Fluids in Metamorphism

BJÖRN JAMTVEIT, Guest Editor

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Fluids in Metamorphism

Guest Editor: Bjørn Jamtveit

Metamorphism: From Patterns to Processes
Bjørn Jamtveit

Metamorphism: The Role of Fluids
Bjørn Jamtveit and Håkon Austrheim

Replacement Processes in the Earth’s Crust
Andrew Putnis and Timm John

The Mechanics of Metamorphic Fluid Expulsion
James A. D. Connolly

Alteration of the Oceanic Lithosphere and Implications for Seafloor Processes
Wolfgang Bach and Gretchen L. Früh-Green

Metamorphic Fluids and Global Environmental Changes
Henrik Svensen and Bjørn Jamtveit

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Fracture-controlled fluid infiltration of high-grade metamorphic rocks (granulites) at Mount Trollslottet, Queen Maud Land, Antarctica. The introduction of external fluids hydrated the original granulites to form lower-grade amphibolites (green color). This is an example of fluid-controlled retrograde metamorphism. Field geologist in red anorak for scale. Photograph courtesy of Håkon Austrheim, PGP, University of Oslo.

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SOCIETY NEWS EDITOR: Kevin Murphy
kevin@minerosoc.org

The Clay Minerals Society of America 490, de la Couronne Québec, QC G1K 9A9, Canada
Tel.: +1 418-653-0333; fax: +1 418-653-0777
office@minerosoc.org
www.minerosoc.org

SOCIETY NEWS EDITOR: Pierre Tremblay
ptremblay@mineralogicalsociety.ca

Mineralogical Society of Canada 490, de la Couronne Québec, QC G1K 9A9, Canada
Tel.: +1 418-653-0333; fax: +1 418-653-0777
office@minerosoc.org
www.minerosoc.org

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SOCIETY NEWS EDITOR: Steve Hillier
s.hiller@macaulay.ac.uk

The Clay Minerals Society 3635 Concorde Pkwy Ste 500 Chantilly, VA 20151-1125, USA
Tel.: +1 703-652-9960; fax: +1 703-652-9951
cms@clays.org
www.clays.org

The Clay Geological Society (GS) is an international organization with members from 54 countries, founded in 1955 for students and scientists involved in research, practice, study and teaching of geochemistry. Our programs include co-hosting the annual Goldschmidt Conference™, editorial oversight of Geochimica et Cosmochimica Acta (GCA) supporting geochemical symposia through our Meeting Assistance Program, and supporting student development through our Student Travel Grant Program. Additionally, GS annually recognizes excellence in geochemistry through its medals, lectures and awards. Members receive a subscription to Elements, special member rates for GCA and G-cubed, publication discounts, and conference discounts.

SOCIETY NEWS EDITOR: Seth Davis
seth.davis@geochemsoc.org

Geological Society of America (GSA) was founded in 1887 to promote geoscience education and research. It supports the many facets of geoscience by stimulating research and disseminating the results of geoscience to the public, politicians, and other decision-makers. GSA’s membership includes the Geochemical Society, the Geophysical Society, the Geomorphological Society, and the Hydrogeological Society. The Geochemical Society is to promote mineralogy and geochemistry and to encourage research and development. AAG membership includes the AAG journal, Geochemistry: Exploration. Environment. Analysis; the AAG newsletter, EXPLORE, and Elements.

SOCIETY NEWS EDITOR: David Lenz
dlentz@unb.ca

Association of Applied Geochemists P.O. Box 26099 Nepean, ON K2J 9RO, Canada Tel.: +1 613-828-0199; fax: +1 613-828-9288 office@appiledgeochemists.org www.appliedgeochemists.org

The European Association of Geochemistry was founded in 1985 to promote geochemistry education and research in Europe. It is now recognized as the premiere geochemical organization in Europe. The European Association of Geochemistry holds a large international meeting in Europe encouraging interaction between geochemists and researchers in associated fields and disciplines, and promoting teaching in the public and private sectors.

SOCIETY NEWS EDITOR: Lianne G. Benning
lgb@geochem.aca

Membership information: www.eag.eu.com/membership

The International Association of Geochemistry (IAGC) has been a pre-eminent international geochemical organization for over 40 years. Its principal objectives are to foster cooperation in, and advancement of, applied geochemistry, by sponsoring specialist scientific symposia and the activities organized by its working groups and by supporting its journal, Applied Geochemistry. The administration and activities of IAGC are conducted by its Council, comprising an Executive and ten regional members. Day-to-day administration is performed through the IAGC business office.

SOCIETY NEWS EDITOR: Mel Gascoyne
mgascoyne@grainite.mb.ca

IAGC Business Office, Box 501 Pinawa, Manitoba R0E 1L0, Canada
Tel.: +1 204 285-3322; fax: +1 204 285-3336
www.iagc.ca

Società Italiana di Mineralogia e Petrologia (I.M.P.), established in 1948, is the national body representing all researchers dealing with mineralogy, petrology, and related disciplines. Membership benefits include receiving the European Journal of Mineralogy, phy and Elements, and reduced registration fee for the annual meeting.

SOCIETY NEWS EDITOR: Marco Pasero
[pasero@imp.cnr.it]
Società Italiana di Mineralogia e Petrologia Dip. di Scienze della Terra Università di Pisa, Via S. Maria 53 I-56126 Pisa, Italy
Tel.: +39 050 2215704 Fax: +39 050 2215830 society@socminpet.it www.socminpet.it

The International Association of Geoanalysts is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Major activities include the management of proficiency testing programmes for bulk rock and micro-analytical methods, the provision of an accreditation of reference materials and the publication of the Association’s official journal, Geostandards and Geostand. Analytical Research.

SOCIETY NEWS EDITOR: Michael Wiedenbeck
michaelwgf@potsdam.de

International Association of Geoanalysts 13 Bedford Street Keyworth, Nottingham NG12 5JF United Kingdom http://geoanalysts.org

The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1919, the Society promotes together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes links between mineralogical science and education and technology through annual conferences, field trips, invited lectures, and publishing. There are two active groups: the Clay Minerals Group, which is affiliated with the European Clay Groups Association, and the Petrology Group. Membership benefits include subscriptions to Mineralogia and Elements.

SOCIETY NEWS EDITOR: Zbigniew Sawkowicz
(zbigniew.sawkowicz@uj.edu.pl)

Mineralogical Society of Poland Al. Mickiewicza 30, 30-059 Kraków, Poland Tel.: +48 12 6334180 ptmin@ptmin.pl www.ptmin.agh.edu.pl

The Società Española de Mineralogía n/pvsm@agh.edu.es www.ahu.es/sem

The Swiss Society of Mineralogy and Petrology was founded in 1924 by professionals from academia and industry and by amateurs to promote knowledge in the fields of mineralogy, petrology and geochemistry and to advance professional and public societies. The Society organizes annual conferences and training of young researchers via seminars and special publications. The SEM Bulletin published scientific news, reviews, abstracts, and reviews. Membership benefits include receiving the European Journal of Mineralogy (EJM), and Elements. The SEM society is a member of the international mineralogical and paleontological societies. The Swiss Society of Mineralogy and Petrology is an educational organization for researchers in the scientific and public communities. The Society coorganizes the annual Swiss Geoscience Meeting and publishes the Swiss Journal of Geosciences jointly with the national geological and paleontological societies.

SOCIETY NEWS EDITOR: Urs Schaltegger
urs.schaltegger@unige.ch

Swiss Society of Mineralogy and Petrology Université de Genève Section des Sciences de la Terre et de l’Environnement 13, rue des Maréchaux 1205 Genève, Switzerland
Tel.: +41 22 379 66 24; fax: +41 22 379 32 10 http://ssmp.scautweb.ch

Affiliated Societies

The International Mineralogical Association, the European Mineralogical Union, and the International Association of Clays are affiliated societies of Elements. The affiliated status is reserved for those organizations that serve as an “umbrella” for other groups in the fields of mineralogy, geochemistry, and petrology, but that do not themselves have a membership base.
STRATEGIC OR BLUE SKY RESEARCH?

