

Oxygen, carbon and strontium isotopic constraints on fluid movement during the Acadian metamorphism in South-central Maine

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$\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic tracers have been used to constrain the timing, as well as the magnitude and direction of cross-layer fluid flow in Acadian metamorphic rocks in south-central Maine. The area contains pelites, calcareous greywackes and the ~100 m thick Waterville Limestone which were isoclinally folded and then intruded by granitoid plutons during the Devonian Acadian orogeny. Metamorphism to andalusite and sillimanite facies and granitic plutonism are thought to be closely associated. Baumgartner and Ferry (1991) and Ferry (in press) use the progress of decarbonation reactions to estimate metamorphic time-integrated fluid fluxes up to $\sim 2.10^4 \text{ m}^3/\text{m}^2$, with the flow up-temperature and layer parallel (lithological units strike at a high angle to isograds). This study tests predictions of this model by: 1) Determining the timing of fluid-flow from small-scale Rb–Sr isochron systematics. 2) Estimating the magnitude of the cross-layer component. Significant

cross-layer flow might cause the observed decarbonation with significantly lower time-integrated fluxes. 3) Assessing H_2O and CO_2 diffusion distances. These have implications for the scale on which reaction-progress fluid flux estimates should be made.

Rb–Sr isochron ages from samples sawn into ~1 cm slices cluster around the ~380 Ma age of granite plutonism and are consistent with plutonism, metamorphism and the high porosity associated with fluid-movement being contemporaneous (Fig. 1). The Sr-isotopic profile (Fig. 4 below) indicates Sr-isotopic diffusion distances of ~0.8 m and this is confirmed by preservation of a depositional or diagenetic pre-Acadian Rb–Sr isochron age of $416 \pm 27 \text{ Ma}$ (2σ error, initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.71147 \pm 78$, MSWD = 28) constructed by averaging samples in 5 m intervals in phyllitic rocks. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio confirms that the phyllites and Waterville Limestone (380 Ma $^{87}\text{Sr}/^{86}\text{Sr} = 0.7088$) never reached strontium isotopic equilibrium.

Figs 2, 3 and 4 show $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and 380 Ma $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic profiles across one margin of the ~100 m-thick Waterville Limestone sampled at garnet grade. The $\delta^{18}\text{O}$ profile shows calcite compositions from the marble and estimated calcite compositions from quartz presuming that $D_{\text{qtz-calc}} = 1.88$ at $450 < 198 > \text{C}$. The 380 Ma $^{87}\text{Sr}/^{86}\text{Sr}$ profile is calculated from present day $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios. A profile calculated from the depositional/diagenetic 416 Ma age and present day $^{87}\text{Rb}/^{86}\text{Sr}$ ratios indicates a step-function Sr-isotopic profile immediately prior to the Acadian metamorphism. The oxygen, carbon and strontium isotopic profiles all indicate advective displacements from phyllite to limestone, diffusive broadening and transport with near-equilibrium fluid-solid exchange on a mineral scale. The $\delta^{18}\text{O}$ advection distance of $-1.5 \pm 0.4 \text{ m}$ (1σ) implies a time-integrated flux of $-2.4 \pm$

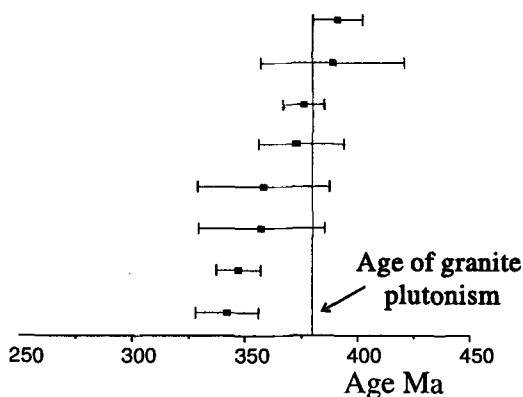


FIG. 1. Cumulate diagram showing Rb–Sr isochrons constructed from ~1 cm scale sampling. Errors are 2σ .

