

Fault-controlled, kilometre-scale fluid-rock interaction in a late-orogenic setting: insights from C and O isotope profiles from Lismore, Scotland

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The Isle of Lismore is located off the west coast of Scotland, adjacent to the regional SW-NE striking Great Glen Fault (GGF) that cuts through the entire Scottish mainland. Metalimestones of the Lismore Limestone Formation dominate the bedrock and are interlayered with minor metapelites, all deposited during the Neoproterozoic Era and metamorphosed at greenschist facies conditions during the Grampian phase of the Caledonian Orogeny at ca. 470 Ma (Treagus 2013). The GGF formed in the late stages of the Caledonian Orogeny at ca. 430 Ma and is constituted by a ca. 3 km wide fault zone with a ca. 300 m wide zone of principal displacement at its centre (Stewart et al. 2001).

Field observations and samples were collected along a ca. 2 km long profile perpendicular to the GGF. Veins of calcite, ankerite and quartz were observed. Vein density was estimated from field photographs and show a general decrease from ca. 11% at 0.6 km distance from the centre of Loch Linnhe, the approximate centre of the GGF, to ca. 4% at 2.3 km distance, indicative of fluid infiltration from the GGF and probably decreasing fluid fluxes with increased distance from the GGF. The proportion of ankerite is largest close to the GGF and could indicate mass transfer of Fe, in addition to Ca and CO₂, during fluid infiltration.

Stable isotope analyses of vein samples show an increase in $\delta^{18}\text{O}_{\text{VSMOW}}$ from ca. 16‰ to 19.9‰ with increasing distance from the GGF. Wall rock samples show similar trends with isotopic shifts of 16.0 to 20.2‰ for $\delta^{18}\text{O}$ and ca. 2‰ to 7‰ for $\delta^{13}\text{C}_{\text{VPDB}}$. These isotopic shifts are attributed to fluid-rock interaction caused by vein-channelled fluid infiltration from the GGF and represent fluid:rock ratios of up to F/R = 43. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ correlate for most wall rock samples ($R^2 = 0.65$), which strongly argues for modification of isotopic ratios by fluids and implies pervasive fluid-rock isotopic equilibration by channelled fluid flow to at least 2 km distance from the GGF. Only samples collected >2.3 km from the GGF show possibly retained primary sedimentary $\delta^{13}\text{C}$ signatures, at which point fluid-rock interaction may have been less pervasive.

Chromatographic modelling (see Lewerentz & Skelton 2018, and references therein) of the three isotopic datasets yields three independently estimated, within-error-agreeing time-integrated fluid fluxes of ca. 100 to 1,000 m³·m⁻² for vein-controlled fluid flow away from the GGF. For the wall rock data, the oxygen and carbon isotope fronts are located at 155±40.2 m and 76.4±34.1 m from the GGF, respectively. The lag between the carbon and oxygen isotope fronts is used to estimate the X_{CO₂} of the fluid to 0.17–0.69, assuming a binary H₂O-CO₂ fluid. Based on results from the chromatographic modelling, field measurements of vein spacing, as well as assumptions for chemical diffusion in the pore fluid ($D_c = 3.07 \cdot 10^{-10} - 9.82 \cdot 10^{-11}$) and porosity for deformation-controlled intermittent movement of close-spaced cracks ($\phi = 10^{-3} - 10^{-4}$), the timescale of fluid flow is estimated to 100 – 100,000 years. This implies time-averaged fluid and carbon fluxes of 0.001 to 0.1 m³·m⁻²·yr⁻¹ and 1 – 10,000 mol C·m⁻²·yr⁻¹ (0.044 – 440 kg CO₂·m⁻²·yr⁻¹), respectively.

References

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