The Execution of Serendipity

Susan Stipp

As an academic scientist, I share concerns with colleagues about decreasing support for basic research. Governments are putting increasing pressure on research funding agencies to favour projects that promise to solve specific problems, to produce a product or a process that has economic value. Whether explicitly announced or subtly understated, the concept “from idea to invoice” rings from calls for proposals. From discussions with colleagues and from my own experience, I know this to be true in the US and Japan, at the European Commission, in the British funding bodies, for several Danish agencies, in other Scandinavian countries, in Switzerland, in Germany, and so on. Applications require scientists to put the right words in the box for economic impact. And we, as academic researchers, who have students to support, instruments to acquire and keep running, and H-indexes to nurture, are under increasing pressure to either learn the applied research funding rules as the game changes, or perish.

Basic research, where the aim is to discover the fundamental principles of how the world works, is driven by curiosity. There is a passion at the base that motivates the scientist, and the results that come out are often very different than those sought at the outset. In the past 20 years, basic research has become unpopular. Academia, “the ivory tower”, has gained the reputation of being cut off from “the real world”, a place where products come out are often very different than those sought at the outset. In the past 20 years, basic research has become unpopular. Academia, “the ivory tower”, has gained the reputation of being cut off from “the real world”, a place where researchers selfishly follow tangents to esoteric ends. Politicians claim that tax payers provided research budgets that were far less affluent than now, scientists were cut off from “the real world”, a place where the standard of living has increased, governments have decreased the relative funding for higher education and academic research. In the years after World War II, when Europe was struggling to get back on its feet and North Americans were far less affluent than now, scientists were highly respected and tax payers provided research budgets that were proportionally much larger.

Unfortunately, it does not appear that politicians will lose their love of applications-driven research in the near future. Can we adapt? Of course we can. Students are often eager to work on topics where the goal is clear, where their results will be “used for something”. The public is often excited about topics recognised as strategic by governments requires that politicians have insight into what natural phenomena remain to be discovered and how to use them. Physicists curious about the internal structure of the atomic nucleus in the 1930s answered their need for counting nuclear particles by developing circuits, which then led to electronics and the silicon revolution that has changed the way our world functions. There was no strategic funding that kick-started the electronics revolution. Think how it would have been without computers. What about the colossal developments in genetics? In modelling and simulation at all scales? In communication and transport? Strategic research can encourage improvements and developments, but curiosity-driven research is essential for the big breakthroughs.

The theme of this Elements issue is an excellent example of the value of fundamental science in our own discipline. Metamorphic petrology is seen by some as a field where it is hard to make a case for its worth to society. That could not be further from the truth! How can we forget the importance of metamorphic processes in concentrating the metals that have been essential for the advancement of society and culture as far back as the Bronze Age – and our growing concern now as resources become scarce? But metamorphic geology has important contributions to offer society from the fundamental side as well. Although one of the first lessons in geology is: “The present is the key to the past”, modern geologists have realized that rocks are the textbook where one can learn the fundamental principles of global change, a critical issue today. The articles in this issue of Elements tell us how we can read exciting chapters of Earth’s history from the textures and composition of metamorphic rocks.

The current funding system, where research ought to have a direct link to application, has been with us for at least 20 years. It is interesting that as society has in general become wealthier, where the standard of living has increased, governments have decreased the relative funding for higher education and academic research. In the years after World War II, when Europe was struggling to get back on its feet and North Americans were far less affluent than now, scientists were highly respected and tax payers provided research budgets that were proportionally much larger.

With goal-directed research, there is little room for serendipity and few resources to follow a flash of inspiration.
THANKING SUSAN STIPP

Reluctantly, we bid farewell to Susan Stipp as principal editor of *Elements*. Susan joined the team in 2007 and has the distinction of being both the first woman to serve as principal editor and the first person appointed from outside the USA or the UK. Susan has been instrumental in developing the magazine, following on from the founding editors. She worked at a critical time, helping to firmly establish a new journal in a highly competitive environment. She contributed great energy and enthusiasm to all aspects of the tasks. She was often the person with a new insight or a novel perspective on an issue. This was reflected by her editorial contributions on topics such as who should decide on how research funding should be spent, the need for much more interdisciplinary research, the ethical issues associated with our diminishing Earth resources, and the gender bias that still damages the career prospects of many women working in science. Susan will be missed for her energy, insights, integrity, and honesty, and for adding that spark that brought life to many of our debates. Susan has been instrumental in developing *Elements* and the first person appointed from outside the USA or the UK. She worked at a critical time, helping to firmly establish a new journal in a highly competitive environment. She contributed great energy and enthusiasm to all aspects of the tasks. She was often the person with a new insight or a novel perspective on an issue. This was reflected by her editorial contributions on topics such as who should decide on how research funding should be spent, the need for much more interdisciplinary research, the ethical issues associated with our diminishing Earth resources, and the gender bias that still damages the career prospects of many women working in science. Susan will be missed for her energy, insights, integrity, and honesty, and for adding that spark that brought life to many of our debates.

Susan was in charge of the following issues: Critical Zone (v3n5), Phosphates (v4n2), Carbon Dioxide Sequestration (v4n5), Bentonites (v5n2), Metal Stable Isotopes (v5n6), and Fluids in Metamorphism (v6n3). Susan has also encouraged and nurtured a number of topics that will be featured in upcoming issues of *Elements*. We thank Susan for her outstanding contributions; she will be greatly missed by the editorial team.

David Vaughan, on behalf of the editorial team

FROM THE EDITORS

THIS ISSUE

An issue on metamorphism has been on the wish list of the *Elements* editorial team for several years, and Bruce Watson, during his time as principal editor, worked hard to bring it to reality. Now, finally, here it is.

Imagine a collection of papers on metamorphic petrology without a single P–T–t diagram! And serpentinization of ultramafic rocks at mid-ocean ridges is not what first comes to mind when one thinks of metamorphism. Guest editor Bjørn Jamtveit chose to highlight the continuum between diagenesis, contact metamorphism, and regional metamorphism. So we hope you will enjoy this different perspective on the role of fluids in shaping the Earth’s crust. I was especially intrigued by the final article on the potential impact of the metamorphism of carbonate rocks on global climate change.

Among the other offerings in this issue is a very interesting article about Linus Pauling’s participation in the 1993 CMS meeting (page 188). And in Parting Shots, Ian Parsons surprises us once again, this time with the origin of the name Calgary (page 199).

EDITORS MEETING

*Elements* editors will hold their annual meeting just prior to the Goldschmidt Conference in Knoxville, Tennessee. We will welcome incoming principal editor Georges Calas, who will officially start his term of office in 2011. During this invaluable day-long meeting, the editors will plan the upcoming year, discuss any issue developing on the horizon, and plan *Elements* thematic content for the second half of 2011 and part of 2012.

VINCENT BOIVIN 1983–2010

Vincent Boivin, the young graphic artist who has been typesetting *Elements* since 2006 and who was *Elements*’ webmaster, died on March 30, at the age of 27. I introduced Vincent and Michel Guay in volume 4, number 2 (page 78) as the magicians who take unformatted text and turn it into *Elements*’ colorful layout. Each time I took an issue to press, I spent a day with Michel and Vincent to do final corrections, and over the years, we developed a real camaraderie. I appreciated Vincent’s appetite for life, his cheerful disposition, his wonderful sense of humor, and his courage.

Vincent was a cancer survivor from childhood, and a little over one year ago, he was diagnosed with lung cancer, a potential side effect of the medications he took as a child. He cheerfully worked through major surgery and aggressive chemotherapy. For a few months, it seemed like he had beaten the beast. But in November, he learned that the cancer had returned and that medicine could not do anything more for him. Michel and I visited him just a few days before he died. Even then, he was interested in catching up on our news, and we had no inkling the end would come so fast. We will miss him so much!

