0.5, the observed amphibole-out curve is a melting reaction above 4.5 kb. Between 3.5 and 4.5 kb, the upper temperature stability of amphibole is limited by the dehydration curve, although that curve lies above the H_2O-saturated amphibole-out curve. Below 3.5 kb, the upper stability limit is still the dehydration curve, but the amphibole-out curve now lies below the H_2O-saturated curve.

Fig. 4c correctly predicts observed melting behavior at 5.5 kb. The amphibole-out curve for $X^{fl}_{H_2O}$ = 0.5 lies above the curve for $X^{fl}_{H_2O}$ = 1. The 0.5 curve also lies near a temperature stability maximum, because when $X^{fl}_{H_2O}$ is less than 0.44, the amphibole-out curve descends in temperature with decreasing $X^{fl}_{H_2O}$.

6. Summary

Experiments and theory developed in this paper indicate that the upper temperature limit of amphibole stability in a melt is a function of pressure, temperature and $f^{m}_{H_2O}$, the fugacity of H_2O in the melt. Moreover, to fully characterize amphibole stability, we must relate those intensive parameters to possible reactions involving amphibole. In calcalkaline melts, it appears that the upper temperature stability limit of amphibole for any $X^{fl}_{H_2O}$ may represent either an incongruent melting or a dehydration reaction, depending upon total pressure and composition of the fluid phase in equilibrium with the melt. The *maximum* upper temperature stability limit may lie either above or below the H_2O-saturated upper temperature stability limit, depending upon total pressure.

The maximum upper temperature stability limit was determined experimentally at 5.5 kb in andesite melt. The temperature is 940°C, at a H_2O content in melt of 4.5 percent ($X^{fl}_{H_2O}$ = 0.44). The maximum at 5.5 kb represents the point at which amphibole breakdown changes from a predominantly melting reaction (eq. 2) to a dehydration reaction (eq. 4). Amphibole continues to melt partially at H_2O contents in melt less than 4.5 percent, but H_2O produced by its dehydration is greater than that required to enter the amount of liquid produced by its melting.

7. Petrologic applications

The maximum temperature stability limit of amphibole determined at 5.5 kb, 940°C, is probably applicable to most calcalkaline melts. Because the maximum amphibole-out curve (fig. 4c) has a very steep slope, 950°C probably is the upper temperature limit of amphibole stability in calcalkaline melts whose fluid phase contains only H_2O and CO_2 at depths less than 35 km. It is possible that the halogens may increase amphibole stability, however.

Amphibole is also a possible index to H_2O content of calcalkaline melts. The presence of amphibole phenocrysts cannot of itself indicate H_2O content, because the upper stability limit of amphibole may change very little with wide variations in $X^{fl}_{H_2O}$ (fig. 4c). However, while the amphibole-out curve may change very little with $X^{fl}_{H_2O}$, the other silicate liquidi change considerably in temperature isobarically and may lie above or below the amphibole-out curve for a particular $X^{fl}_{H_2O}$. For example, in Paricutin andesite the plagioclase liquidus is higher in temperature than the family of amphibole-out curves unless H_2O content in melt is more than 6 percent [16]. Petrographic criteria indicating coexisting plagioclase and amphibole phenocrysts in an andesite of that composition would be strong evidence that H_2O content in the magma was near 6 percent.

The principles of amphibole stability developed for andesite melt are undoubtedly applicable to basalt melt. The H_2O-undersaturated partial melting of amphibole-bearing basalt may play a very important role in generation of the calc-alkaline suite [3]. This study affirms the possibility of such a mechanism, since amphibole is shown to exist near or above its H_2O-saturated stability limit in silicate melts over a wide range of water-undersaturated conditions. Indeed, fig. 4c suggests that at 9 kb amphibole may be as stable when $X^{fl}_{H_2O}$ = 0.3 as when $X^{fl}_{H_2O}$ = 1.0.

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References

[1] H.S. Yoder and I. Kushiro, Melting of a hydrous phase: phlogopite, Am. J. Sci. (Schairer Vol.) 267-A (1969) 558.

[2] A.L. Boettcher, The system CaO-Al_2O_3-SiO_2-H_2O at high pressures and temperatures, J. Petrology 11 (1970) 337.

[3] J.R. Holloway and C.W. Burnham, Melting relations of basalt with equilibrium water pressure less than total pressure, J. Petrology (1972) in press.

[4] G.M. Anderson, Some thermodynamics of dehydration equilibria, Am. J. Sci. 269 (1970) 392.

[5] J.R. Holloway, C.W. Burnham, and G.L. Millhollen, Generation of H_2O-CO_2 mixtures for use in hydrothermal experimentation, J. Geophys. Res. 73 (1968) 6598.

[6] P.J. Wyllie and O.F. Tuttle, Effect of carbon dioxide on the melting of granite and feldspars, Am. J. Sci. 257 (1959) 648.

[7] C.W. Burnham and N.F. Davis, The role of H_2O in silicate melts I. *P-V-T*. relations in the system $NaAlSi_3O_8$-H_2O to 10 kilobars and 1000°C, Am. J. Sci. 270 (1971) 54.

[8] D.H. Eggler, Water-saturated and undersaturated melting relations in a Paricutin andesite and an estimate of water content in the natural magma, Contrib. Mineral. Petrol. (1971) in press.

[9] H.R. Shaw, Hydrogen osmosis in hydrothermal experiments, in: Researches in Geochemistry, ed. P.H. Abelson, vol. 2, (Wiley, New York, 1967) 521.

[10] D.H. Eggler, The effects of oxygen and water fugacity on melting relations in a typical orogenic andesite, in preparation.

[11] J.C. Allen and A.L. Boettcher, The stability of amphiboles in basalts and andesites at high pressures, Geol. Soc. Am. Abstracts 3 (1971) 490.

[12] R.E.T. Hill and A.L. Boettcher, Water in the earth's mantle: Melting curves of basalt-water and basalt-water-carbon dioxide, Science 167 (1970) 980.

[13] R.J. Williams, Reaction constants in the system Fe-MgO-SiO_2-O_2 at 1 atm between 900° and 1300°C: experimental results, Am. J. Sci. 270 (1971) 334.

[14] R.B. Merrill, J.K. Robertson, and P.J. Wyllie, Melting reactions in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O to 20 kilobars compared with results for other feldspar-quartz-H_2O and rock-H_2O systems, J. Geology 78 (1970) 558.

[15] G.L. Millhollen, Melting of nepheline syenite with H_2O and H_2O+CO_2, and the effect of dilution of the aqueous phase on the beginning of melting, Am. J. Sci. 270 (1971) 244.

[16] D.H. Eggler, Water-saturated and undersaturated melting relations in two natural andesites, Geol. Soc. Am. Abstracts 2 (1970) 544.