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Role of fluid flow in the contact metamorphism of siliceous dolomitic limestones—Discussion

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Ferry (1994) presented a one-dimensional model of reaction progress during contact metamorphism of siliceous dolomitic limestones for three scenarios: (1) fluid flow toward higher temperatures, (2) fluid flow toward lower temperatures, and (3) heating of a rock with a fixed porosity. He then compared the effects of input fluid flux, flow direction, and porosity on the distribution of reaction products and implied through applications to specific aureoles that the results allow inference of the hydrology of contact metamorphic aureoles. The models used for the calculations are derived from consideration of conservation of mass. Specific simplifying assumptions are implicitly made regarding conservation of energy in application to contact metamorphism. These assumptions, which are necessary to allow analytical solutions, are (1) that the peak metamorphic temperature profile is representative of conditions under which flow occurred, and (2) that the fluid flow and reactions would not consume significant amounts of energy so as to modify the temperature profile. However, as shown below, both of these assumptions are violated. As a result the conclusions regarding effects of flow on metamorphic assemblages in contact aureoles and the applications described in Ferry (1994) are invalid. In addition, other studies in which the reaction-flow model of Ferry (1989) was applied to contact aureoles to infer flow direction, time-integrated fluid flux, and permeability also violate conservation of energy. In general, this analysis illustrates how simplifying assumptions aimed at gaining a first-order understanding of metamorphism can have nontrivial consequences and lead to erroneous results.

Contact metamorphism is a manifestation of the thermal energy, Q, provided by cooling and release of latent heat of an intrusion. This energy is partitioned principally into three heat sinks in the aureole: (1) temperature increases in the rocks, (2) hydrothermal fluid flow, and (3) heats of prograde metamorphic reactions, which are typically endothermic. Energy that is consumed to heat fluids or drive metamorphic reactions becomes unavailable for increasing the temperatures of rocks. All the comparisons in Ferry (1994) are for a single fixed-temperature profile, which in applications is typically assumed to be the observed peak metamorphic temperature profile. Reaction progress and the amount of fluid flow were then varied. Over the range of parameters considered, the flow and metamorphic reactions consume significant amounts of energy in comparison with the temperature term. Thus, conservation of energy is violated: the comparisons are implicitly not on an equal-energy basis, as is a premise of the analysis. In other words, for the extent of flow prescribed and the reaction progress predicted in the models in Ferry (1994), the temperature profile cannot be assumed to be constant, and such an assumption can exaggerate the significance of fluid flow in driving reactions.

To quantify the above argument I consider both a simple calculation and a numerical model. The partitioning of energy in an aureole in one dimension can be expressed as

$$Q = \int_0^\infty \rho C \Delta T \, dx + \int_0^\infty \int_0^\infty C_w u \frac{dT}{dx} \, dx \, dt + \int_0^\infty \Delta H \, dx$$

where each term on the right represents the three sinks described above, and x is distance from the contact, ρ is rock density (~2750 kg/m³), C is the rock heat capacity [~1000 J/(kg·°C)], C_w is the fluid heat capacity [~4200 J/(kg·°C)], ΔT is the maximum temperature change at each point from background ($x = \infty$), u is the fluid mass flux [kg/(m²·s), positive inward], ΔH is the heat consumed by metamorphic reactions (J/m³), and t is time. For a constant fluid flux with distance and flow from cool rocks to the contact where temperature is at a maximum, the advective heat-flow term is replaced by $C_w u' \Delta T_0$, where ΔT_0 is the temperature change from background at the contact, and u' is the time-integrated flux.

