Fluid flow in Vermont and New Hampshire, U.S.A.: A 3-D perspective

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Rationale and background

Quantification of fluid fluxes is fundamental to our understanding of fluid–rock interaction processes, and heat and mass transfer in the Earth's crust, during regional metamorphism. A number of researchers have recently attempted to quantify (time-integrated) fluid fluxes, using various 1-D models. The Acadian metamorphic belt in New England, U.S.A. has been a focus for applying, testing and comparing these models. Ferry (1992) predicts regional-scale east-west horizontal fluid flow in the Waits River Formation, E. Vermont (Fig. 1), by applying his 'gradient flow' model, which calculates (time-integrated) fluid fluxes along an assumed P-T gradient from measured extents of reaction and an assumed protolith mineralogy. Chamberlain & Conrad (1993) record a westward component of fluid flow across the near-vertical contact between the Pinney Hollow and Ottauquechee Formations from advection of an isotopic discontinuity (Fig. 1). Although these conclusions appear consistent, they depend critically on assumptions regarding the attitude of strata at the time of fluid infiltration. In this study, the relative timing of fluid infiltration is predicted from the inter-relationship between deformation, lithology and fluid-rock interaction. In this framework, the approach of Skelton et al. (in press) is followed to determine 3-D fluid flow patterns from 1-D time-integrated fluid flux vectors obtained using reaction front advection theory (Bickle & Baker 1990). In contrast to previous work, layer-parallel fluid flow is predicted within near-vertical strata which strike north-south (Fig. 1).

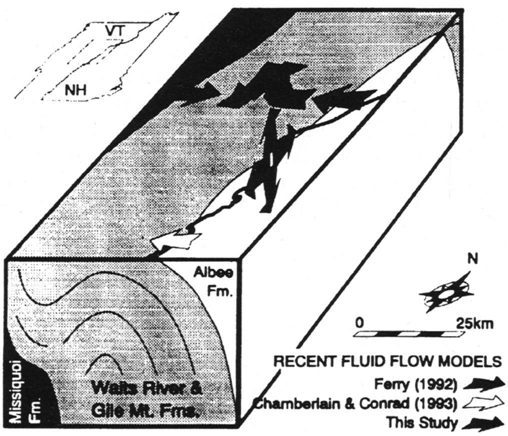

FIG. 1. Schematic block section of Vermont and New Hampshire showing fluid flow patterns predicted by this study and other recent models.

Geology

The rocks of E. Vermont and W. New Hampshire are Ordovician in age. In brief, green chloritic schists of the Missiquoi Formation are unconformably overlain by interbedded marbles and quartzites of the Waits River Formation (predominantly marble) and the Gile Mountain Formation (predominantly quartzite), which are separated from grey schists of the Albee Formation by the Monroe line, a structural boundary of uncertain origin. Two stages of Acadian deformation are observed to affect these rocks. The early (nappe) stage involved the development of steeply-inclined, west-facing nappes. The late (dome) stage involved uplift of the Waits River and Gile Mountain Formations into broad domes (Fig. 1). Peak metamorphism straddled nappe and dome stages of Acadian deformation. Metabasite dykes were emplaced within the Albee Formation (E. Vermont & W. New Hampshire) and the Missiquoi Formation (Central Vermont) prior to Acadian metamorphism.

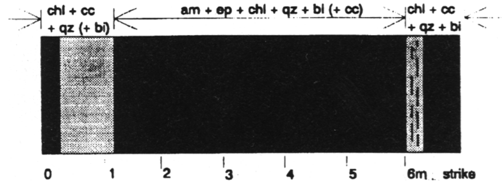

FIG. 2. Modal profile across a metabasite dyke, hosted by the Albee Formation.

