, the analyses of both olivine and clinopyroxene at 9 kb 1,220° C can be used to calculate a possible residual liquid composition (Table 15) assuming 15% crystallization (5% olivine, 10% clinopyroxene). As with the olivine tholeiite, fractionation produces little change in  $\text{SiO}_2$  content but an increase in  $\text{Al}_2\text{O}_3$ ,  $\text{Na}_2\text{O}$  and normative plagioclase contents, and a decrease in 100 Mg/Mg + Fe<sup>++</sup> ratio (Figs. 8, 9). The absence of orthopyroxene and more calcic nature of the clinopyroxene prevent marked enrichment in CaO content though it must be pointed out that a higher proportion of olivine to clinopyroxene than that assumed in Table 15 would result in more marked increase in  $\text{Al}_2\text{O}_3$  content and increasing  $\text{SiO}_2$  and CaO contents. In terms of normative minerals, the separation of olivine and clinopyroxene results in increased nepheline and derivative liquids remain critically undersaturated with low or moderate degrees of fractionation.

The analytical data on phases crystallized from the olivine basalt composition at 9 kb are insufficient for a quantitative discussion of fractionation. However, the appearance of both orthopyroxene and clinopyroxene with olivine in the 9 kb, 1,260° C run will cause derivative liquids to move towards high  $\text{Al}_2\text{O}_3$ , CaO, and  $\text{Na}_2\text{O}$  contents while maintaining approximately constant  $\text{SiO}_2$ . Derivative liquids would almost certainly become nepheline-normative with sufficient fractionation. The absence of orthopyroxene in the 1,240° C, 9 kb run indicates a more calcic clinopyroxene and fractionation beyond this temperature would probably show decreasing CaO content.

In general, analyses of natural high- $\text{Al}_2\text{O}_3$  basalts in the literature have higher  $\text{SiO}_2$  contents than the calculated compositions. Closer similarity in this component would be produced if a slightly greater proportion of olivine crystallized before the appearance of orthopyroxene and we anticipate that this would happen in the olivine tholeiite at slightly lower pressures than 9 kb. We anticipate a transition with increasing pressure between the low pressure fractionation trend to quartz tholeiite without  $\text{Al}_2\text{O}_3$  enrichment and the higher pressure trend to high-alumina olivine tholeiites or high-alumina alkali olivine basalts. Increasing pressure will enlarge the temperature interval between the appearance of olivine and plagioclase and will also gradually extend the field of orthopyroxene crystallization into olivine-normative (particularly with Ol > 15%) compositions. Thus