Palaeohydrology of the Beinn an Dubhaich aureole, Skye, and inferred mechanisms of fluid infiltration in carbonates

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Introduction

The Beinn an Dubhaich granite on Skye is a small, Tertiary late-stage pluton, which intruded Ordovician chert-bearing dolostones and dolomitic limestones of the Durness Group at 0.5–1.0 kbar, with consequent host-rock deformation, calc-silicate formation by predominantly internally-buffered reaction (Holness 1992), and fluoro-silicate skarns (Tilley 1951). This study is an attempt to unravel the complex hydrothermal system of the aureole, using standard petrography coupled with stable isotope analysis to distinguish between magmatic and meteoric fluid sources, and mechanisms of fluid infiltration. Tracers for magmatic fluid include fluorine, spinel, magnetite and phlogopite. Although disseminated skarn minerals are only seen at high grades, fluorine-bearing minerals occur throughout the aureole, both prograde and retrograde, showing that the hydrothermal system contained a significant magmatic component throughout its history. Retrogressive veins also contain ankerite, again consistent with a major component of fluid which had passed through the magnetite-rich skarn at the contact.

Since quartz is found in isolated chert nodules in the unmetamorphosed protolith and only rarely as detrital grains, and the short duration of the metamorphic event precluded extensive solid-state diffusion, calc-silicates in nodule-free rock are the result of infiltration of a silica-bearing fluid, consistent with similar distributions of skarn minerals. The mechanisms of fluid infiltration (ie. pervasive versus fracture flow) can thus be inferred from mineral distribution.

Mechanisms of fluid infiltration

Equilibrium dihedral angles can be used to predict the P-T-X conditions under which pervasive grain-edge flow driven by surface energies can occur. Experimental determination of H_2O-CO_2-NaCl fluid dihedral angles in static carbonates shows that dolostones are impermeable to grain-edge fluid flow, and limestones are only permeable at about 1 kbar to fluids of $0.2 < X_{CO_2} < 0.6$ (Holness and Graham 1991; 1994). However, in systems impermeable under static conditions, pervasive grain-boundary flow may occur during ductile deformation (Holness and Graham 1994). Thus we predict that pervasive flow may have occurred in the Beinn an Dubhaich limestones for intermediate H_2O-CO_2 fluid compositions, and during ductile deformation for all fluids. Beinn an Dubhaich dolostones would have been permeable only to flow along fractures until either the rock had de-dolomitised sufficiently to permit connected porosity along calcite three-grain junctions, or to permit ductile deformation. At very high temperatures dolomite may become sufficiently weak to permit deformation-enhanced pervasive permeability.

The inferred infiltration mechanisms of the Skye carbonates are consistent with these predictions, although no definite evidence was found for grain-edge porosity in undeformed limestones. Early prograde minerals in undeformed limestones occur in veins, but are scattered throughout highly-deformed tremolite-grade limestones. At high grades, diopside and forsterite are scattered in the recrystallised calcite matrix, with diopsides displaying a weak preferred orientation, attesting to earlier deformation. Magnetite and spinel occur with forsterite along small-scale shear zones. Calc-silicates and skarn minerals in dolostones occur in veins, except in some forsterite- and in all periclase-grade samples. Retrogressive fluids form veins, except in a few limestones which remained ductile during retrogression. The fractures used by the retrogressive fluids are often those used during prograde infiltration.

Stable isotopic results

42 samples were chosen to include all metamorphic grades, and all types of calc-silicate

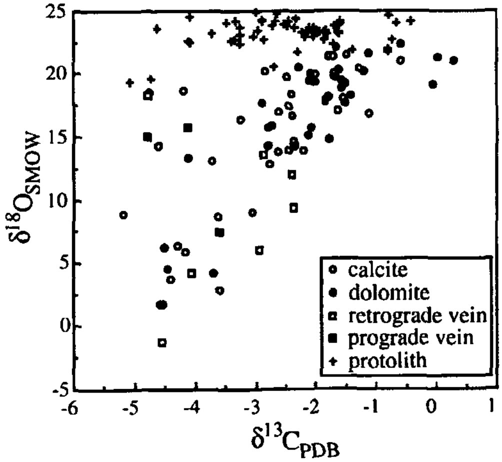

FIG. 1. Stable isotopic data for Skye carbonates (this study) and protolith Balnakeil and Croisaphuill carbonates from Durness, Scotland (this study and Wright 1985), in standard permil notation. Errors are $\pm 0.2‰$.

distribution. Carbonates from the corresponding Formations at Durness were also analysed to obtain protolith isotopic ratios (Figure 1). Co-existing calcite-dolomite pairs were obtained for all samples using sequential extraction from constrained grain-size powders (to obtain minimum estimates of $\delta^{18}O_{dol}$-$\delta^{18}O$cal, or $\Delta^{18}O$). The protoliths have tightly constrained $\delta^{18}O$ of 20–25‰ with a large range of $\delta^{13}C$ (−5 to 0‰). The Skye rocks have the same $\delta^{13}C$ range, but lower $\delta^{18}O$, especially those of vein samples (both prograde and retrogressive), consistent with involvement of magmatic and/or meteoric fluid.

The samples were divided into 6 groups on the basis of lithology and inferred infiltration mechanism, to compare the extent of calcite-dolomite disequilibrium (Figure 2).

Calcite in veined dolostones is a fluid infiltration-driven reaction product, with a more depleted composition than the host dolomite. Reaction-product calcite in dolomites in which pervasive flow was inferred was also out of equilibrium with the host, attesting to the slow recrystallisation rates of dolomite, and probable channelling of the fluid phase. In contrast, the two groups of limestones showed almost equilibrium calcite-dolomite pairs, reflecting both a smaller fluid/ calcite ratio, and relatively rapid isotopic alteration of the small amounts of dispersed dolomite during deformation-induced pervasive flow.

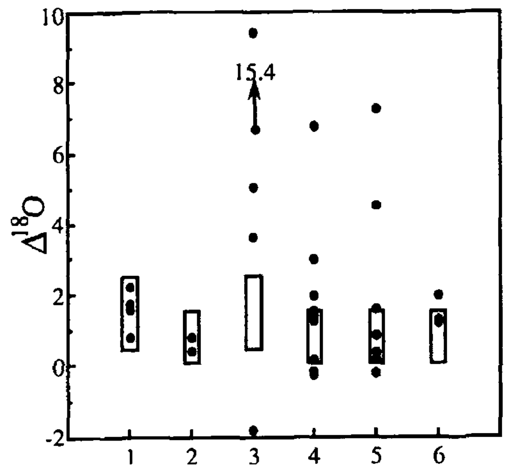

FIG. 2. $\Delta^{18}O$ (‰) as a function of lithology and inferred infiltration mechanism. 1- strongly deformed limestones; 2-high grade limestones with weak diopside orientation; 3-veined talc-grade dolostones; 4-veined high-grade dolostones; 5-high-grade dolostones with pervasive flow; 6-periclase marbles. The boxes show equilibrium values (O'Neil and Epstein 1966, Sheppard and Schwarcz 1970). $\Delta^{18}O$ for the protolith ranges from 0.3–2.3‰.

Conclusions

Inferred fluid infiltration mechanisms in the complex hydrothermal system of the Beinn an Dubhaich granite are consistent with predictions made on the basis of experimental dihedral angle data, and confirm the importance of ductile deformation and hydrofracture in controlling carbonate permeability. No definite evidence of surface energy-driven grain-edge porosity was found, due either to insufficient time for textural equilibration, or the shallow level of the intrusion.

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