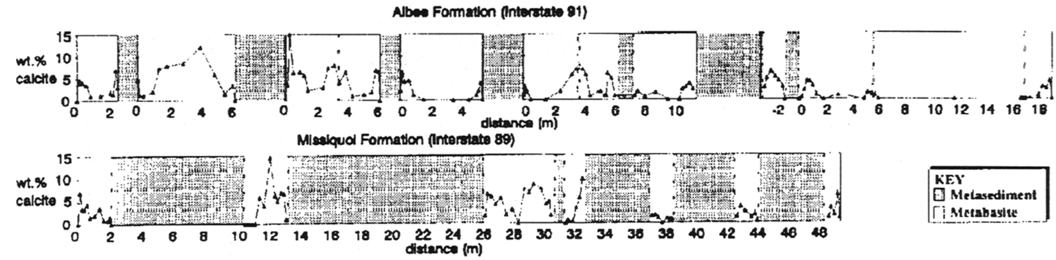

FIG. 3. Reaction progress profiles across suites of metabasite dykes from (i) Albee Formation (I91) and (ii) Missiquoi Formation (I89)

Metabasites as fluid flux markers

Metabasites within the Albee and Missiquoi Formations are characterised by zonation of the following assemblages (Fig. 2):
dyke interiors (unreacted); am + ep + ab + sph + chl + qz ± bi,
dyke margins (reacted); chl + cc + qz + ab + sph + ep ± bi,
which are related by the reaction; am + ep + H_2O + CO_2 = chl + cc + qz.

The cross-layer component of the time-integrated fluid fluxes is calculated from the widths of reacted margins using reaction front advection theory.

Reacted margins are identified on profiles of reaction progress constructed across suites of dykes from the Albee and Missiquoi Formations (Fig. 3). Reaction progress was quantified in the field by recording the pressure of CO_2 evolved by reacting a sample, of known volume, with excess dilute HCl in a sealed reaction vessel.

Discussion

From Fig. 3, carbonation of dyke margins is symmetric. Therefore, fluid flow must be parallel to the dyke margins (Fig. 3). As the dykes are near vertical and strike north-south, the direction of fluid flow can range from horizontal (north-south) to vertical (up-down). The buoyancy of the fluid predicts upwards flow. Also, in the case of a carbonation reaction, the gradient flow model (Ferry 1992) predicts upwards flow.

Critical to this interpretation is the timing of fluid infiltration relative to the nappe and dome stages of Acadian deformation. In the Albee Formation, peak metamorphic biotites occur throughout metabasite dykes, commonly in random orientations, but aligned within (nappe-stage) schistose bands (near the dyke margins). Calcite is localised to schistose bands and is not itself deformed. It may thus be inferred that fluid flow was (i) deformation-controlled, and (ii) post-dated (nappe-stage) deformation. It is therefore probable that the attitude of strata has not changed significantly since fluid-infiltration.

Recumbent fold-hinges offer an opportunity to contrast the roles of lithology and deformation in controlling fluid flow. Three field examples (Fig. 4) infer that fluid escapes through recumbent (nappe-stage) antiformal fold closures as opposed to escaping vertically through the fold limbs. It follows that deformation is the primary control of fluid flow.

References

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Chamberlain, C. P. and Conrad, M. E. (1993) *Geochim. Cosmochim. Acta*, **57**, 2613–29.
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Skelton, A. D. L., Graham, C. M. and Bickle, M. J. Lithological and Structural Controls on Regional 3-D Fluid Flow Patterns during Greenschist Facies Metamorphism of the Dalradian of the SW Scottish Highlands (submitted to J. Pet.).

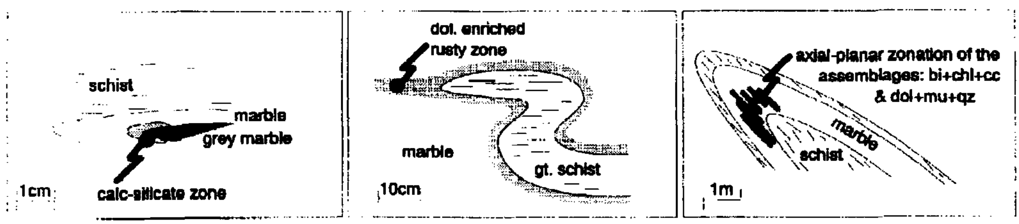

FIG. 4. Field-sketches of recumbent fold-hinges showing the effects of fluid infiltration.