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PLANET IN FLUX

THE CHALLENGE OF METAMORPHIC PETROLOGY

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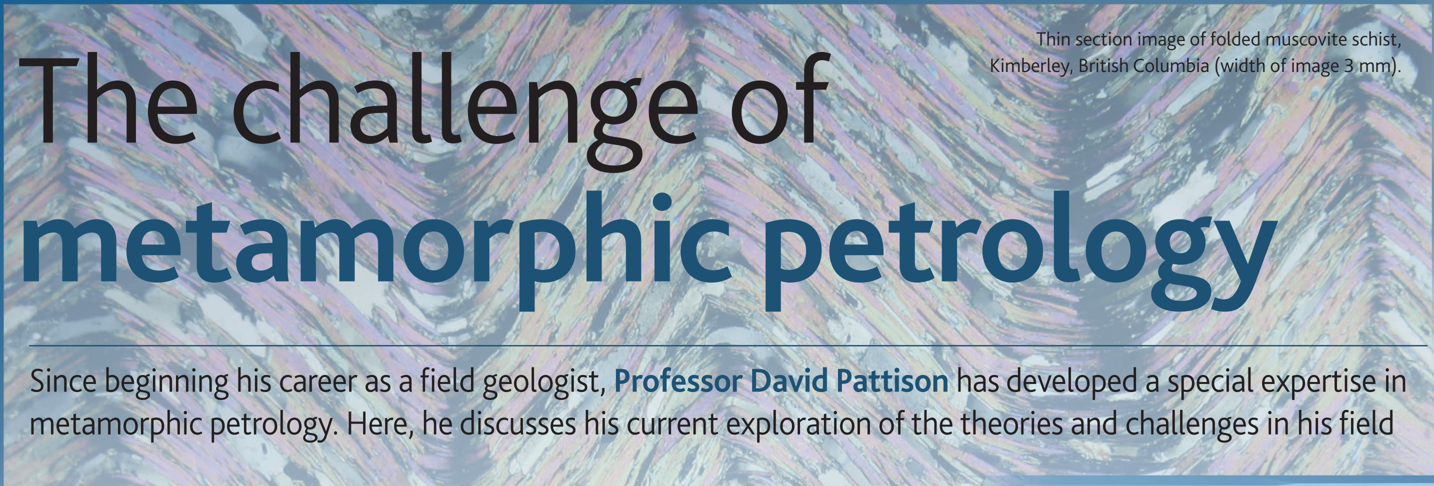

Thin section image of folded muscovite schist, Kimberley, British Columbia (width of image 3 mm).

The challenge of metamorphic petrology

Since beginning his career as a field geologist, **Professor David Pattison** has developed a special expertise in metamorphic petrology. Here, he discusses his current exploration of the theories and challenges in his field

To begin, can you outline the central aims and objectives of your current project?

Metamorphic petrology is concerned with the mineralogical and textural changes that occur when rocks get buried and heated inside the Earth. Like any other specialised discipline in geology, it provides unique and irreplaceable information on how the Earth works. Think of the different tradespeople who build a house – plumbers, electricians, etc. Each brings specialised skills that are essential to the success of the house. The best tradespeople (and geoscientists) are those who are leading experts in their chosen trade or field, yet can apply this expertise and communicate with experts in other trades (fields) to solve bigger problems. This philosophy underpins my research: I aim, first, to improve our understanding of metamorphic processes and develop improved techniques of metamorphic petrology and, second, to integrate this enhanced expertise with other geoscience disciplines (analysis of rock deformation, determination of geologic ages) to solve broader problems in Earth Science.

Why are thermodynamically predicted phase diagrams important?

Thermodynamically-predicted phase diagrams show how mineral associations in rocks change as temperature and pressure vary. They are one of the most powerful tools we have for determining the burial and heating 'life cycle' of metamorphic rocks. Every metamorphic rock started out life as an unmetamorphosed rock – such as mudstone, volcanic rock or granite. If these rocks get caught up where the Earth's tectonic plates collide – like is happening today in the Himalayan Mountains, where India is inexorably colliding with Asia, or in the Andes, where the floor of the Pacific Ocean is being dragged underneath South America – they get buried, squeezed, heated and recrystallised, ie. metamorphosed. We can't see this in action of course, because the rocks being metamorphosed are under the mountains. However, when mountain ranges cease growing, they become eroded and their 'roots' of metamorphosed rock become exposed. The mineral assemblages and textures of metamorphic rocks now exposed at the surface encode their journey of burying, heating and squeezing, and we use phase diagrams to quantify this pressure-temperature history. Tectonic processes have been occurring almost since the beginning of the Earth 4.5 billion years ago, so if we can read the metamorphic record correctly, it tells us how the Earth's crust has behaved since its birth.