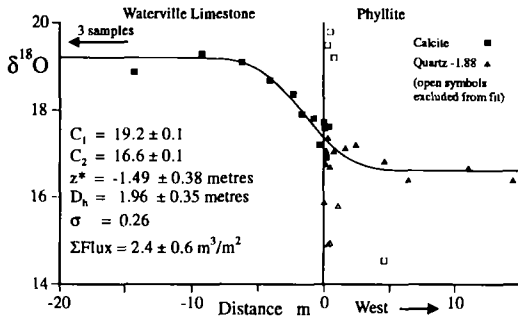


FIG. 2. $\delta^{18}\text{O}$ in calcite (or calculated from quartz) profile across Waterville Limestone-phyllite contact. Curve is least-squares best fit for advective-diffusive transport with uniform flow for four unknown parameters, C_1 initial $\delta^{18}\text{O}$ in limestone, C_2 initial $\delta^{18}\text{O}$ in phyllite, z^* advective displacement, D_h diffusion distance (\sqrt{Dt}), after Bickle and Baker (1990). Errors are 1σ .

$0.6 \text{ m}^3/\text{m}^2$. This is an order of magnitude less than the $\sim 25 \text{ m}^3/\text{m}^2$ which would be needed to cause the observed decarbonation entirely by cross-layer flow (Ferry, 1987) and confirms that layer parallel flow must predominate.

CO_2 and Sr fluid concentrations may be inferred by comparison of $\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ advection and diffusion distances with those of $\delta^{18}\text{O}$, which are insensitive to $\text{H}_2\text{O}-\text{CO}_2$ fluid composition. Table 1 lists fluid X_{CO_2} and Sr concentrations estimates. Inferred X_{CO_2} values are low and comparable to the value of 0.09 ± 0.05 (2σ) calculated from mineral equilibria using thermodynamic data. Sr concentrations are compatible with moderately saline fluids, although the uncertainty from error propagation is large.

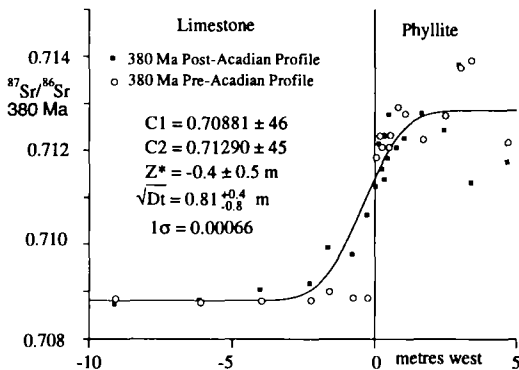


FIG. 4. $^{87}\text{Sr}/^{86}\text{Sr}$ profile across Waterville Limestone-phyllite contact. Fit for same model as fig. 2.

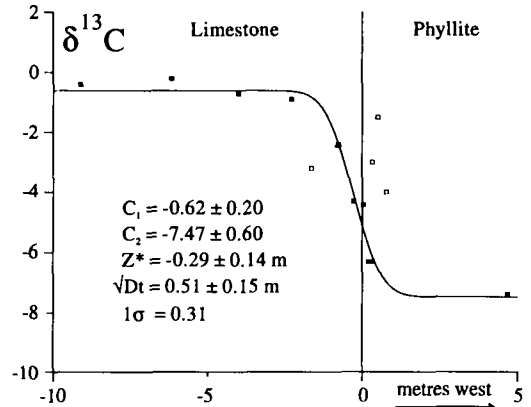


FIG. 3. $\delta^{13}\text{C}$ Profile across Waterville Limestone-phyllite contact. Fit for same model as fig. 2.

TABLE 1. Estimates of fluid composition

	X_{CO_2}	Sr ppm
Advection	0.06 ± 0.03	224 ± 473
Diffusion	0.02 ± 0.01	142 ± 149

The $\sim 0.5 \text{ m}$ diffusion distance for $\delta^{13}\text{C}$ implies that mineral assemblages should be buffered to uniform X_{CO_2} over a $\sim 0.5 \text{ m}$ scale. Variations in reaction progress over scales smaller than this may be driven by diffusive exchange and differences in bulk rock composition. Calculation of fluid fluxes should integrate reaction progress over distances in which fluid composition may be homogenised by diffusion. Comparison of mineralogical estimates of X_{CO_2} gradients and $\delta^{13}\text{C}$ isotopic gradients could provide important constraints on whether the mineralogy and isotopic compositions are buffered in the same fluid flow event.

References

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