

Fig. 5. Stability limit of amphibole in an albite-rich quartz tholeiite, comparing synthesis runs with reversals.

thesis boundary appears to be rather sharp and reproducible.

The solidus was difficult to locate for these basaltic compositions due to the formation of quench amphibole and the formation of only a small amount of glass near the solidus. It was estimated from the runs plotted in figs. 4 and 5 and by comparison with YODER and TILLEY's (1962) and LAMBERT and WYLLIE's (1968) data. The solidus for the alkali olivine basalt with 26% normative olivine is thought to be 50–75° higher than that for the quartz-normative tholeiite.

The upper stability of amphibole in supersolidus runs will involve reaction with melt as well as vapor, but these data have been included to place gross limits on the possible slopes for the supersolidus curves. GREEN and RINGWOOD (1967) found amphibole between 10.1 and 16.8 kb at 1100 °C with $P_{H_2O} < P_T$ in the alkali olivine basalt and this is used in fig. 6 to tentatively fix the amphibole stability. Yoder and Tilley's data on the stability of amphibole in various basalts have been consulted to estimate the amphibole stability in the quartz tholeiite (fig. 7).

The subsolidus reaction of amphibolite to eclogite is not likely to be a sharp transition but a gradual reaction among amphibole, garnet and pyroxenes (and feldspars?). It is best thought of as a sliding reaction with a number of substitutions in each phase and may be

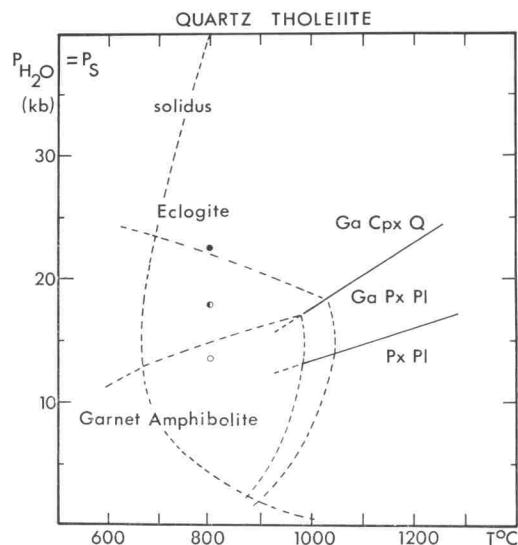


Fig. 6. Combination of present data for the alkali olivine basalt with that of GREEN and RINGWOOD (1967). Sa = Sanidine, Ga = Garnet, Pxs = Pyroxenes, Pl = Plagioclase, Ol = Olivine.

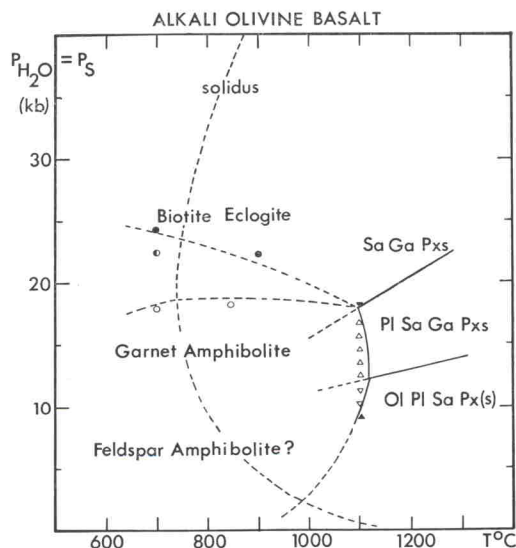
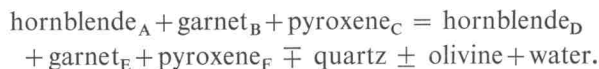


Fig. 7. Combination of the present data for the quartz tholeiite with that of GREEN and RINGWOOD (1967) and data for the amphibole stability from the Silberbach eclogite as determined by YODER and TILLEY (1962).

generalized as:



The hornblende etc. on each side of the reaction will form a solid solution shifting with $\Delta P, T$ to any of a

large number of end members. The area over which this sliding reaction will occur has not been determined experimentally and much longer run times (≈ 1 month) may be needed to establish this zone.