How did you decide upon the study areas under investigation?

I started my career at Edinburgh University in Scotland, the birthplace of metamorphic geology. I looked at a lot of sequences of metamorphic rocks and built up a good idea of the natural patterns they show. I then became involved with the massive advances in thermodynamic modelling going on at that time to see if I could reproduce what I observed. While these methods did an excellent job in some situations, they didn't in others. Even though we are getting closer all the time, that dilemma persists to this day. The challenge is to separate the possible problems of thermodynamic modelling from other possible factors, such as kinetic factors, to account for the mismatch between prediction and observation.

What findings have generated the most excitement?

Two areas of my research that have been generating interest in the community lately are: first, natural geological evidence I have

provided for kinetic (rather than equilibrium) controls on metamorphism in some settings; and second, a predictive method for determining when such kinetic 'perturbations' of the equilibrium model may be expected. This latter method is based on the rate at which the energetic driving force for mineral reactions builds up so that it can overcome the kinetic barriers to reaction – it actually varies a lot. The exciting part is, I don't know how important or widespread this will turn out to be, but it really is a fundamental issue. The only way to find out is to go looking for evidence of it in Nature!

Will your ongoing research benefit the wider geological community?

My research lies at the heart of how we interpret the mineral assemblages and textures of metamorphic rocks, and it is these that inform us about the depth-temperature-deformation journey they have experienced. This in turn tells us how rocks are recycled throughout Earth's history, where and how ancient mountains have formed, and how these are related to plate tectonics and other fundamental Earth processes.

Pattison (**left**) and colleague Dr Rob Berman (**right**) on two-billion-year-old folded schists, Baffin Island, Canada. © Brett Hamilton

Rock transformation

A geoscientist at the University of Calgary, Canada, is investigating pure and applied problems in metamorphic petrology to advance learning in this wonderfully explorative domain of Earth Sciences

EARTH'S TECTONIC PLATES are in a constant state of movement: diverging, converging and transforming our landscape – quite literally shaping history. Metamorphic petrology, a specialised branch of geology, explores the changes in the minerals and textures of rocks that become buried and heated during these endlessly evolving tectonic processes. Along with the natural wonder of the multitude of colours, minerals and patterns found in such metamorphic rocks, metamorphic petrology provides a means to gain fundamental insight into the evolution and behaviour of the Earth. It allows us to decode the pressure-temperature journey of Earth materials that get recycled in tectonic processes. Some metamorphic minerals can be dated, allowing us to estimate how fast this recycling takes place. Comprehension of these processes, in turn, allows us to better understand how and where ore deposits – which provide us with metals and other mineral products – form.

Funded by the Discovery Grant scheme of the Natural Sciences and Engineering Research Council of Canada (NSERC), Professor David Pattison is leading research that hopes to advance the theory and techniques of metamorphic petrology. He wants to understand what controls metamorphic processes deep in the Earth, allowing for the consideration of the interplay between equilibrium, kinetics and rock deformation. By bringing this improved understanding to bear on diverse parts of the Canadian landscape, Pattison intends to contribute to a broader overall objective of Earth Science: to understand the processes and evolution of the Earth's crust.

INITIAL ANALYSIS OF METAMORPHIC ROCKS

In the initial stage of investigation, practical fieldwork is undertaken in which Pattison and his students walk over the ground, sometimes many kilometers a day, making a map of where different rocks occur, taking structural measurements, observing and recording subtle changes in the minerals and textures of the rocks, and collecting samples. The samples are then taken back to the lab for closer examination and analysis. After cutting a thin slice, approximately 1/30 mm thick, the rock can be examined under a specialised microscope by shining light through the sample. This technique allows Pattison and other researchers to identify the minerals in the rock and examine the way in which the minerals fit together, something known as the rock texture.

Those samples that have the most informative minerals and textures are then analysed chemically using an extensive range of methods. The most common of these methods allows researchers to analyse the chemical composition of the minerals and of the whole rock. With this information, it is then possible to use chemical thermodynamics to calculate mineral stability diagrams. "Different minerals, or groups of minerals known as mineral assemblages, occur at different conditions of temperature and pressure. Pressure is directly related to depth," explains Pattison. Matching the minerals in the natural rock samples with those in the phase diagram allows researchers to determine the temperature and depth at which the rock formed.

