

Perspectives on Metamorphic Processes and Fluids

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Aqueous fluids make things happen inside the Earth. They considerably speed heat and mass transfer and induce weakness and instabilities in rock masses. Water is instrumental in localising deformation, enabling tectonic response to plate motion; it also markedly decreases the

melting temperature of silicate rocks and lowers the viscosity of silicate magmas. Aqueous fluids transport large quantities of dissolved material. Questions to answer in the future include: What determines where fluids go inside the Earth? What determines their quantity and rate of flow? What are the chemical effects of flowing fluids on the rocks and local fluids with which they interact? And what consequences are there for mineralisation and rock deformation?

KEYWORDS: fluids, metamorphism, rates of deformation, heat sources, mineral deposits, geodynamics

EVOLUTION OF METAMORPHIC PETROLOGY

Metamorphic petrology has developed geodynamically over the last twenty years. As near-surface rock units become buried, they metamorphose if temperature (T) and pressure (P) are favourable. Transformation of mineral assemblages can also occur when rocks are transported closer to a heat source (such as a magmatic intrusion), a concentration of radiogenic elements (K, U, Th), or where deformational work is locally converted to heat. The latter two cases generate heat within the crust, whereas the first relies on the mantle as the heat source. By considering heat balance, we are beginning to understand the extent to which mantle heat contributes to the metamorphism of both oceanic and continental crust. This is important information for deciphering the extent of ancient plate tectonics as recorded by metamorphic rocks. It is also a key for determining whether such very long-term processes could have any impact on the scale of human experience.

One can derive the equilibration pressures and temperatures experienced by metamorphic rocks by comparing their mineral assemblages with experimental and thermodynamic data. Chemically zoned and overgrown minerals can reveal segments of P - T - t (pressure-temperature-time) pathways that record the burial and exhumation history of the rock. These P - T - t paths can be correlated with structural features and tectonic indicators that can be mapped, and from them, geodynamic evolution can be estimated. In many cases, burial and exhumation do not occur within the same tectonic episode. Sometimes the two processes can be separated by tens of millions of years. Rates of burial and exhumation can proceed at speeds typical of plate movement (1 mm to 10 cm y^{-1}), or much slower (0.01 to 0.5 mm y^{-1}), at rates associated with erosion. Geochronology shows that regional deformation proceeds in spurts of activity separated by pauses. A region might suffer migrating orogenesis over hundreds of millions of years, whereas individual episodes of tectonic activity could be on a million-year

timescale. Because age data are lacking, it is often uncertain if tectonic motion has been continuous and controlled by large-scale remote forces, or if it has been perturbed by local changes in P (depth), T , stress, or fluid influx. We must consider the possibility that rock heating and related fluid release in the deep crust occur in multiple, sequential episodes, which become recorded in new metamorphic minerals. Slow fluid migration requires long-term, mid-crustal fluid storage. Stored metamorphic fluids contribute to regional (exhumation) and local deformation (faulting, earthquakes) only during much later tectonic episodes.

Metamorphic rocks provide a rich legacy of textures and compositions that allow us to understand the processes of plate-scale tectonics. These same relationships also provide criteria for interpreting where to find the riches of the Earth's crust, such as fluids, minerals and heat. There are now good criteria for indicating when such resources can be exploited and when they cannot.

VARIETIES OF METAMORPHIC FLUIDS

Any fluid that is modified by fluid-rock interaction (at any P or T) is considered to be a metamorphic fluid. This interpretation includes shallow fluids that have equilibrated with the atmosphere (meteoric fluid, as in weathering). Much of our understanding of oxidation/reduction and precipitation/dissolution reactions between groundwaters, minerals and metals has come from geochemical observations. This understanding is very important in construction, mineral processing and underground engineering.

Metamorphic fluids are released from deep inside the continents by devolatilization in response to tectonic transport toward a heat supply. These fluids are *products of prograde metamorphism*. On the other hand, metamorphic fluids on the ocean floor and in the continental crust are the *cause of retrograde metamorphism*. When hot and dry rocks are infiltrated by fluids, hydrated and carbonated minerals form in and near fractures and in shear zones. Fluid production and fluid migration are very episodic events inside the Earth's crust.

