Metamorphic carbon fluxes: how much and how fast?

Katy Evans
Department of Applied Geology, Curtin University of Technology, GPO Box U1987, Bentley, WA 6845, Australia

The current rise in atmospheric CO₂ and proposed links with global climate change provide a strong motivation to understand the processes that control the nature and magnitude of CO₂ cycling. Much attention has been focused on short time scale (t < 1000 yr) fluctuations in atmospheric CO₂ levels that result from cycling of carbon between biological, atmospheric, and oceanic reservoirs (e.g., IPCC, 2007). However, cycling on longer time scales via metamorphic processes is also worthy of attention, as discussed by Skelton (2011, p. 43 in this issue of Geology). The annual metamorphic carbon flux is ~0.01% of the atmospheric carbon reservoir (Gaillardet and Galy, 2008) but the metamorphic carbon cycle is generally assumed to be at steady-state on the time scales of interest (e.g., Berner, 2001; Gaillardet and Galy, 2008), which allows metamorphic CO₂ cycling to be ignored in predictions of the future evolution of atmospheric CO₂ levels.

However, there is evidence that metamorphic CO₂ cycling is not steady-state on any but the longest time scales. Release of methane and CO₂ by metamorphism of sediments affected by the emplacement of large igneous provinces (LIP) has been proposed as the cause for rapid global warming events such as the Paleocene-Eocene thermal maximum (Svensen and Jamtveit, 2010). Loss of atmospheric CO₂ by weathering of uplifted rocks in the Himalayas has been proposed as a cause of relatively cool recent temperatures (Raymo and Ruddiman, 1992). Other researchers have proposed that CO₂ emissions by metamorphic processes during mountain building exceed those consumed by weathering (e.g., Becker et al., 2008), that burial of carbon-rich sediments in the Himalayas over the past 125 m.y. caused removal of CO₂ from the atmosphere (Selverstone and Gutzler, 1993), or that CO₂ emissions and consumption associated with Himalayan orogenesis did not cause detectable changes in surface temperature (Kerrick and Caldeira, 1999). The variety of proposed scenarios reflects the complex and poorly understood nature of metamorphic carbon cycling. Carbon in the Earth’s crust occurs as reduced or elemental carbon in graphite, methane, and other hydrocarbon phases, as oxidised carbon in carbonates, dissolved ionic species such as bicarbonate, or CO₂ in a gas or liquid phase. Processes that transfer carbon between forms and reservoirs include diagenesis, hydrocarbon maturation, metamorphic devolatilization, silicate melting, fluid immiscibility, fluid mixing, carbonation, and mineral precipitation. Buried carbon may be immobilized within the Earth’s crust in carbonate, calc-silicate minerals, or hydrocarbons, transferred to the mantle (Yaxley and Brey, 2004) by subduction, returned to the atmosphere and oceans by fluid devolatilization (e.g., Becker et al., 2008), or transported and redeposited in the crust by open-system processes such as melting and melt loss, or devolatilization followed by carbonate or graphite vein formation (e.g., Evans et al., 2002).

The processes that have the greatest potential to affect exospheric CO₂ budgets are open system processes. Open systems, for the purposes of this discussion, are geological reservoirs that are infiltrated by fluids that react with the reservoir and then leave. Such processes result in changes in the composition of the reservoir, the infiltrating fluids, and the reservoirs that the fluids are drawn from and released into. Open system processes are difficult to study because the geological record only provides information on the final state of the reservoir. Nevertheless, it is essential to know the quantity and composition of the infiltrating fluids, fluid flow geometry, and the absolute timing and duration of fluid flow events if the role of metamorphic carbon cycling in the global carbon cycle is to be understood. These parameters can only be inferred indirectly, and often such inferences provide an ambiguous continuum of non-unique solutions that provide qualitative insights into the fluid flow process, but are unable to provide useful quantitative predictions for climate change studies.

The importance of open system processes has driven intensive research. Early researchers (e.g., Skippen and Trommsdorff, 1975) used ternary isobaric T-X(CO₂) diagrams to understand the evolution of fluid composition in compositionally simple (CaO-MgO-SiO₂-CO₂-H₂O) systems. Such work enables distinction between closed and open system conditions, and recognition of processes such as fluid mixing, but cannot provide information on the geometry, duration, or absolute quantities of fluid flow. Inverse models based on the advection-diffusion mass balance equation (e.g., Baumgartner and Ferry, 1991) allow isotopic or bulk composition profiles to be used to obtain estimates of time-integrated fluid fluxes. Studies based on mineral compositions (e.g., Ferry, 1994) are consistent with large (10⁶–10⁸ moles m⁻²) up-temperature layer-parallel fluxes and negligible layer-perpendicular flows, whereas those based on isotopic profiles across compositionally distinct layers (Skelton et al., 1995, 1997) indicated that layer-perpendicular fluid fluxes were of the order of 10³–10⁵ moles m⁻². Subsequent work that integrated the two approaches (e.g., Evans and Bickle, 1999; Evans et al., 2002) suggested that metamorphic fluid flow was indeed largely layer-parallel but down-temperature, and that small layer-perpendicular fluxes had a disproportionately large effect on the mineralogy of infiltrated layers (e.g., Ferry, 2007).