These three terms can be calculated directly for the models presented in Ferry (1994). The first term on the right is simply obtained from the integral of the right term of Equation 1 of Ferry (1994). It represents a total energy of 1000 J/(kg·°C) × 2750 kg/m³ × 721 °C·km = 2.0 × 10^{12} J/m². For the second term, consider a time-integrated input fluid flux of 200 mol/cm² of pure water (= 3.6 × 10^4 kg/m²). For this calculation, heating of fluid produced along the flow path by decarbonation reactions is at first ignored so as to consider heating of only the input fluid using the simplification above. This term then represents 3.6 × 10^4 kg/m²·500 °C·4200 J/(kg·°C) = 7.6 × 10^{10} J/m² or about 3.8% of the temperature term. In addition, for models in Ferry (1994) with an input flux of 200 mol/cm², about 300 mol/cm² of fluid is produced by metamorphic reactions in the aureole (the difference between the input and exit fluid fluxes; see dotted lines in Figs. 5–8 of Ferry, 1994). For an assumption of even

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production of metamorphic fluids throughout the aureole, these metamorphic fluids are heated on average about 200 °C. Thus, heating of metamorphic fluids adds another 4.5×10^{10} J/m^2 (2.3% of the temperature term) to the advective term. The advective term would represent energy released to the aureole if the flow were outward from the contact to lower temperatures or energy consumed if the flow were inward and toward higher temperatures. Finally, the heat consumed in reactions assumed to be driven by this flow can also be calculated from the amount of metamorphic fluid produced. Production of 1 mole of CO_2 in metamorphic reactions consumes about 8×10^4 J (Walther and Orville, 1982). Thus, the total energy consumed by reactions is 2.4×10^{11} J/m^2 or about 12% of the energy used just to heat the rocks. In these calculations, I have assumed that the density and heat capacity of rocks and the heat capacity of fluids are constant. These parameters vary by about 10–15% for typical rocks and metamorphic pressures and temperatures, and so this represents a rough uncertainty on the calculation.

These calculations imply that for the case of up-temperature fluid flow, about 18% more energy is consumed with a fluid influx of 200 mol/cm^2 than for no flow at all. For an input flux of 1000 mol/cm^2, about 4.7×10^{11} J/m^2 or 24% of the energy used to heat the rocks is consumed by heating the input and metamorphic fluids, and another 25% is consumed by metamorphic reactions (reaction progress increases with fluid flow in the model; see figures in Ferry, 1994); thus, the total energy consumption is about 1.5 times that for the case of no inward fluid flow.

