

TABLE 1. COMPOSITIONS OF PHASES AND BULK ROCK

| Analysis phase<br><i>P</i> (bars)<br><i>T</i> (°C)<br>wt % H <sub>2</sub> O<br>in melt | 1<br>bulk<br>rock | 2<br>opx<br>(phenocrysts in<br>natural rock) | 3<br>plag | 4<br>opx<br>1,000<br>980<br>4.3 | 5<br>opx<br>5,620<br>1,070<br>2.5 | 6<br>opx<br>5,430<br>1,010<br>4.6 | 7<br>opx<br>10,000<br>1,000<br>4.6 |
|--|-------------------|--|-----------|---------------------------------|-----------------------------------|-----------------------------------|------------------------------------|
| SiO <sub>2</sub>   | 59.1              | 54.7   | 54.4      | 51.4                            | 52.3                              | 52.4                              | 51.0                               |
| TiO <sub>2</sub>   | 0.94              | 0.31   | 0.05      | 0.50                            | 0.34                              | 0.33                              | 0.41                               |
| Al <sub>2</sub> O <sub>3</sub>   | 17.8              | 1.45   | 28.8      | 0.79                            | 1.60                              | 1.99                              | 1.09                               |
| FeO*   | 6.43              | 18.2   | 0.22      | 22.5                            | 21.0                              | 19.4                              | 22.3                               |
| MgO  | 3.05              | 24.7   | 0.00      | 22.5                            | 22.6                              | 24.2                              | 21.5                               |
| CaO  | 6.85              | 1.35   | 11.9      | 1.75                            | 1.42                              | 1.51                              | 1.67                               |
| Na <sub>2</sub> O  | 4.27              | 0.07   | 4.8       | n.d.                            | 0.09                              | n.d.                              | 0.05                               |
| K <sub>2</sub> O   | 1.08              | 0.01   | 0.18      | n.d.                            | 0.09                              | n.d.                              | 0.01                               |
| Total  | 99.52             | 100.79                                       | 100.35    | 99.44                           | 99.44                             | 99.83                             | 98.03                              |

\*Total Fe as FeO. Opx = Orthopyroxene, plag = Plagioclase.

than magnetite. In the  $f_{O_2}$ - $T$  range we consider reasonable for natural conditions, between the dotted lines on Figure 3, magnetite and ilmenite crystallize 20° to 45°C below the orthopyroxene liquidus and well below the plagioclase liquidus.

Phase relations at H<sub>2</sub>O-saturated conditions at the QFM buffer appear in  $P$ - $T$  projection in Figure 1 and at H<sub>2</sub>O-undersaturated conditions in Figure 2. Figure 2 also shows the relation between weight percent H<sub>2</sub>O in the liquid and  $X^{H_2O}$ , as discussed by Eggler (1972a). Water-undersaturated liquids for anhydrous phases are drawn for H<sub>2</sub>O contents in melts of 2.0 and 4.7 percent H<sub>2</sub>O. Melting curves for orthopyroxene and plagioclase do not have the same slope because of differences in the  $\Delta V_r$  and  $\Delta S_r$  of the melting reactions. The curves are nearly linear at low H<sub>2</sub>O contents and become steeper, relative to the dry liquid, with increasing H<sub>2</sub>O content.

Phase relations are clarified by calculation of a  $T$ - $X$  section from Figures 1 and 2. Figure 4 clearly shows the melting relations as a function of H<sub>2</sub>O content and  $X^{H_2O}$  at 5 kb total pressure. In the calculation we assume melting temperatures with pure CO<sub>2</sub> are those of the dry liquid. The diagram also contrasts melting of Mount Hood andesite with a Paricutin andesite (Eggler, 1972a). Liquid slopes are similar for the two rocks, but their relative positions are different. For example, plagioclase is the liquidus phase in the Mount

Hood andesite for all H<sub>2</sub>O contents, while orthopyroxene assumes the liquidus in the Paricutin andesite at about 2 percent H<sub>2</sub>O.

Oxides are also stable to higher temperature in the Mount Hood andesite. As at 1 atm, ilmenite appears first, but the relation between ilmenite and magnetite is not entirely clear, inasmuch as in 1 kb H<sub>2</sub>O-saturated runs, magnetite appears with ilmenite, but at 2 kb, magnetite crystallizes at least 60°C below ilmenite. H<sub>2</sub>O-undersaturated runs indicate that at the QFM buffer, ilmenite appears at least 35°C below the silicate liquidus and magnetite becomes unstable relative to ilmenite with increasing pressure.

The upper temperature limit of amphibole stability is 950°C at 12 kb and H<sub>2</sub>O-saturated conditions (Allen and Boettcher, 1971; Fig. 1). Recent investigations (Hill and Boettcher, 1970; Holloway and Burnham, 1972; Holloway, 1973; Eggler, 1972b) have shown that under H<sub>2</sub>O-undersaturated conditions the upper temperature limit of amphibole stability may either increase or decrease relative to the H<sub>2</sub>O-saturated stability curve. In the pressure range to 10 kb, however, the amphibole-out curve will lie within 20°C of the H<sub>2</sub>O-saturated curve unless the melt contains less than about 3.5 wt percent H<sub>2</sub>O. Runs on Mount Hood andesite at 5.5 kb containing 4.0 to 4.7 percent H<sub>2</sub>O show that amphibole is as stable, within experimental limits, as when the melt is H<sub>2</sub>O saturated (10 percent H<sub>2</sub>O). However, under