5. Interpretation

The present data suggest that eclogite will form at the expense of amphibolite when pressures are somewhere in the region of 10–30 kb at medium temperatures for basaltic rocks at high water pressures. This generally confirms LAMBERT and WYLLIE's (1968) experiments, but the difference between syntheses and reversals found here suggests that their synthesis experiments may be in error and should not be used for any specific argument as to magma generation in the upper mantle. Stability of one amphibole in a basaltic rock or under its own composition is no guide to the behavior of another amphibole in an ultramafic rock. Certainly their incoming of garnet at $P > 18$ kb (LAMBERT and WYLLIE, 1970) is open to doubt as no garnet nuclei were available in the starting mix. Tighter reversals are needed before evaluating the possibility that crustal eclogites form at high water pressures.

Garnet amphibolites lacking feldspar are expected to have higher densities ($3.2\text{--}3.4\text{ g/cm}^3$) and higher estimated seismic velocities ($V_p = 7.6\text{--}8.0\text{ km/s}$) than previously thought possible for hydrated basic rocks, and may be important in the lower crust or upper mantle ($< 70\text{ km}$), if water pressures are high. Garnet amphibolites lacking feldspar have been found in high-pressure crustal rocks (ESSENE, 1967) and may be widespread in the lower crust.

The apparent stability of biotite in the potassic alkali olivine basalt suggests that trioctahedral mica may be an important hydrous phase in the upper mantle. The decomposition of several amphiboles at high water pressures (fig. 3) apparently involves formation of another sheet silicate (talc) at high water pressures. SCLAR (1970) has synthesized a 10 \AA micaceous phase in the system $\text{MgO-SiO}_2\text{-H}_2\text{O}$ at $P > 30\text{ kb}$ and $T < 500\text{ }^\circ\text{C}$ but has not yet shown whether this phase is stable by reversals nor reported its relation to other phases of $\approx 10\text{ \AA}$ – as attapulgite. KUSHIRO *et al.* (1967) have examined phlogopite at high pressures and claim it is stable to at least 100 kb, but they have located a solidus in the system outside their stability field for phlogopite, whereas LUTH (1967) has shown that phlogopite breakdown

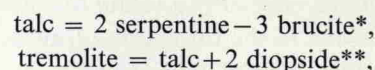
curve intersects the solidus at only 2 kb water pressure. This suggests that Kushiro *et al.* may have had $P_{\text{H}_2\text{O}} \ll P_T$ in their runs; they may have also had trouble with quench phlogopite. In a later series of experiments, YODER and KUSHIRO (1969) confirmed Luth's data and showed that phlogopite remains stable up to $1200\text{ }^\circ\text{C}$ and 40 kb.

Appendix I

The thermodynamic calculations in fig. 3 were all based on experimental data, and extended to higher pressures and temperatures with the well-known relations

$$\left(\frac{\delta\Delta G}{\delta T}\right)_P = -\Delta S, \quad \left(\frac{\delta\Delta G}{\delta P}\right)_T = \Delta V.$$

The free energy data for water were taken from BURNHAM *et al.* (1968) below 10 kb, and above 10 kb from SHARP (1962). Measured high-temperature entropies ($S_T - S_{298}$) are not available for talc, tremolite or "hornblende" and were estimated by summing the high-temperature entropies of other silicates:



and the entropy of "hornblende" was assumed equal to tremolite. From these estimates, the high-temperature entropies of talc and tremolite were fitted to the quadratic equation of the form

$$S_T - S_{298} = a \ln T + b10^{-3}T + c10^5T^{-2} + d,$$

where the values of a , b , c , d are given in table 1.

TABLE 1

	a	b	c	d
Talc	+126.26	-5.06	+24.89	-745.82
Tremolite	+232.00	+10.02	+38.63	-1365.52

The molar volumes (V^0) of the silicates were taken from ROBIE *et al.* (1967) and the standard entropies (S_{298}^0) from ROBIE (1966); these data are not available for "hornblende" and were estimated: $V^0 = 270.5\text{ cm}^3$, $S_{298}^0 = 131.6\text{ e.u.}$ In making the calculations the com-

* Entropy data for serpentine and brucite are from KING *et al.* (1967).

** High-temperature entropy data for diopside are from KELLEY (1960).