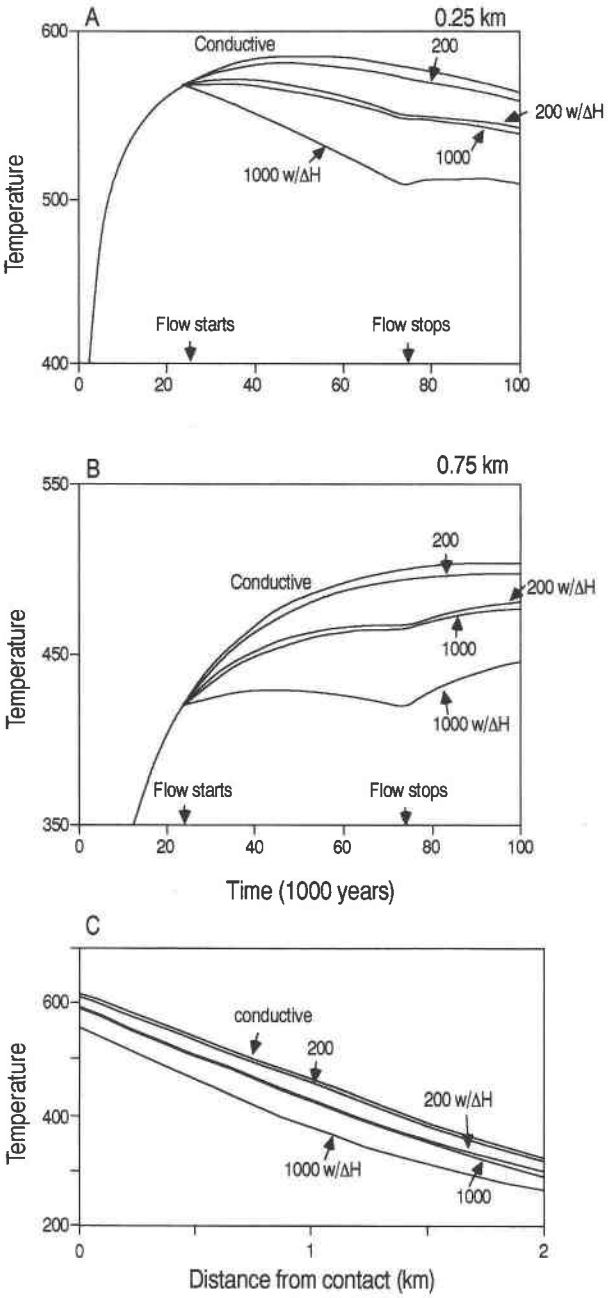
The curves calculated by Ferry (1994) imply simply that more metamorphism is produced in cases in which more energy is consumed. In other words, a 6 km wide intrusion must produce more metamorphism or drive more hydrothermal fluid flow than a 4 km wide intrusion if the final temperatures in the aureole are fixed to be the same. Because of the significant differences in energy consumption, it is invalid to compare both (1) the effects of variation in any one process [e.g., amount of input flux, as in Fig. 6 of Ferry (1994)] and (2) the effects of different processes in producing a distribution of reactions. With regard to the first comparison, for example, energy consumption more than doubles along the vertical axis of Figures 5 and 6 in Ferry (1994) showing fluid flow in the direction of increasing temperature. With regard to the second comparison, for example, in the discussion of Figure 9, Ferry (1994) argued that one can discriminate between the effects of no flow and up-temperature flow by the distribution of reaction progress in an aureole. The comparison in Figure 9 however, is, not on an equal-energy basis (the integrals under the curves, which essentially represent heat consumed during metamorphism, are clearly not equal). Similarly, because of the opposing flow directions and significant transport of heat, the effects of inward and outward flow in Ferry (1994) cannot be directly compared. If the calculations are made on an equal-energy basis, reaction progress in models with up-temperature flow must converge to zero as the flow increases (and temperatures would be much lower), the opposite of what is shown in the Figures 5 and 6 of Ferry (1994).

Other common problems with regard to conservation of energy in the application of reaction-flow models in contact metamorphism are (1) that even a conductive profile in contact metamorphism is not constant, and (2) the maximum-temperature profile does not accurately represent the thermal state of the aureole at any time. A simple one-dimensional model of heat and fluid flow adjacent to an intrusion illustrates these two effects and shows how accounting for conservation of energy limits the significance of up-temperature flow in driving metamorphic reactions. To follow closely the analysis above, a one-dimensional model was used in which an intrusion with a half-width of 2 km and an initial temperature of 1150 °C was emplaced into a domain with an initial temperature of 150 °C. The maximum temperatures produced by conduction [thermal diffusivity of 1×10^{-6} m^2/s, thermal conductivity of 2.5 W/(m·°C)] are higher than those given by Equation 1 of Ferry (1994). (Note that the equation cited by Ferry to approximate a thermal profile is for instantaneous heating of a half-space to a new fixed temperature. Temperatures only increase. It does not represent accurately the thermal evolution of a contact aureole, where rocks in the inner aureole are cooling from high peak temperatures while temperatures in rocks farther out are still increasing.) Thus, this model is a conservative one for demonstrating violation of energy conservation [that is, more heat is consumed in the form of temperature increases than in the model in Ferry (1994)]. As a representative example, a case was examined in which fluid flowed up-temperature from 25000 to 75000 yr yielding time-integrated fluxes of 200 or 1000 mol/cm^2 (as in Ferry, 1994). This interval is around the time that peak conductive temperatures are attained in the inner aureole (Fig. 1A). Models with flow during other time intervals yielded similar results. Flow was allowed only within the aureole; the intrusion was assumed to be impermeable, exactly as assumed by Ferry (1994) in his models. Heat of reaction was consumed proportionally to the fluid flow, using values appropriate for the amount of fluid released calculated by Ferry (1994). Flow of the added fluid produced from the metamorphic reactions was not considered in this model. These are all conservative assumptions because a higher maximum-temperature profile than that from Equation 1 would naturally result in greater reaction progress, and because of the time-transgressive nature of heating with distance from the contact, a greater flow would have to be maintained at all times to attain a flux of, say, 200 mol/cm^2 both near and away from the contact during times of peak heating (maximum temperatures are not yet attained at 0.75 km at 75000 yr; Fig. 1B).