Some metamorphic fluids – those trapped in fluid inclusions – have geochemical signatures of equilibration with higher-grade metamorphic, mantle, or magmatic mineral assemblages. Deep fluid infiltration is rarely pervasive, but rather is focussed in spaced channel ways. Similarly, retrograde fluid flow is predominantly focussed in regions of internal structural weakness or in zones of external tectonic disturbance. Geochemical studies show which elements are sensitive to fluid migration near crystalline-rock reservoirs and repositories. Latest-generation ion microprobes can analyse rock slices using a one-micrometer-diameter spot size (e.g. Gordon et al. 2009) to obtain isotope data for interpreting age, duration and intensity of fluid-transport processes.

CHEMICALLY CONCENTRATED METAMORPHIC FLUIDS

Heating of buried rock causes volatile species and anions, such as OH^- , CO_3^{2-} , S^{2-} , SO_4^{2-} and NH_4^+ , to be released. Metamorphic fluids are predominantly H_2O ; CO_2 is the dominant carbon species, whereas CO and CH_4 are generally insignificant. In some ocean-floor systems, CH_4 is an important component and is associated with biological input or activity of the Fe(II)/Fe(III) redox couple. Reduced nitrogen and sulfur gases (NH_3 , H_2S , S_2) are the stable species in metamorphic fluids when graphite or diamond is present. Many metamorphic fluids contain minor amounts of ions, including Cl^- , that bind with metal cations. Such fluids can become quite concentrated at depth (e.g. Newton and Manning 2010), especially close to the temperatures where crustal rocks melt (e.g. Hack et al. 2007). New work to investigate how metal and

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silicate solubilities change in natural fluids in the P - T - X (pressure-temperature-composition) gradients of the upper crust are providing insight into the natural processes needed to concentrate rare elements to form mineral deposits.

TIMESCALES OF METAMORPHISM AND FLUID MIGRATION

Timescales for heating in prograde regional and contact metamorphic systems are mainly determined by the distance through which heat must be conducted from a finite heat source, for example, transposed asthenospheric mantle or a magma body. The rate at which minerals release fluid in such systems thus depends on the heat supply. In higher-temperature regimes, natural compaction and localised shearing govern fluid expulsion. Length scales and mass fluxes related to fluid migration depend on the extent to which fluids are focussed through narrow flow channels.

The lower density of metamorphic fluids (i.e. for H_2O , ca. 1 g cm^{-3}) compared to rock (ca. 3 g cm^{-3}) means that buoyant fluids migrate upward when they can. Flow along grain boundaries is typical in hotter settings (more ductile rheological behaviour), whereas fracture flow is expected in the P - T range of brittle rock. Hydrofracturing, which occurs in response to rapid fluid release and fast deformation (high strain-rate), can occur even in the P - T range where rocks are nominally ductile.

The many parameters that control fluid flow are not easily interpreted from geological observations, which require us to read rock evolution in an inverse or backwards sense. In the field, it is difficult to define actual fluid channel ways in three dimensions, even from a mined ore deposit where sequential slices through the volume are revealed. It is rarely obvious which specific fluid-flow indicators belong to a particular mineralisation episode that is related to a known heat source. Attempts to quantify crustal-scale fluid migration profit from new geochemical approaches. Such techniques measure *ratios of elements* that have been demonstrated to be characteristic of partitioning among various fluids, melts and minerals. A vital aspect still to be resolved on all scales is the efficiency of fluid recirculation within the lithosphere. In other words, when is fluid migration single-pass rather than multiple-pass? When do fluids only move upwards, in advection, and when do they follow more circular pathways, as in convection (e.g. Wood and Walther 1986)?

