SHORT COMMUNICATIONS

Estimation equations for F in fractional crystallisation and partial melting

A WELL-KNOWN equation for partial melting (Shaw, 1970; Arth, 1976) is given by

$$\left(\frac{C_L}{C_0}\right)_i = [A_i + FB_i]^{-1} \tag{1}$$

where $A_i = \sum_{r=1}^{M} K_{ri}p_r$ and $B_i = 1 - \Sigma K_{ri}\omega_r$.

The above equation refers to the condition where the liquid phase remains in equilibrium with the residual solid phase. The quantity C_0 is the initial concentration in the solid of the ith trace element, C_L is the trace element concentration in the liquid, p_r is the initial weight fraction of the rth solid phase, ω_r is the fraction of liquid contributed by the rth phase during melting and F is the fraction of melting. The K_{ri} values are the solid–liquid distribution coefficients with respect to the ith trace element and the rth mineral. M is the number of minerals involved.

The equation of relevance to fractional crystallisation (McIntire, 1963; Arth, 1976) is given by

$$\left(\frac{C_L}{C_I}\right)_i = F'^{G_i} \tag{2}$$

where $G_i = -1 + \sum_{r=1}^{M} K_{ri}W_r$.

The left-hand side of (2) is the ratio, for the ith trace element, of the concentration in the differentiated liquid (C_L) to that in the original melt (C_I). M is the number of precipitating minerals and W_r is the fractional weight of the rth precipitating mineral. K_{ri} is the solid–liquid distribution coefficient with respect to the ith trace element and the rth mineral, and F' denotes the fraction of liquid remaining.

Computational procedures have been developed by which estimates can be obtained for F or F' for the general case where p_r, ω_r or W_r are unknown (see, for example, Bardsley and Briggs, 1984, and references therein). Sometimes, however, the investigator may wish to estimate the F or F' magnitudes associated with specified values of the above parameters. Given this situation, it is possible to estimate F or F' using simple equations which can be evaluated using a hand calculator. To our knowledge, the estimating equations presented below have not appeared previously in the literature.

Individual estimates of F or F' for a given trace element are often obtained on the basis of a rearrangement of (1) or (2) respectively. We adopt the more general approach here of using all the trace element data to produce a single estimate. As noted by Bardsley and Briggs (1984), the ratio C_0/C_L in (1) is a linear function of F, and the ratio in (C_L/C_I) is a linear function of $\ln F'$ in (2). Given a set of trace element concentration values, a least-squares criterion of fit will yield the required estimating equations by finding the minimum of the equations

$$\sum_i \left(A_i + FB_i - \frac{C_0}{C_L}\right)^2 \tag{3}$$

$$\sum_i \left[G_i \ln F' - \ln\left(\frac{C_L}{C_I}\right)\right]^2 \tag{4}$$

obtained from (1) and (2) respectively. Minimising (3) with respect to F and (4) with respect to $\ln F'$ give the estimating equations:

$$\hat{F} = \left\{\Sigma B_i\left[\left(\frac{C_0}{C_L}\right)_i - A_i\right]\right\} / \Sigma B_i^2 \tag{5}$$

$$\hat{F}' = \exp\left\{\left[\Sigma G_i \ln\left(\frac{C_L}{C_I}\right)_i\right] / \Sigma G_i^2\right\}. \tag{6}$$

It should be noted that the above estimators were obtained on the basis of unconstrained minimisation. A bad fit to the assumed magmatic model could therefore give rise to 'impossible' values such as $\hat{F}$ or $\hat{F}'$ beyond the 0, 1 interval or negative predicted concentrations of some trace elements.

References

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Hetaerolite from Eastern Cliff, Kennack Sands, Cornwall: the first British occurrence

HETAEROLITE ($ZnMn_2O_4$) is a relatively rare mineral, having been reported from only a few localities world-wide. It was first described from Sterling Hill, New Jersey, associated with chalcophanite by Moore (1877), who considered it to be the zinc analogue of hausmannite. In a subsequent examination of the Sterling Hill material, Palache (1910) identified a hydrous phase, hydrohetaerolite. Other reports of hetaerolite from North America include those from the Lucky Cuss Mine, Tombstone, Cochise County, Arizona (Butler *et al.*, 1938; Rasor, 1939; Hewett and Fleischer, 1960), Franklin Mine, New Jersey and Leadville, Colorado (Frondel and Heinrich, 1942), the Domeroy Property, Pioneer District, Pinal County, Arizona (Dean *et al.*, 1952), Contact Mine, Grant County, New Mexico (Hewett and Fleischer, 1960), 79 Mine, Banner District, Gila County, Arizona (Keith, 1972), Bisbee, Arizona (Graeme, 1981) and Mohawk Mine, San Bernardino, California (Pemberton, 1983). The first description of a European occurrence of hetaerolite was probably that by Udubasa *et al.* (1973) for material from the Pb-Zn deposit at Rodna, Romania. More recently, hetaerolite, associated with smithsonite, has been reported from Moesnet, Belgium (Fransolet and Mélon, 1975). A brief review of hetaerolite occurrences is presented by Frenzel (1980). The present paper reports the first British occurrence of the mineral.

Occurrence. During the course of a systematic study by one of us (VH) of the extensive secondary mineral veins which cut serpentinized peridotites of the Lizard Complex, small, black crystals of hetaerolite were collected from an area of Eastern Cliffs (at National Grid Reference SW 74251665), in the neighbourhood of Kennack Sands. The hetaerolite-bearing veins are thin, usually no wider than 4 cm, typically planar, and are generally of NE-SW orientation, although this is quite variable. They extend laterally for a maximum distance of about 30 m before thinning and terminating. The veins occur in different forms. Some are composite in that they are made up of a series of parallel-sided discrete veins, others are anastomosing, and several bifurcate. They are composed mostly of a soft, white, fine-grained to massive mineral shown by X-ray diffraction to be lizardite. Calcite predominates in some of the veins. Other veins which also cut the serpentinized peridotite contain hematite.

Description. During the course of this work hetaerolite was initially identified in a lizardite vein, up to 2 mm thick which cuts serpentinized peridotite. Individual hetaerolite crystals within this vein are small, generally less than 0.75 mm across. Subsequently, however, other veins from the same locality were shown to contain crystal aggregates up to 4 mm across which, in places, have coalesced to form irregular lenses of hetaerolite parallel to the length of the vein and up to 9 mm long. Because hetaerolite is more resistant to weathering than lizardite, hetaerolite crystals stand out on exposed surfaces. The crystals are black, opaque and have a sub-metallic lustre. Individual crystals are octahedral, and show well-developed faces, whilst crystals within aggregates commonly show twinning.

Results. Hetaerolite crystals from Kennack Sands were initially examined using a JEOL 35 CF scanning electron microscope equipped with an energy-dispersive analyser, and operated at 21 kV, in the Department of Metallurgy and Materials Science, University College, Cardiff. The ED X-ray spectrum of the mineral showed peaks due to Zn and Mn. The crystals were also analysed at the British Museum (Natural History) using X-ray and electron-microprobe techniques. The X-ray powder