A TWO-PYROXENE THERMOMETER: D. H. Lindsley, Dept. of Earth and Space Sciences, State Univ. of New York, Stony Brook, N. Y. 11794

The CaSiO₃ contents of coexisting high-Ca and low-Ca pyroxenes have long been recognized as potential geothermometers for lunar and terrestrial rocks. Several approaches have been taken towards extracting the thermometric information [e.g., 1-10]. All these thermometers suffer from inadequate experimental control or thermodynamic treatment or both. The optimum two-pyroxene thermometer would involve a thermodynamic solution model accounting for the effects of minor (non-quad) components and for quad phase relations. In the absence of that model, we present a rationale for projecting natural pyroxene compositions onto the quad (Andersen and Lindsley, this volume) and a graphical geothermometer that is based on successful solution models for Di-En [11] and Hd-Fs [12] plus the currently available experimental data within the quad. These models permit calculation of binary phase diagrams for coexisting pyroxenes over a range of temperatures and pressures (even for conditions at which one or more pyroxenes may be metastable with respect to other phases such as liquid, olivine, and/or a silica phase); these calculated phase diagrams form the cornerstones of the thermometer presented here.

Reversed isobaric and isothermal phase diagrams for the quad [e.g., 13, 14, 15] show that the augite solvus bends sharply ("kinks") approximately where it crosses the line at which En = 0.50, making simple projections like those of [2] and of [3] inappropriate, but a graphical approach attractive. The segment of the augite solvus between the Di-En join and En = 0.50 tends to point almost directly toward FeSiO₃. To a first approximation I interpret these results as follows: (1) For En ≥ 0.50, the M₁ site of augite is filled with Mg, and Fe mixes ideally on the M₂ site. Thus, for Mg-rich augites the isotherms will start at appropriate compositions on the Di-En join and extend radially toward FeSiO₃ until En = 0.50 (see Fig. 1), in accord with the suggestion of [1]. (2) For En < 0.50, Fe and Mg mix on both sites, and the isotherms "kink" (or curve sharply) to become more nearly horizontal.

The isotherms for En < 0.50 in Fig. 1 are based on: (a) reversed experimental data where available (including unpublished isotherms at 1100º and 1200ºC); (b) compositions of three coexisting pyroxenes (Fig. 2); (c) the trace of the consolute temperature for pig + aug as a function of X (= Fe/Fe + Mg), atomic (Fig. 3); (d) linear interpolation in the absence of other data. Temperatures derived from Fig. 1 (T₁) can be corrected for pressure (when known) by the approximations (P in kbar, T in ºC):

\[ \text{Cpx: } T_p = T_1 + P(1.63 - 2.104X + T_1(0.0027 + 0.0013X)) \]
\[ \text{Opx: } T_p = T_1 + P(0.33 - 0.98X + T_1(0.002 + 0.0075X)) \]

COMMENTS: (A) Figure 1 yields submagmatic temperatures for Mg-rich Skaergaard and Bushveld pyroxenes. Reconnaissance experiments on early Skaergaard compositions show that augites in equilibrium with opx and early melt have much lower CaSiO₃ contents (approx. Wo35-38 at 1123ºC) than do the published trends, which are here interpreted as due to subsolidus granule-exsolution of opx from aug. Appropriate textures exist, but previously have been called intercumulus. (B) Figure 1 is topologically similar to a diagram presented by [9]; however, their diagram lacks the "kinks" at En = 0.50, and their three-pyroxene triangles and aug-pig consolute points are more Fe-rich for a given temperature. (C) Figure 2 is believed correct for quad pyroxenes, and has been used for consistency in constructing Fig. 1. Many Mg-rich natural pyroxenes are relatively Al-rich, and Al stabilizes aug + opx relative to pig. Accordingly, for natural pyroxenes with X < approx. 0.4, pigeonite breakdown curves based on natural pyroxenes [e.g., 7, 16] may well be more appropriate than those shown here. To apply Fig. 1 to some natural aug + opx pairs that formed close to the pig field, it may be therefore necessary to extrapolate the aug + opx

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boundaries.


Fig. 1. Graphical geothermometer (T, °C) for coexisting aug, pig (Wo = 0.10) and/or opx (Wo ≤ 0.05). Portions are metastable with respect to liquid, olivine and/or a silica phase. Isotherms dashed where uncertain or in "forbidden zone".

Fig. 2. Three-px equilibria determined by [17]. A, aug; P, pig; O, opx.

Fig. 3. Temperatures (1 atm) of the aug + pig + opx assemblage and of the aug-pig consolute point as functions of X. I, reversed; arrow, half-reversal; dot, calculated from solution models.