Fluids flow in the direction of least resistance for a given pressure gradient, but they become consumed by reaction to form volatilised minerals or hydrous melts, or they enter existing magmas. In brittle rocks, fluids follow existing lithological and structural heterogeneities. Making new faults in homogeneous media is less efficient than exploiting previous weaknesses. Thereafter, the original heterogeneities are preferentially and repeatedly reactivated with little displacement. Thus, we would expect continuous overprinting of isotope signatures, requiring careful sample selection before measurement to be able to distinguish these events. Detailing the processes that lead to focussed rock weakening is also fundamental to understanding the mechanics of how deep metamorphic rocks are exhumed. Focussed rock weakening is a vital part of the metamorphic cycle for mineralisation and exhumation, and sometimes requires the participation of fluids that were released by deeper metamorphic reactions.

THEMES FOR FUTURE RESEARCH

Many aspects of fundamental research in metamorphic petrology are as important for the development of technological applications as they are for understanding the tectonometamorphic evolution of the Earth. The next decade will see advances in macroscopic-scale geophysical interpretations and the correlation of field relationships from the

regional to the hand-specimen scale. At higher resolution, several directions are possible. Detailed chemical and isotopic study, focussed on microstructures, will help us to understand time-dependent stress relaxation and mass-transport properties.

On the grand scale, we will need to quantify the flux of volatiles subducted into the mantle of the Earth and compare the result with the amount of primordial volatiles stored in minerals. Further, we will need to determine the mechanisms controlling the passage of H_2O and CO_2 from a subducted slab into the mantle-wedge regime where volcanic arc magmas are generated. Subsequently, rising volatiles become important components in near-surface hydrothermal systems. At the outcrop scale, we must determine the role of water accessibility in large-scale rock weakening that leads to major tectonic processes, such as earthquakes, crustal-scale shearing, thinning of the lithosphere, subduction and magma intrusion. We need to define the rock mechanics related to the transition from porous-media flow in fluid source regions to focussed flow in fractures and shear zones. We need to determine the role of hydrous and carbonate minerals in promoting rock failure. Such study is also relevant for mine safety and efforts to sequester CO_2 (e.g. Cole and Oelkers 2008).

In terms of geochemistry, we must determine the relative importance of oxidised versus reduced species of C, S and N in magmatic and hydrothermal processes under various O_2 fugacities. We must also explore the driving forces of mass transport along natural pressure gradients and along temperature gradients away from natural heat sources. We must determine the roles of sulphur, chlorine and other aqueous species in metal transport in combined-volatile systems.

With respect to power generation from geothermal sources, natural advective heating by rising fluids is a faster mode of heat transfer than conduction. However, advection is restricted in both space and time by the availability of transport pathways and requires sites where hydrothermal or geothermal systems are linked to magma intrusion at shallow depth. Outside volcanic areas, supplies of sufficiently hot fluid are insufficient for viable power generation.

Finally, from the perspective of the natural resource industry, the development of robotics will be necessary for deep mining – for heat, hydrocarbons, minerals and metals. As with space travel, harvesting resources from the deep Earth is not suited to participation of the human body.

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REFERENCES

- Cole and Oelkers (eds) (2008) Carbon Dioxide Sequestration. *Elements* 4(5)
- Gordon SM, Grove M, Whitney DL, Schmitt AK, Teyssier C (2009) Fluid-rock interaction in orogenic crust tracked by zircon depth profiling. *Geology* 37: 735-738
- Hack AC, Thompson AB, Aerts M (2007) Phase relations involving hydrous silicate melts, aqueous fluids, and minerals. In: Liebscher A, Heinrich CA (eds) *Fluid-Fluid Interactions. Reviews in Mineralogy & Geochemistry* 65, Mineralogical Society of America, Chantilly, VA, pp 129-185
- Newton RC, Manning CE (2010) Role of saline fluids in deep-crustal and upper-mantle metasomatism: insights from experimental studies. *Geofluids* 10: 58-72
- Wood BJ, Walther JV (1986) Fluid flow during metamorphism and its implications for fluid-rock ratios. In: Walther JV, Wood BJ (eds) *Fluid-Rock Interactions during Metamorphism*. Springer, New York, pp 89-108 ■