Pierrette Tremblay, Managing Editor

Sincere thanks to the guest editors and authors I have worked with over the past three years. Warm wishes to Pierrette and the editorial team for the wonderful experience of working with you. It has been very rewarding to help *Elements* grow from a fledgling publication, when we were still a little worried about the long run, to a mature periodical with a respectable and growing citation index. I wish *Elements* continued success in producing issues that bring the excitement and drama felt by the specialists of each theme to a more general readership! Congratulations *Elements* on your fifth birthday!

Susan L. S. Stipp*


* Susan Stipp was the principal editor in charge of this issue.

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EDITORIAL Cont’d from page 139

Funding bodies that “earmark” or “cigar-box” sums of money for topics that are labelled “strategic” are often happy to fund proposals where a promised development is solidly founded on a set of experiments to establish basic understanding. Unfortunately however, if one strictly follows the rules for applications-driven research, one should not pursue even a single interesting tangent. In principle, the funding is given only for research that is directed toward reaching the contracted goal. This is a shame because the unexpected phenomena and the spin-offs can be more valuable than the promised product. It is a shame for the researcher who misses the satisfaction of following his/her insight to an exciting end, but it is even more of a shame for the funding body and society, who will undoubtedly miss many benefits from today’s generation of Ørsteds.

George Whitesides, well known for his work in many branches of chemistry and materials and who has the highest H-index of all living chemists, gave the plenary lecture at a recent meeting. A young fellow, referring to the frustrating lack of funding for basic research in the current science landscape, asked how he got the funding to do what he really wanted to do. Professor Whitesides did not hesitate for an instant before he answered, “Lie, cheat and steal”. With goal-directed research, there is little room for serendipity and few resources to follow a flash of inspiration. Perhaps George Whitesides has a point. As academic researchers, we can choose to bootleg experiments to follow promising tangents on the side of projects intended to deliver a product or process. Or we can hope that our politicians soon realise the huge risk of lost opportunities and swing the funding pendulum back to a system where curiosity-driven, blue sky research is offered a fairer share of the cake. We can hope.

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I recently had the pleasure of travelling around a wide range of university departments in Europe and North America, courtesy of the Mineralogical Society of America Distinguished Lecturer programme, and a very interesting and enjoyable experience it was. One feature of academic departments today is that, wherever you go, you find really interesting work being done by enthusiastic people who are in touch with the frontiers of their field. The days are long gone (if they ever existed, I am relying on rumours I heard from greybeards back in my youth) when the only people worth talking to, if you were a world leader in your field, were a few colleagues in elite institutions. Of course this means that more and more researchers are carrying out investigations with an underlying purpose and curiosity that goes beyond just doing more of what they have always done. This has to be a good thing, especially where the training of young researchers is concerned, but there is one interesting result that we have to live with: it has now become a requirement of funding agencies and journal editors alike that everything we do must be clearly identified as of profound and lasting significance.

Choosing to embark only on research that will be of profound significance sounds fine (who would vote the other way?), except that none of us (I think) really knows in advance whether or not the work we are starting is going to make a fundamental contribution to human understanding. As Susan Stipp has emphasised in her editorial in this issue, truly original research is often the research which ends up going in completely unexpected directions. Which brings me to a dilemma for the 21st century scientist: Should we try to ensure that everything we do has underlying significance and search for deep meanings in all our data, to ensure that we don't become complacent and repetitive? Or should we concentrate on doing what we enjoy and are good at, for "the pleasure of finding things out," and then if need be, dress it up to look like it is potentially profound and relevant to get it past our peers?

At the beginning of the 20th century, most scientists seem to have been naturally modest people, but by the end, even those who had much to be modest about had learnt to push their work forward as though it held the key to the universe. Einstein's revolutionary paper in March 1905 was entitled “On a heuristic viewpoint concerning the production and transformation of light”; today, perhaps it would have to be called “Energy comes in quanta: Say goodbye to waves” before any potential reviewers or readers would sit up and take notice. It is easy to poke fun at over-the-top attempts to claim a major advance by people who have just rediscovered the wheel, but I am not sure we should do so too severely, because these are also people who have enthusiasm and drive, which means that sometimes they really do break new ground. Cynics don't waste time pursuing lost causes, but they never actually make new breakthroughs either. On the other hand, overly enthusiastic claims for one's work are usually just a mild embarrassment in later life, not career stoppers (although there have been some exceptions!). The fact is that some people feel comfortable making brash claims for the importance of what they do, while others remain reserved and self-effacing. Despite the international nature of science, a certain amount of national stereotyping is still possible here, though I have noticed that if an Englishman modestly suggests that his latest work really says nothing very new, in recent years his fellow-countrymen have become rather too keen to simply agree.

It has now become a requirement of funding agencies and journal editors alike that everything we do must be clearly identified as of profound and lasting significance.

What is more invidious, and arguably a greater hindrance to the progress of science, than claiming profound significance for the mundane is when authors of papers claim that their studies provide proof for the established hypothesis of the day. A paper saying that the majority view is correct is relatively easy to get past referees, so what sometimes happens is that quite mundane observations are cited as providing “tests” or “proofs” of currently popular hypotheses. This makes the study appear more profound and significant, but also boosts the status of the hypothesis, perhaps undeservedly. A test is possible when a particular hypothesis predicts one result while alternative hypotheses predict different answers. By this definition, many observations that are supposed to verify the veracity of a hypothesis are simply consistent with it, but might also be consistent with all other hypotheses as well. For example, an isochore constructed for a selected fluid inclusion from a metamorphic rock may pass through the P-T conditions at which the host mineral is supposed to have formed. However the isochore also passes through a swath of other P-T conditions, while if other nearby fluid inclusions are considered, there may be little P-T space remaining outside the wedge of possible conditions. But if some of the data give the answer we expect, it is amazing how often these data are emphasised. What a sad reflection it is on how we sometimes use our sophisticated modern facilities if we only accept their evidence when it agrees with our pre-existing (and therefore ill-informed) prejudices!

If we can agree that such an attitude is wrong, should we reject the pressure to show that all our work is of wider significance beyond its immediate subject? One approach would be to go back to making the observations and reporting the results for the love of it, not worrying about whether or not they address burning issues of general interest. That might seem a very pure and objective way of doing science, but it also runs the risk of enshrining mediocrity by removing the incentive to move on. We don't give medals to people because they have reached the average age for researchers and have published an average number of papers that have received an average number of citations; we give them to people who do exceptional work.

Instead, I put in a plea to keep faith with the brash and arrogant who are trying to move in new directions, but let's not make it easy for them to fake it. Reviewers should be ruthless in pointing out whether papers solve problems or simply add to an already massive pile of inconclusive data. If the necessary measurements to resolve the problem were not made, the work was not done adequately. If the required measurements are beyond our current technologies, why waste time trying to solve the problem now? But when there are good data helping us to understand better how the world works, we need researchers/authors who have been trained to think about the potential implications of their work and are prepared to push them at the community. Otherwise, no one will notice. So by all means pursue your science for the pleasure of discovery, but unless you have a natural flair for your subject that allows you to see the value of your work and its wider significance as a matter of instinct, then having to demonstrate these things in order to get funded or published may be good discipline, and not such a bad thing after all.

Bruce Yardley
University of Leeds
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$_2^-$, S$^-$, SO$_4^{2-}$ and NH$_4^+$, to be released. Metamorphic fluids are predominantly H$_2$O; 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$_2$S, 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...
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$_2$O, 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 volatileised 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$_2$O 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 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.

ACKNOWLEDGMENTS

I am grateful to James Connolly, Håkon Austrheim and Bjørn Jamtveit for comments.