TABLE 2. RESULTS OF EXPERIMENTAL RUNS AT H<sub>2</sub>O-SATURATED CONDITIONS

| P(kb) | T, °C | Conditions of run              |            |                                     |      | Initial (%H <sub>2</sub> O)  | Phases present* |
|-------|-------|--------------------------------|------------|-------------------------------------|------|------------------------------|-----------------|
|       |       | P <sub>H<sub>2</sub></sub> (b) | Time (hrs) | -log f <sub>O<sub>2</sub></sub> (b) |      |                              |                 |
| 0.50  | 1,090 | 8.6                            | 5.5        | 9.69                                | 3.4  | gl, pl                       |                 |
| 0.50  | 1,060 | 8.6                            | 17.5       | 10.13                               | 5.0  | gl, pl                       |                 |
| 1.00  | 1,050 | 18.1                           | 23         | 10.35                               | 10.5 | gl, pl                       |                 |
| 1.00  | 1,030 | 18.1                           | 23         | 10.66                               | 6.6  | gl, pl, opx(tr.)             |                 |
| 1.02  | 1,000 | 7.0                            | 28         | 10.28                               | 6.0  | gl, pl, opx, il, mt(sa)      |                 |
| 1.00  | 980   | 7.4                            | 36         | 10.68                               | 6.7  | gl, pl, opx, il, mt          |                 |
| 2.12  | 1,000 | 30.0                           | 27         | 10.92                               | 8.7  | gl                           |                 |
| 2.12  | 975   | 30.0                           | 27         | 11.34                               | 7.8  | gl, pl(sa), opx(tr.)         |                 |
| 2.04  | 955   | 28.6                           | 21         | 11.68                               | 7.5  | gl, pl, opx, il              |                 |
| 2.04  | 935   | 28.6                           | 21         | 12.04                               | 8.3  | gl, pl, opx, il              |                 |
| 2.07  | 925   | 28.6                           | 24         | 12.21                               | 10.8 | gl, opx, pl, hb, il          |                 |
| 2.07  | 905   | 28.6                           | 24         | 12.59                               | 10.4 | gl, opx, cpx(sa), pl, hb, il |                 |
| 5.52  | 925   | 78.0                           | 12         | 12.06                               | 15.7 | gl, hb, opx(sa), pl          |                 |
| 5.52  | 900   | 78.0                           | 12         | 12.54                               | 13.7 | gl, hb, opx, pl              |                 |
| 6.27  | 965   | 98.7                           | 2.25       | 11.37                               | 14.5 | gl                           |                 |
| 6.27  | 950   | 66.2                           | 20         | 11.29                               | 13.2 | gl, opx(sa), pl(tr.)         |                 |

\*gl = glass, pl = plagioclase, opx = orthopyroxene, cpx = clinopyroxene, il = ilmenite-hematite solid solution, mt = magnetite-ulvöspinel solid solution, tr. = trace, sa = small amount.

H<sub>2</sub>O-undersaturated conditions, amphibole is never stable at temperatures near the plagioclase liquidus.

### Phase Compositions

Orthopyroxenes encountered in run products are moderately aluminous (Table 4); in some cases, certain grains inverted upon quenching to a clinopyroxene which had a small extinction angle. No plagioclase, amphibole, or clinopyroxene could be analyzed from run products. Amphiboles should be similar to tschermakitic hornblendes from Paricutin andesite runs (Egglar, 1972b) and clinopyroxenes should be similar to those in Paricutin runs, which contained 42 mole percent wollastonite and a maximum of 4.4 percent Al<sub>2</sub>O<sub>3</sub> at 10 kb.

### OXIDE FRACTIONATION IN THE CALC-ALKALINE SUITE

Various geochemical arguments regarding the fractional crystallization hypothesis of andesite origin have been reviewed by Green and Ringwood (1968). Phase equilibria questions revolve about the problem of iron oxide stability. Model system studies (Osborn, 1959; Roeder and Osborn, 1966; Egglar and Osborn, 1969) and mass-balance calculations

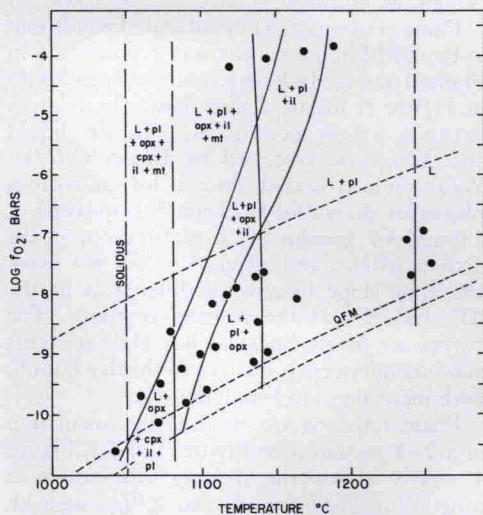


Figure 3. Phase relations for Mt. Hood andesite as a function of  $f_{O_2}$  at 1 atm total pressure. Stability limits are long dashed where approximately located. Short dashes contain region of  $f_{O_2}$  values expected in natural magmas.

show that magnetite must be subtracted from a basalt melt, along with silicates, to yield an andesite melt derivative. An iron-rich oxide phase must therefore be stable in a parent basalt melt, each succeeding melt, and the