The results shown in Figure 1 illustrate that an assumption of any constant thermal profile in the application of reaction-flow models to contact metamorphism is not reasonable. For input fluxes of 1000 mol/cm^2 and

accounting for heats of reaction, maximum temperatures in regions that had not yet reached peak temperatures before fluid flow started are suppressed by 50 °C or more vs. temperatures for the pure conductive profile.

In several recent studies, the reaction-flow model of Ferry (1989) was applied to contact aureoles for the case of a constant thermal profile equal to the maximum temperatures observed in the aureole. Where calculated fluxes exceeded 200 mol/cm² in these studies it is likely that conservation of energy was violated. A few examples in which fluxes were calculated that were orders of magnitude greater than this value include: Hope Valley pendants (Ferry, 1989; input flux of up to 2.5×10^5 cm³/cm² or > 10000 mol/cm²), Twin Lakes pendant (Davis and Ferry, 1993; input flux of up to 1.3×10^5 cm³/cm² or about 7000 mol/cm²), and Notch Peak (Ferry and Dipple, 1992; input flux of 20000 mol/cm² for essentially the same thermal profile as in Fig. 1 of Ferry, 1994). Furthermore, these estimates are minimum estimates thought to be necessary to produce the observed reactions because of the use of the maximum-temperature profile in the reaction-flow models (e.g., Dipple, 1994).



As shown above, simple energy balance in an aureole requires that inward flow must result locally in lower temperatures and less reaction progress, and vice versa. This pattern is evident in two-dimensional models in which energy and fluid mass and momentum are all conserved (e.g., Parmentier and Schedl, 1981). Consideration of conservation of energy and the energy balance expressed in the equation above implies that the most direct way to infer directions of fluid flow is observations of the pattern of isotherms and isograds. Higher temperatures, such as along fault zones, would suggest focused outward flow of hot fluids (e.g., Nabelek and Labotka, 1993). Similarly, where isotherms and reaction progress are depressed, as in the wall rocks of the Skaergaard intrusion (Manning et al., 1993), flow was probably inward toward higher temperatures.

Ferry (1994) argued that conservation of energy was not violated in applications of his model because the Peclet number (*Pe*, the ratio of heat transfer by fluid advection to heat transfer by conduction) for reasonable times of flow was <10, for which Bickle and McKenzie (1987) concluded that heat transfer is in a "diffusive" (or conductive) regime. This argument is flawed for two reasons. First, it ignores both the effect of heats of reaction and the finite amount of energy available during contact metamorphism. Second, even for cases where $Pe < 10$, thermal profiles can be significantly modified from the purely conductive profile even though the thermal profile is dominated by conduction. Bickle and McKenzie (1987) clearly showed that thermal profiles can be significantly

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Fig. 1. (**A** and **B**) Temperature-time profiles of one-dimensional finite-difference model of heating and fluid flow in an aureole. Data are shown for points 0.25 (**A**) and 0.75 (**B**) km from the contact of a 4 km wide infinite dike. Temperature is in degrees Celsius. Flow is inward from cool rocks to the contact from 25000 to 75000 yr. Five cases are considered: conductive heating and no fluid flow or reaction; time-integrated input fluxes of 200 and 1000 mol/cm² and no heat of reaction; and flows with heats of reaction proportional to calculations in Ferry (1994). Reaction is assumed to progress linearly with fluid flux. (**C**) Thermal profiles at 75000 yr, that is, immediately at the end of all fluid flow, for the five cases considered in **A**. Temperature is in degrees Celsius. Note that the overall gradient is not greatly modified, but the absolute temperatures are different for the cases with high fluid fluxes. Heat capacity of H_2O in the model is assumed to be constant at 4180 J/(kg·°C); other parameters are given in the text.