REFERENCES

ALVIN VAN VALKENBURG AWARD TO MAIK LANG

Maik Lang, a research scientist at the Department of Geological Sciences of the University of Michigan, has been selected to receive the 2010 Alvin Van Valkenburg Award. The award will be presented on 27 June during the Gordon Research Conference on Research at High Pressure, which will be held at Holderness School, Holderness, New Hampshire, from 27 June to 2 July, 2010. The Gordon Conference on Research at High Pressure is one of the longest-running Gordon Conferences and covers a wide range of high-pressure research areas, from planetary interiors to novel high-pressure material structure. Traditionally the attendees of this conference have honored a promising young scientist conducting high-pressure research. The award is named after Alvin Van Valkenburg, inventor of the diamond anvil cell and one of the most important and best-loved pioneers in the field of high-pressure research.

Maik has been a member of Rod Ewing's research group for over three years. During the first two years, he was supported by the German Science Foundation as a postdoctoral fellow. He worked on radiation effects as part of the BES/DOE team. This past year, he was supported by the Energy Frontier Research Center – Materials Science of Actinide Materials, with a research focus on the behavior of materials under extreme environments (theme #3 of the EFRC).

DEXTER PERKINS, NORTH DAKOTA PROFESSOR OF THE YEAR

Dexter Perkins III has been recognized as the 2010 North Dakota Professor of the Year. Dex has worked diligently for the past 15 years to improve geoscience education at all levels. He is an international leader in the scholarship of teaching and learning, and has made important contributions to the design and implementation of active classroom practices, assessment of learning, and research on the cognitive aspects of student learning. In addition to his mineralogy course, he also teaches introductory environmental geology, routinely offers field experience to students, and supervises students in independent research projects. He developed the Geoscience Digital Image Library (GeoDIL, www.geodil.com/index.asp) and has shared his experience by contributing over 100 teaching activities, essays, and articles to the Teaching Mineralogy and Teaching Petrology collections through the On the Cutting Edge program for professional development of geoscience faculty (http://serc.carleton.edu/). He was one of the authors in the Elements’ teaching issue (volume 3, number 2, 2007).

ERIC ESSENE 1939–2010

Eric J. Essene died on May 20, 2010, at home in Ann Arbor, Michigan, following a courageous battle with cancer. Eric Essene completed his PhD at the University of California, Berkeley, in 1967 under the direction of William S. Fyfe. He joined the University of Michigan as an assistant professor in 1970, where he enjoyed a very productive and distinguished career, retiring in 2009 as the William C. Kelly Chair of Geological Sciences. Author of well over 200 scientific publications in peer-reviewed journals, Professor Essene made numerous and profound contributions in broad areas of mineralogy, petrology, and geochemistry. Another of Eric’s enduring legacies is his direction and codirection of over 100 MS and PhD students, many of whom have gone on to stellar careers in the geosciences and are themselves training the next generation of geoscientists. Eric Essene received many awards and honors, including the Bowen Medal from the American Geophysical Union in 1991, the first Sokol Award for excellence in graduate education of the sciences from the University of Michigan in 1993, and the Penrose Medal for lifetime achievement from the Geological Society of America in 2010. He was elected Fellow of the Mineralogical Society of America in 1981 and Fellow of the American Geophysical Union in 1991. For the last several years Eric had not been able to attend scientific meetings. He kept in touch with the scientific community—often daily—through the MSA talk list. The MSA talk list enabled Eric to continue to engage fully in the intellectual discourse at which he clearly excelled and which he deeply loved. Our scientific community has lost a vibrant and dynamic colleague who possessed a keen, adventurous intellect. He will be greatly missed! Donations in honor of Eric can be made to the Eric J. Essene Endowment for Graduate Student Fellowships c/o Dept. of Geological Sciences, University of Michigan, 2534 C. C. Little Bldg, Ann Arbor, MI 48109-1005 or online at www.lsa.umich.edu/alumni/giveonline.

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Håkon Austrheim is a professor of metamorphic petrology at the Physics of Geological Processes (PGP) center, University of Oslo. His research is field based, and his main interests are the role of fluids in metamorphism and metasomatism of the deep crust and, in particular, how fluid-driven eclogite formation influences the petrophysical properties and consequently the geodynamics of collision and subduction zones. He is currently working on CO₂ sequestration in ultramafic rocks and applies field data and principles from metamorphic petrology to environmental issues.

Wolfgang Bach completed a PhD in 1996 at the University of Gießen, Germany, where he had received his Diploma in mineralogy five years earlier. Between 1996 and 2005 he worked at the Woods Hole Oceanographic Institution on deep-sea hydrothermal processes. He is currently a professor at the University of Bremen, where he leads the “Petrology of the Ocean Crust” research group. His research interests include hydrothermal geochemistry, ocean–crust–mantle geochemical exchange budgets, fluid–rock interactions, and geomicrobiology. He has spent almost two years at sea on various drilling and diving expeditions.

James A. D. Connolly is a professor in the Earth Science Department of the Swiss Federal Institute of Technology. He was born on the muddy shores of the Gowanus Canal in Brooklyn, New York, and received a BA in geology from Colby College in 1979, an MSc in geology from Arizona State University, and a PhD in geochemistry and mineralogy from the Pennsylvania State University in 1987. His research interests include the role of two-phase flow in the expulsion of fluids from rocks and the coupling of petrologic and geophysical processes.

Gretchen L. Früh-Green is a senior research scientist at the Institute of Geochemistry and Petrology of the ETH Zurich, where she leads the Marine Geology and Geochemistry group. She and her students are active in petrological and geochemical studies of fluid–rock–(microbe) interaction and geochemical fluxes associated with the alteration of submarine crustal and mantle sequences in various tectonic environments as exposed in modern ocean basins and in ophiolites. Many of these studies focus on serpentinization processes and understanding the production of volatiles and hydrocarbons during hydrothermal activity at slow-spreading ridges, and they have resulted in the discovery of new hydrothermal systems on the seafloor.

Bjørn Jamtveit is a professor of petrology at the University of Oslo and director of PGP (Physics of Geological Processes), a Norwegian Center of Excellence at the University of Oslo. He received his PhD in Oslo in 1990 and spent the next two years as a postdoc at the University of Bristol. Bjørn’s main research interests are in the general area of fluid–rock interaction, and in particular in the behavior of such systems in far-from-equilibrium situations. His research includes studies of fluid flow during metamorphism, oscillatory mineral growth in hydrothermal environments, the coupling of metamorphic reactions to fluid migration and fracturing, and pattern formation during travertine growth. In the cross-disciplinary PGP center, these and other problems are addressed by a combination of field studies, computer simulations, and physical experiments.

Timm John is a metamorphic petrologist–geochemist at the Institut für Mineralogie at the University of Münster, Germany. He has broad interests in the evolution of microstructures in minerals as a result of reequilibration mechanisms associated with changes in physical and chemical conditions. His current work is on the role of aqueous fluids in such processes and involves a spectrum of analytical techniques to study fluid–mineral interactions. He studied physics at the University of Newcastle, Australia, and geology at Birkbeck College, London, UK, before completing a PhD at the University of Cambridge.

Andrew Putnis is a professor of mineralogy at the University of Münster, Germany. He has broad interests in the evolution of microstructures in minerals as a result of reequilibration mechanisms associated with changes in physical and chemical conditions. His current work is on the role of aqueous fluids in such processes and involves a spectrum of analytical techniques to study fluid–mineral interactions. He studied physics at the University of Newcastle, Australia, and geology at Birkbeck College, London, UK, before completing a PhD at the University of Cambridge.