Forward models based on finite difference or finite element approaches (e.g., Lyubetskaya and Ague, 2009) allow assessment of the sensitivity of model systems to parameters such as anisotropy and spatially heterogeneous permeability and porosity; temporal variations in porosity and permeability as a function of mineral dissolution, precipitation and deformation; and the production and consumption of heat by radiogenic elements and by exothermic and endothermic reactions (e.g., Lyubetskaya and Ague, 2009).

Inverse models thus provide information on the evolution of fluid compositions and flow geometry, while forward models can be used to draw broad conclusions on the nature and timing of transport of carbon by metamorphic fluid flow. The least accessible parameters, currently, in studies of metamorphic fluid flow are those that relate to the timing and duration of metamorphic fluid flow. This is because rocks preserve a time-integrated record of fluid flow, and deconvolution of time-integrated observations into a time-resolved fluid flow history is extremely challenging. Metamorphic porosities and permeabilities and diffusion rates are required if temporal information is to be obtained, but these parameters are difficult to measure at metamorphic pressures and temperatures, and are highly heterogeneous in natural rocks. However, such information has begun to be derived from experimental studies (e.g., Wark and Watson, 1998; Wark and Watson, 2004; Giger et al., 2007).

Skelton (2011) has combined experimental constraints on porosity-permeability and diffusion with results from inverse models based on the advection-diffusion mass balance equation to provide estimates of carbon
flux rates and the duration of metamorphic fluid flow. Such estimates provide a significant advance in our ability to predict the effect of metamorphic processes on global carbon budgets.

Skelton estimates that metamorphic carbon fluxes through metasedimentary rocks that experienced greenschist facies regional metamorphism are 0.5–7 moles C m⁻² yr⁻¹. This value is similar to values estimated for Himalayan carbon fluxes from hot springs (e.g., Becker et al., 2008), and to other estimates of metamorphic decarbonation rates (e.g., Kerrick and Caldeira, 1999). A possible interpretation is that carbon fluxes at depth are comparable to those at the surface, and thus that much of the carbon released by metamorphic devolatilization is released into the atmosphere after transport to the surface. However, caution in such interpretation is necessary; focused fluid fluxes will be larger than those for diffuse fluid release for comparable volume-averaged fluxes, so further knowledge of fluid flow geometry is required to support this conclusion.

Time scales estimated for the fluid flow event are of the order of 4,000 yr. This estimate is valuable, not only because it provides an estimate of the rate at which metamorphic carbon is released, but because it provides an independent constraint on the time scale of regional metamorphic events. Conventional conduction-based models for metamorphic heating and cooling require time scales on the order of 10⁴–10⁶ m.y. (England and Thompson, 1984), while controversial recent work based on diffusion profiles in garnet and apatite (Oliver et al., 2000; Ague and Baxter, 2007; Pollington and Baxter, 2010) indicate shorter time scales, of the order of 10³–10⁸ m.y. The time scale estimate of Skelton is shorter than the shortest of previous estimates, but pertains only to active fluid flow, and indicates that fluid flows for only a short proportion of the time during which metamorphism is occurring, and that devolatilized fluid is expelled rapidly.

The implications for the consequences of metamorphic degassing on the exosphere are profound. If metamorphic degassing is as rapid, and as effectively transferred to the surface, as the results of Skelton imply, then pulses of orogenesis add CO₂ to the exosphere rapidly compared to the silicate weathering that eventually sequesters the CO₂. In this case, metamorphic degassing and silicate weathering are effectively decoupled, and metamorphic degassing cannot be assumed to be at steady-state at time scales less than those of a full orogenic cycle (10⁸ m.y.). In the future, a continuation of the advances in determination of metamorphic permeabilities and diffusion rates, and a growing number of in situ micron-scale, and even nanometer-scale, isotope analytical studies of metamorphic minerals, combined with the approach described by Skelton, are likely to generate rapid developments in the ability to map fluid flow and carbon fluxes, not only in space, but in time.

REFERENCES CITED


Printed in USA

GEOLOGY, January 2011