modified when $Pe < 10$ (e.g., see their Fig. 1A; see also my Fig. 1C). Applications of reaction-flow models to contact metamorphism for an assumption of conductive heat flow should only be for $Pe \ll 1$, should account for the time-transgressive nature of heating, and should consider the heats of metamorphic reactions produced by the flow.

It has also been argued (e.g., Ferry and Dipple, 1992) that application of reaction-flow models may be appropriate when the flow is confined to one bed only because, on the scale of an aureole, violation of conservation of energy is minimal if the thermal profile is buffered by surrounding units. Indeed, in terms of the total heat budget of an intrusion the thermal effects of advection and flow-induced reaction progress can be reduced proportionally to the abundance of high-permeability units along the contact, but a rigorous calculation should be performed, using fluxes calculated for the time-transgressive temperature profile, not the maximum-temperature profile. Furthermore, observations of deflected isotherms near fault zones imply that the thermal effects of focused flow can still be evident locally or along a single horizon.

We do not understand in detail the controls on the distribution of metamorphic minerals in contact (or regional) metamorphism. Reaction-flow models will likely be critical in relating observed distributions to the effects of heat and fluid flow and reaction kinetics. To obtain meaningful information, however, conservation of energy must be demonstrated, not stated or implied, for the basic reason that it is the energy provided by the intrusion that produces the metamorphism and drives the fluid flow. In contrast to the conclusions of Ferry (1994, p. 720), because energy available during contact metamorphism is finite, it is impossible and potentially misleading to characterize important aspects of metamorphic fluid flow independent of an understanding, or at least an accounting, of the physical mechanisms of heat and fluid transfer.

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References cited

Bickle, M.J., and McKenzie, D. (1987) The transport of heat and matter by fluids during metamorphism. Contributions to Mineralogy and Petrology, 95, 384–392.

Davis, S.R., and Ferry, J.M. (1993) Fluid infiltration during contact metamorphism of interbedded marble and calc-silicate hornfels, Twin Lake area, central Sierra Nevada, California. Journal of Metamorphic Geology, 11, 71–88.

Dipple, G. (1994) Infiltration-driven metamorphic reactions during the thermal evolution of contact aureoles. Geological Society of America Abstracts with Programs, 26, A41.

Ferry, J.M. (1989) Contact metamorphism of roof pendants at Hope Valley, Alpine County, California, USA: A record of the hydrothermal system of the Sierra Nevada batholith. Contributions to Mineralogy and Petrology, 101, 402–417.

——— (1994) Role of fluid flow in the contact metamorphism of siliceous dolomitic limestones. American Mineralogist, 79, 719–736.

Ferry, J.M., and Dipple, G.M. (1992) Models for coupled fluid flow, mineral reaction, and isotopic alteration during contact metamorphism: The Notch Peak aureole, Utah. American Mineralogist, 77, 577–591.

Manning, C.E., Ingebritsen, S.E., and Bird, D.K. (1993) Missing mineral zones in contact metamorphosed basalts. American Journal of Science, 293, 894–938.

Nabelek, P.I., and Labotka, T.C. (1993) Implications of geochemical fronts in the Notch Peak contact-metamorphic aureole, Utah. USA. Earth and Planetary Science Letters, 119, 539–559.

Parmentier, E.M., and Schedl, A. (1981) Thermal aureoles of igneous intrusions: Some possible indications of hydrothermal convective cooling. Journal of Geology, 89, 1–22.

Walther, J.V., and Orville, P.M. (1982) Volatile production and transport in regional metamorphism. Contributions to Mineralogy and Petrology, 79, 252–257.

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