Henrik Svensen is a senior researcher in geology at the University of Oslo (Physics of Geological Processes), where he received an MSc on contact metamorphism in 1996 and a PhD on the geochemistry of metamorphic fluids in 2000. The last ten years of his research have been devoted to fluid flow and to fluid expulsion in sedimentary basins affected by igneous intrusions. Contact metamorphism, fluid generation, and fluid venting are among his central research topics, with key field areas located in South Africa and Siberia, supplemented by borehole and seismic studies in offshore Norway. He was awarded the status of Young Outstanding Scientist by the Norwegian Research Council in 2007, as a result of a project devoted to the connections linking large igneous provinces, volcanic basins, and environmental crises.
Tracking changes over time

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Metamorphic rocks make up a substantial portion of the Earth’s evolving lithosphere. Understanding metamorphism is central to interpreting large-scale geodynamic processes and interactions among the geosphere, the hydrosphere, the atmosphere, and the biosphere. In this issue of Elements, we emphasize the critical role of fluids in controlling the rates and mechanisms of metamorphic processes. The patterns observed over a wide range of scales in metamorphic rocks are not just passive recorders of tectonic events. They also reveal that the complex coupling of chemical reactions, transport, and deformation processes that constitute metamorphism sometimes operates surprisingly far from equilibrium.

KEYWORDS: metamorphism, rates of metamorphism, role of fluids, metasomatism, effects of metamorphism, prograde, retrograde

CHANGE
According to Winkler (1979), “Metamorphism is the process of mineralogical and structural changes of rocks in their solid state in response to physical and chemical conditions which differ from the conditions prevailing during the formation of the rocks; however, the changes occurring within the domains of weathering and diagenesis are commonly excluded.” Yet, in terms of the processes involved, there is no sharp distinction between diagenesis, weathering, and metamorphism. Neither is there any discontinuity between metamorphism and the onset of igneous processes during partial melting of metamorphic rocks at high temperature.

Although the very concept of metamorphism implies change, the study of metamorphic rocks has, until recently, focused mainly on the observed state of the rock, rather than on the change itself. This is illustrated by the recent volume Landmark Papers: Metamorphic Petrology, published by the Mineralogical Society of Great Britain and Ireland (Evans 2007). Out of 15 key papers from the period 1912 to 1987, only one (Wood and Walther 1983) explicitly and quantitatively addresses the timescales of metamorphic processes. This reflects the fact that time was not considered as a variable in most of the literature on metamorphism until the late 1970s. However, important advances toward quantifying metamorphic processes were made during this period. Early works on the kinetics of metamorphism include Brown, Fythe, and Turner (1962); Martin and Fythe (1970); Elliott (1973); Fletcher and Hofmann (1974); Loomis (1976); and Fisher (1978) and references therein. However, even in the 1980s, time was mainly considered to be the number of years since metamorphism occurred.

This is not to imply that metamorphic petrologists were uninterested in the processes of metamorphism until recently. Field and petrographic observations were frequently interpreted in terms of underlying processes in a qualitative way. However, the complexity of metamorphic rocks made it difficult to develop models for the processes that were both quantitative and conceptually realistic. Moreover, the timescale of metamorphism makes it challenging to study experimentally under conditions resembling nature. Now, with the developments in computation and the conceptual advances made in studies of complex, nature-like systems, the situation has changed dramatically. We now have the tools to investigate processes in many complex systems in an effective way, and this also applies to metamorphic rocks. Often, the challenge is more in how to constrain and test models of metamorphism than in carrying out the modeling itself.

Thus, from a conceptual point of view, time has now become the fourth dimension, in which the patterns and properties observed in rocks have evolved. Accordingly, over the last two decades, there has been a gradual shift in focus from structures to processes in the study of metamorphic environments. Metamorphic petrologists have become increasingly interested in metamorphism, that is, the change itself, and thus in understanding how the observed pattern came to be. Increasing efforts, with recently developed instruments and techniques, are now being made to quantitatively characterize the often very complex patterns in metamorphic rocks. The art of petrography, which by many was considered obsolete, is about to become fashionable again, as the focus changes from being to becoming.

Figures 1–5 illustrate some of the most important changes that can take place during metamorphism. These include changes in mineralogy and mineral composition (Figs. 1, 2), microstructure (Fig. 3), and rock composition (Fig. 4). Such changes may have profound effects on physical properties, such as density (Fig. 1), porosity, strength, and mode of deformation (cf. Escartin et al. 2001). Through its effects on rock properties, metamorphism can significantly influence the way the Earth’s crust responds when subjected to the forces of plate tectonics. It affects the way mountains form and evolve (Fisher 2002) and thus also the evolution of landscapes at the Earth’s surface. Metamorphic rock properties affect how oceanic plates bend and are subducted during collision with a continent (Escartin et al. 2001;
Ranero et al. 2003), and through its effects on fluid migration, metamorphism also influences the chemical differentiation of the Earth’s crust, including the formation of major ore deposits (e.g. Phillips and Powell 2009).

CAUSES AND RATES

Metamorphism occurs whenever a rock is subjected to conditions under which its mineral assemblage is no longer stable (for either thermodynamic or kinetic reasons). In systems lacking fluid, the rate of change is generally too slow to have significant effect on rock properties (Putnis and John 2010 this issue). In this issue of Elements, we are mainly interested in metamorphism that has a direct or indirect effect on the evolution of the Earth’s crust, on a scale that is observable in the field, and therefore in metamorphism in the presence of fluids.

As Connolly (2010 this issue) points out, metamorphism during a rise in temperature (prograde metamorphism) is normally associated with fluid production through metamorphic devolatilization reactions, where structural water is released from minerals (Fig. 2). In this case, the rate of heating controls the rate of metamorphism and thus the rate of fluid production. Large-scale heating associated with plate tectonics is a slow process. A temperature increase of a few degrees per million years produces average fluid fluxes on the order of $10^{-10}$ m$^3$ m$^{-2}$ s$^{-1}$, while the fluid-producing reactions actually take place. Although this may seem like a small amount, the real fluid migration velocity through the pores or fractures of the rock is approximately equal to flux/porosity. Even for a relatively high porosity of 1%, the true fluid migration velocity would be on the order of 0.3 m/year, and if the fluid is focused into preferred channels, local velocity would increase even further. Thus, even during prograde regional metamorphism, fluid flow rates and associated flow-related transport processes can, at least locally, be significant on human timescales.

Fluid production driven by local heat sources, such as igneous intrusions (contact metamorphism), can be even faster. During the development of large igneous provinces, the emplacement of large volumes of magma into sedimentary basins often results in the release of metamorphic fluids at such rates and in such quantities that they can even affect global climate and cause major perturbations in the biosphere, as for example during the Permian–Triassic extinction event (Svensen and Jamtveit 2010 this issue).

**Figure 1** Dark, fine-grained basalt, such as (A), is transformed into a spectacular, coarse-grained, green and red eclogite (B) during metamorphism at high pressure and temperature. During the metamorphic transition, augite (pyroxene), plagioclase, and olivine in the basalt are transformed into garnet (red), omphacite (green), and clinzoisite (white). Density increases from about 2.9 g/cm$^3$ to about 3.5 g/cm$^3$, making the rock’s transition important for large-scale geodynamic processes, including basin subsidence and subduction.

**Figure 2** Dark, fine-grained sedimentary shale, such as (A), is transformed at intermediate pressure and temperature into bright, shiny, mica schist with large garnet crystals (B). During this transition, the rock loses several weight percent H$_2$O. Such a transition is an important source of metamorphic fluid. Scale for these samples is similar to that of Figure 1.
In contrast to prograde metamorphism, which produces fluids at a rate controlled by heat transport, retrograde metamorphism is normally associated with consumption of fluid. This happens when a metamorphic rock formed at elevated temperature is exposed to fluid at lower temperature. Obviously, the rate may be limited by the rate of fluid supply. In some cases, in particular where fluid supply is controlled by seismic activity and the generation of fracture networks, fluid migration rates can be much greater than those associated with prograde metamorphism. Fast migration increases the likelihood that fluid will come into contact with rock under far-from-equilibrium conditions. In such situations, volume changes associated with rapid reaction lead to large perturbations of the local stress field. Retrograde metamorphism is therefore a very dynamic process, in which reaction, deformation, and transport are intimately coupled. It often results in striking patterns, such as metasomatic fronts, complex replacement structures (Putnis and John 2010), and reaction-driven fracture patterns (Fig. 5; Jamtveit and Austrheim 2010 this issue). These nonequilibrium patterns, which are observable from the nanometer to the outcrop scale, contain key information about the mechanisms of retrograde metamorphism and thus about the way the Earth’s crust becomes hydrated and, in some cases, carbonated.