TOOLS OF THE TRADE

Yet, this method is by no means foolproof. As such, Pattison is presently researching two aspects of metamorphic petrology to improve the 'tools of the trade' of this discipline. By working with experts in thermodynamic modelling, Pattison wants to predict more accurately the patterns of regularity found in metamorphic mineral associations in the natural world. "If we can't reproduce what Nature tells us is there," explains Pattison, "then we can't trust the thermodynamic models, and that means maybe we can't trust the pressure and temperature information we extract for other rocks using these models." Refinement of extant thermodynamic models could therefore increase accuracy in matching thermodynamically predicted mineral assemblages with natural assemblages.

The second aspect of study is one that Pattison considers to be fundamental to the discipline,

Thin section image of andalusite crystals in deformed hornfels, Nelson, British Columbia (width of image 2 mm).

PURE AND APPLIED PROBLEMS IN METAMORPHIC PETROLOGY

OBJECTIVES

- To improve the specialised 'tools of the trade' of metamorphic petrology, in particular phase equilibria and the interplay between equilibrium and kinetics in metamorphic processes
- To apply these new techniques to address broader problems in Earth Sciences relating to tectonics, ore deposits, geochronology and geophysics

KEY COLLABORATORS

Christian de Capitani, University of Basel, Switzerland • **Fred Gaidies,** Carleton University, Ontario, Canada • **Frank Spear**, Rennselaer Polytechnic Institute, New York, USA • **Dave Waters**, University of Oxford, UK • **Richard White**, University of Mainz, Germany

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DAVE PATTISON is Professor in the Department of Geoscience at University of Calgary specialising in metamorphic petrology. He graduated with a BSc in Geology from Queen's University, Ontario in 1980, spent a year at University of British Columbia and completed his PhD at Edinburgh University in 1985. After a two-year postdoctoral fellowship at University of Chicago, he was hired at the University of Calgary in 1987. Pattison is a Fellow of the Mineralogical Society of America and recipient of the 2013 Peacock Medal of the Mineralogical Association of Canada.

UNIVERSITY OF CALGARY

as he explains. "A central tenet of metamorphic petrology is that as metamorphic rocks are heated and buried, they behave chemically as if they are always very close to equilibrium, meaning they obey the laws of chemical thermodynamics". It is this assumption that allows researchers to use thermodynamically-calculated phase diagrams to estimate the pressure and temperature of formation of metamorphic rocks.

Yet in some circumstances, Pattison has discovered that the energetic force that drives these mineral changes is not large enough to overcome the energetic barriers to the changes. The rocks, therefore, might not always follow an equilibrium path. This creates an obvious problem if they are interpreted as always having their most energetically stable configuration of minerals.

EQUILIBRIUM, KINETICS AND ROCK DEFORMATION

Pattison's ongoing research has led him to explore further the interplay between equilibrium, kinetics and rock deformation, a cutting edge area in metamorphic petrology. Kinetics measures the mechanisms and rates by which mineralogical changes occur in metamorphic rocks, a reality which Pattison explains in terms of force: "Every process needs an energetic 'push' to get it going and if the push is too small, or the barrier too big, it will not happen, or can be delayed". Deformation is concerned with how minerals become pressed against each other during the burying and squeezing process, and this can reduce the energetic barriers to reaction. As such, the focus of his research is the interrelated nature of these three factors in governing mineral formation.

While acknowledging these factors, the fact that metamorphic minerals do occur in broadly regular patterns the world over means that the equilibrium model is a good way of initially analysing the mineralogy and pressure-temperature history of metamorphic rocks. However, at a finer scale within these broad patterns, this behaviour may not always pertain. Some rocks contain minerals that, according to an equilibrium assessment, should not be present. Other rocks show a record of mineral growth and consumption that differs from predictions. As a result of these examples, Pattison concludes: "We have to pay attention to the kinetic aspects of metamorphism, including the effects of deformation".

CANADIAN MOUNTAIN RANGES, ANCIENT AND MODERN

A long-term objective of Pattison's research is to apply the improved techniques of metamorphic petrology to understand ancient mountain-building processes in Canada's vast and varied landscape. With the assistance of graduate students, Pattison aims to discern the character and time scale of metamorphic areas in the Canadian Cordillera of British Columbia and Yukon, and map out the metamorphic history of parts of the eroded Precambrian Shield of central Canada and Canada's Arctic regions. These studies will allow the group to piece together the geological evolution of these ancient tectonic collisional zones and help better understand the origin of the ore deposits hosted therein. As this exciting area of research develops, so will understanding of the movement, actions and history of the planet.

Staurolite and garnet in metamorphosed turbidite, Coos Canyon, Maine © Darrell Henry

Top: Reaction affinity of garnet formation relative to garnet-free matrix. **Bottom:** Entropy change associated with garnet formation.