Perhaps the most important example of retrograde metamorphism occurs below the seafloor. In this case, metamorphism has a direct impact on the biosphere. Along spreading ridges, the chemical ingredients provided by the expelled fluids drive hydrothermal alteration of the mafic and ultramafic igneous rocks. These fluids are also critical in sustaining the local biosphere (Bach and Früh-Green 2010 this issue).

Hence, both prograde and retrograde metamorphism are key players in the dynamic evolution of the substratum to which life itself is anchored, and the metamorphic fluid is often the medium through which the biosphere and geosphere are connected.

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Metamorphism: The Role of Fluids

Bjørn Jamtveit* and Håkon Austrheim*

The evolution of the Earth’s lithosphere is affected in a major way by metamorphic processes. Metamorphism affects the lithosphere’s chemical and mineralogical composition, as well as its physical properties on scales ranging from a nanometer to the size of tectonic plates. Studies of metamorphism during the last couple of decades have revealed that fluids are as important in a changing lithosphere as water is in the biosphere. History-dependent characteristics of metamorphic rocks, such as their microstructure, compositional variation, and deformation features, reflect the dynamics of fluid–rock interactions. Migration of the fluids produced during prograde metamorphic processes or consumed during retrogression links metamorphism at depth to the evolution of the hydrosphere, the atmosphere, and the biosphere.

Keywords: metamorphic fluids, rate of metamorphism, mechanical effects, fracture patterns

THE EVOLVING LITHOSPHERE

Most of the Earth’s lithosphere evolves under conditions where metamorphic processes are the dominant transformation mechanism. From the early 1980s until quite recently, the metamorphic evolution of the Earth’s crust was to a large extent regarded as a more or less passive recorder of its pressure and temperature history, as dictated by plate tectonics (cf. England and Thompson 1984). Today, however, metamorphism is recognized to be almost as dependent on the presence of fluids as biological systems are on the presence of water (Yardley 2009). Fluid–rock interactions during metamorphism can control large-scale geodynamic processes by defining mechanical strength, and thus they influence the support of mountain belts (Jackson et al. 2004). Fluid–rock interactions can also govern lithosphere density and thus the subsidence of sedimentary basins (Kaus et al. 2005), and they can affect the volatile content of the mantle wedge during subduction, thereby affecting arc magmatism (Kerrick and Connolly 2001a). Metamorphic volatilization processes may furthermore affect the elastic properties of rocks (Boudier et al. 2010) and thus impact our ability to interpret seismic data.

The release and consumption of fluids during metamorphism are two fundamentally different processes. When igneous and metamorphic rocks formed at elevated temperature are exposed to water or other fluids at lower temperature, they usually react, forming minerals with a higher proportion of volatile components. Retrograde metamorphism therefore depends critically on the nature and abundance of externally derived fluids (Jamtveit et al. 2000, 2008). More than any other factor, including pressure and temperature changes, the timing of retrograde metamorphism is controlled by external fluid supply. Near or at the Earth’s surface, similar rock–fluid reactions play an important role in weathering (Røyne et al. 2008), which also involves natural sequestration of CO₂ by carbonate mineral formation (Kelemen and Matter 2008).

A fundamentally different situation arises when volatile-rich sedimentary or metamorphic rocks experience prograde metamorphism. A key process in this case is the expulsion of fluid from the sites where it is generated (Connolly 2010 this issue). Migration of fluids to and from the sites of retrograde and prograde metamorphism plays a key role in the global water and carbon cycles and ultimately in the coupling of metamorphism with the near-surface hydrosphere, atmosphere, and biosphere (e.g. Kerrick and Connolly 2001b; Svensen et al. 2004; Rüpke et al. 2004; Kelemen and Matter 2008).

METAMORPHIC RATE CONTROLS

Interpretation of metamorphic mineral assemblages and microstructures, within the conceptual framework of equilibrium thermodynamics, has provided valuable insight into the conditions of formation of metamorphic rocks (e.g. Spear 1995). The equilibrium assumption is based on the idea that metamorphic reactions are fast compared to the rate of change of externally controlled variables, such as temperature and pressure. Although the equilibrium approach may be a good approximation in some situations, it ignores all history-dependent features of the rocks, thereby excluding the most important sources of direct information about the underlying processes that generated the rock (Fig. 1). The central role of kinetics in controlling both microstructures and mineral assemblages has been illustrated by numerous experimental, theoretical, and petrographic studies over the last two decades (for example, Rubie 1998; Lütgge et al. 2004). Several of these studies identify slow nucleation as a key limiting factor. Moreover, since most phase transformations take place by dissolution–reprecipitation reactions (Putnis 2009), it is clear that fluids are a central ingredient in metamorphism, even when their role is merely catalytic. Limited or transient availability of intergranular fluids has been proposed as the most plausible explanation for slow reaction rates during regional metamorphism (Baxter 2003).
A generic rate law for metamorphic reactions may be expressed by the equation:

\[ R \approx k(T) \Delta G^n A_s \]  

where \( R \) represents the rate of reaction (for example, in mol m\(^{-3}\) s\(^{-1}\)), \( k(T) \) is a temperature-dependent kinetic rate constant, \( \Delta G \) represents the overstepping of the equilibrium condition (or chemical affinity), \( n \) is a constant, and \( A_s \) is the specific surface area. In most models of metamorphic kinetics, the rate of reaction, \( R \), falls with time because the reactions push the system towards equilibrium, causing a decrease in the reaction affinity. Also, as the reaction progresses, the reactive mineral surface area decreases, the amount of reactants diminishes, and the reactant grain may be shielded from the fluid by product phases (e.g. Martin and Fyfe 1970). Such models, however, largely ignore the complexity of reactive fluid–mineral interfaces.

Recent studies have demonstrated that the processes taking place at the interface across which fluids and minerals interact is far more complex than previously thought. The interface itself can evolve in a highly dynamic way, leading to complex pore structures and fracture patterns (e.g. Putnis 2009; Renard et al. 2009). Most importantly, these surface processes generate reactive surface areas that are much larger than those predicted by existing reactive-transport models, and they continue generating new surface area by enhancing fracturing and porosity as the reactions proceed. This is absolutely essential for maintaining reasonable rates of volatilization in the Earth’s crust. Mechanical effects such as reaction-driven fracturing can increase reactive surface area, so for a while, the reaction rate accelerates with time rather than continuously decreasing from the onset of reaction (Røyne et al. 2008; Jamtveit et al. 2009).

For small systems, such as inside mineral inclusions, mechanical effects can have the opposite effect, slowing or even halting reaction progress by preventing the system from expanding, a phenomenon known as mechanical closure (Schmid et al. 2009).

**FLUID PRODUCTION**

Prograde metamorphism in most cases produces fluids through devolatilization. These released fluids tend to move upward because of the difference between their density and the density of the surrounding rock. It has long been recognized that rocks undergoing prograde metamorphism have a discrete fluid phase only during the time that devolatilization reactions are actually taking place (Walther and Orville 1982). If the rate of fluid production is high relative to the rate at which fluid can escape through preexisting permeability, fluid escape will be associated with local hydrofracturing (Flekkøy et al. 2002). Evidence is seen in abundant veining during regional metamorphism of volatile-rich rocks (e.g. Fisher and Brantley 1992; Widmer and Thompson 2001).

The intimate coupling between devolatilization and fluid migration is evident from numerical modeling (Connolly and Podlachikov 1998). Simulations suggest that fluid loss, even on a crustal scale, generates porosity waves as focused
pulses of fluid. The existence of such waves is supported by observations of pipe-like, fluid-release structures associated with the intrusion of sills into sedimentary basins, where heat from the sills has driven fluid production, causing an increase in fluid pressure (Fig. 2; Jamtveit et al. 2004). Recent studies have provided strong evidence that the release of greenhouse gases by metamorphic fluids produced in carbon-rich sedimentary rocks has triggered some of the largest climate changes in the history of the Earth (Svensen et al. 2004).

**FLUID CONSUMPTION**

When metamorphic rocks cool, they often do not back-react with fluids to form a lower-temperature mineral assemblage. The main reason is that fluids produced during prograde metamorphism escape and are no longer available. Supply of external fluids is therefore essential for retrograde metamorphism to proceed. Furthermore, if such external fluids are supplied, they are likely to be strongly out of equilibrium with the rock that they infiltrate. Consequently, retrograde volatilization is often fast and can produce a variety of complex features typical of far-from-equilibrium systems, including dendritic mineral growth and oscillatory variations in the composition of mineral grains.

In a system that is essentially closed to all major components, except the externally supplied volatile components (usually H$_2$O or CO$_2$), volatilization normally results in a significant increase in total solid volume. Under far-from-equilibrium conditions, this can produce local overpressures far beyond what is required to fracture the rock (e.g. Ostapenko 1976; Wheeler 1987). Because the fracturing generates new surface area where volatilization begins, the overall rate of volatilization increases, allowing pervasive fluid–rock interaction at considerably larger scales than would otherwise be possible.

**Serpentinization**

Serpentinization is probably the most important metamorphic hydration process. The reaction of olivine-rich, mantle-derived peridotite to form serpentine is associated with a reduction in rock density from ~3.3 g/cm$^3$ to less than 2.7 g/cm$^3$. Hydration of end-member forsterite (Mg-olivine) can be described by the reaction:

$$2\text{Mg}_2\text{SiO}_4 + 3\text{H}_2\text{O} \rightarrow \text{Mg}_5\text{Si}_2\text{O}_5(\text{OH})_4 + \text{Mg(OH)}_2$$

forsterite + water $\leftrightarrow$ serpentine + brucite

In a natural system, the Fe component of the original olivine is at least partly absorbed by a corresponding Fe component in the brucite. Iron often subsequently contributes to the very important redox reaction that oxidizes ferrous Fe to ferric Fe to form magnetite (Fe$_3$O$_4$), while hydrogen from the water is reduced to H$_2$ (Peretti et al. 1992; Bach et al. 2006). The hydrogen generated can sustain microbial communities (Takai et al. 2004). In the presence of carbon, serpentinization can produce CH$_4$, which has been observed seeping from mid-ocean ridges (Charlou et al. 1998). Such an environment, with possible production of abiotic methane and other hydrocarbons, is regarded as the most likely location for the origin of life (Konn et al. 2009).

Complete serpentinization results in a solid volume increase of nearly 50% and causes a pronounced change in rheology, magnetic properties, and porosity. Reaction (2) also produces considerable heat ($\approx$290 kJ/kg forsterite consumed); serpentinization has therefore been suggested as an explanation for observed heat-flow anomalies in ocean basins (Delescluse and Chamot-Rooke 2008).

The serpentinization rate is highest at temperatures close to 300°C (Martin and Fyfe 1970). At lower temperatures, the kinetic constant, $k(T)$, limits the overall rate, whereas at higher temperatures, the approach to equilibrium decreases the affinity of hydration, $\Delta G$, and thus the reaction rate. The higher the reaction rate and the associated rate of rock-volume increase relative to the rate of ductile deformation, the more probable it is that serpentinization causes fracturing, because there is insufficient time for the rock to accommodate the stress of the extra volume generated. Figure 3 shows fracture patterns developed in serpentinized peridotites. The characteristic length scales of the fractures vary over more than 4 orders of magnitude, from a few meters to less than 100 micrometers.

**Natural CO$_2$ Sequestration**

In the presence of C-bearing fluids, carbonation of peridotite (Fig. 4) produces even more heat than hydration, and the process is expected to be even faster than hydration at temperatures greater than 200°C (Kelemen and Matter 2008). Carbonation is a natural CO$_2$-sequestration process, and although the maximum rate of carbonation occurs at temperatures below the metamorphic regime (150–200°C depending on pressure), the physical and chemical processes involved, and their coupling, are very similar.

![Figure 2](image-url)  
**Figure 2** A satellite image from the Loriesfontein area in the western part of the Karoo Basin, South Africa. The road in the upper left of the image provides scale. The dry landscape is dominated by a relatively flat topography with numerous circular hills. These hills, seen as bright “blobs” in the image, are hydrothermal pipes filled with brecciated and metamorphosed shale. They formed as methane degassed during contact metamorphism of black, organic-rich shale, some 182.5 million years ago. The dolerite intrusions responsible for the contact metamorphism are now about 100 meters below the surface. The methane emitted at the paleosurface contributed significantly to global warming in the Jurassic (Svensen and Jamtveit 2010). The pipes are typically 100–150 meters in diameter.
Petrographic studies indicate that C-bearing fluids often infiltrate peridotite through preexisting fractures developed during seafloor serpentinization. However, carbonate mineral growth itself produces sufficient swelling pressure (e.g. MacDonald and Fyfe 1985) to generate additional fractures. There is little doubt that both serpentinization and carbonation of peridotite are to a major extent influenced by mechanical processes, in particular, generation of reactive surface area by fracturing over a wide range of scales.

**Mechanical Effects**

Most experimental studies on the rates of metamorphic reactions have been carried out using fine-grained rock powders; fracturing cannot be observed. This limits the relevance of the results and the kinetic models based on them. Peridotites, in particular, are often coarse grained and almost invariably undergo extensive fracturing during reaction with fluids (e.g. MacDonald and Fyfe 1985; O’Hanley 1992; Iyer et al. 2008). Some of this fracturing can occur as a response to far-field (tectonic) stresses, but there is ample evidence that the volume change associated with the serpentinization process itself generates stresses sufficient to fracture rocks and mineral grains under a range of conditions (e.g. Iyer et al. 2008; Jamtveit et al. 2008).

To our knowledge, no experimental studies so far have examined the effect of fracturing on metamorphic reaction rates. However, numerical models (e.g. Jamtveit et al. 2008; Røyne et al. 2008) have produced micro- and outcrop-scale structures very similar to those observed in natural systems (Fig. 5). A key feature of such models is that the reaction-driven fracturing accelerates the rate of reaction by increasing the reactive surface area at an early stage of the reaction. Furthermore, because the length of the fractures can easily exceed the typical diffusion distance, the overall volume of rock affected by reaction with fluid is much larger than predicted by a pure reaction–diffusion model. This argument is further strengthened by the fact that fluid-consuming reactions normally increase solid volume, and in the absence of fracturing, preexisting pores would rapidly be clogged by reaction products, blocking fluid transport and halting further reaction.
OPEN VERSUS CLOSED SYSTEMS

The issue of how to deal with thermodynamic equilibrium in open systems relevant to metamorphic rocks was the subject of heated debate in the 1950s and 1960s (Weill and Fyfe 1964 and references therein). In the context of the preceding discussions on metamorphic kinetics, the question of how to deal with open systems reappears as a central issue. The main challenge is the coupling between mass transfer and stress generation. In a reacting rock volume, where open system behavior is possible, there are two limiting scenarios. A system can change its volume and thus perturb the local stress field, or it can maintain a constant volume by exchanging mass with its environment. In practice, a combination of these two occurs, but one or the other often dominates.

The limited volume of fluids available during metamorphism often puts severe constraints on open-system behavior. The early stages of seafloor serpentinization usually lead to very modest changes in rock composition (Bach et al. 2006). This stage is invariably associated with extensive fracturing and formation of characteristic mesh textures (Fig. 5c). Later alteration under open-system conditions follows more of a volume-for-volume replacement process, which is common in other metamorphic processes characterized by high fluid fluxes, such as albitization, rodingitization, scapolitization, etc. Metamorphism accompanied by extensive alteration of chemical composition is often referred to as metasomatism and usually occurs in regions with high thermal gradients, such as around cooling intrusive bodies, or localized zones of deformation that act as fluid channels. Pervasive retrograde metamorphism outside such zones is almost invariably associated with reaction-driven fracturing, highlighting the general importance of mechanical processes for fluid–rock reactions in the lithosphere.

FUTURE PERSPECTIVES

Earth science is no longer a narrative about the past. Increasing the relevance of our science for resolving challenges connected with energy, the environment, water, the carbon cycle, and all natural resources demands focus on the future of our planet. This requires paying more attention to the processes that shape our planet than to its equilibrium state. The future of metamorphic petrology as a relevant field of research requires that we increase our focus on those features of metamorphic rocks that act as a memory of the underlying processes. Such features are not the equilibrium features. More attention is required on the complex patterns of metamorphic rocks, and in particular on the microstructures and their coupling to both chemical and physical processes. We furthermore believe that fluids are essential in controlling the evolution of the lithosphere and that they firmly connect metamorphic processes to the evolution of the hydrosphere, biosphere, and atmosphere.

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Replacement Processes in the Earth’s Crust

Andrew Putnis* and Timm John*

INTRODUCTION

Metamorphic petrology is often concerned with assigning a specific range of pressure and temperature (P, T) conditions over which an observed mineral assemblage is stable. From a sequence of stable mineral assemblages, usually interpreted from micro-structures, textures and inclusions, a schematic pressure–temperature–time (P–T–t) path can be derived that provides valuable constraints on the large-scale geodynamic processes that drive the metamorphism. The metamorphic response to a geodynamic process does however depend on the mechanism of the various phase transitions and on the relative roles of solid-state diffusion (where the rock is considered to be dry) and dissolution–precipitation (in the presence of a free fluid phase). In this context, the mechanism of the metamorphic reactions that take place with increasing metamorphic grade, for example, the isochemical reaction from kyanite to sillimanite, was considered by Carmichael (1969). From a textural study of thin sections, he noted that sillimanite does not grow directly from kyanite but forms by a sequence of dissolution–transport–precipitation sub-reactions. First the kyanite reacts with quartz and K+-bearing fluid to form a solution through which the components diffuse a short distance in the rock and precipitate muscovite. The muscovite in turn reacts with the fluid to form sillimanite and quartz. More complex reactions were explained by similar schemes involving fluid and mass transport, albeit on a small scale.

Carmichael (1969) points out that, even in a closed isochemical system, local mass transport must occur during the re-equilibration of a rock. Thus on a small spatial scale the system is chemically “open,” while on a larger scale it may be closed. Metamorphism accompanied by a change in rock composition is referred to as metasomatism and is normally assumed to be the response to fluid-controlled mass transfer, rather than purely to changes in P–T conditions. However, Carmichael’s example illustrates that the spatial scale at which a system is claimed to be open might be somewhat arbitrary. Thus, one may ask whether the distinction between metamorphism and metasomatism is really useful, or even valid? Is it only a matter of spatial scale or degree of compositional change? Can we recognise the difference between a reaction driven by a change in P–T conditions and one driven by the infiltration of a fluid out of equilibrium with the parent assemblage?

In this article, we focus on reactions that occur when an essentially dry, low-permeability rock is infiltrated by a fluid that induces re-equilibration of the mineral assemblage. Such rocks make up most of the continental crust. Fluid infiltration may or may not be associated with a tectonic event characterized by changing pressure and temperature, and the effect of the fluid composition in changing the mineral assemblage of the rock can vary over a wide spectrum. In a fluid-saturated sedimentary basin undergoing progressive burial, diagenesis and metamorphism, the scale of mass transfer and fluid transport may be limited (Yardley 2009). Here we are not explicitly concerned with the scale of mass transport, but rather with the mechanism of re-equilibration at the fluid–mineral interface.

To determine the mechanism of metamorphic reactions, we need to find examples of interfaces and reaction textures that contain both the “before” (the protolith) and the “after” mineral assemblages – in other words, case studies where the process of conversion is “frozen in”. In the following examples, we illustrate some aspects of the role of fluids in metamorphic reactions and discuss how reactive fluids can pervasively infiltrate a rock. We argue that fluids not only trigger sluggish isochemical reactions but also may drive reactions through compositional changes of the affected system at constant P and T; further, we contend that the common mechanism for replacing one rock type by another is dissolution–precipitation. We use examples...
REPLACEMENT PROCESSES AT LOWER CRUSTAL CONDITIONS AND IN SUBDUCTION ZONES

Metamorphism, fluid flow and mass transfer play a major role in processes in the deep crustal roots of mountain belts and in subduction zones (Austrheim 1987; Philpotts and Ague 2009). For example, the conversion of crustal rocks into eclogite is a very important transformation that takes place along low geothermal gradients. It is associated with changes in rheology, with earthquakes and with arc magmatism. However, geophysical measurements of subducting oceanic lithosphere have shown that eclogitisation of lower crustal rocks (e.g. oceanic gabbro) does not always take place as one would expect from the ambient $P-T$ conditions (Rondenay et al. 2008), and the same observation has been made for the roots of mountain belts (Jackson et al. 2004).

Figure 1 shows a well-studied example of a partial reaction in which granulite is transformed into eclogite in the Bergen Arcs region of western Norway, where the root zone of the former Caledonian mountain belt outcrops today. The eclogite formation is associated with fractures in the rock, and Austrheim (1987) argues that the interface between the eclogite and granulite represents the limit of infiltration of the fluid that promoted the eclogitisation. This suggests that the surrounding granulite was preserved within the stability field of eclogite because element mobility by solid-state diffusion was not possible at the relevant temperature and timescale (Jamtveit et al. 1990).

Many studies of exhumed slices of formerly subducted oceanic rocks have shown that eclogitisation occurred exclusively in the parts of the outcrop, rocks and minerals where fluids infiltrated (e.g. John and Schenk 2003). In the case of a gabbro under low strain, this replacement occurred pseudomorphically, retaining the texture of the gabbro (Fig. 2). Only the eclogitisation itself and the reaction textures indicate fluid infiltration; the conversion of dry gabbro to essentially dry eclogite only locally resulted in the formation of hydrous minerals. The conclusion is that the gabbro-to-eclogite transformation was facilitated by fluid, which provided a faster means of material transport than solid-state diffusion. The process was dissolution, element transport through the fluid and re-precipitation of a more stable assemblage.

Further examples of how fluids affect metamorphic reactions are provided by the blueschist-to-eclogite and eclogite-to-blueschist transformations that are associated with well-known dehydration and hydration reactions (e.g. Peacock 1993). Field evidence shows that the flow field of fluids released from subducting slabs is channelized and that these fluids tend to react with their wall rocks (Breeding and Ague 2002; John et al. 2008). In the Tianshan mountains (China), initial eclogitisation (i.e. dehydration) of blueschists takes place along well-developed reaction selvages associated with veins several metres in length formed by external fluids. In our case study, a profile sampled perpendicular to a vein shows a transitional conversion from blueschist to eclogite towards the vein, which is accompanied by a gradual change in composition from Ca-poor to Ca-rich (Beinlich et al. 2010). Thermodynamic calculations for the two distinct bulk compositions – the Ca-poor blueschist (6–7 wt% CaO) and the Ca-rich eclogite (up to 16 wt% CaO) – indicate that both mineral assemblages are stable at the same peak $P-T$ conditions ($21 \pm 1.5$ kbar and $510 \pm 30^\circ$C); this is also confirmed by conventional geothermobarometry (Beinlich et al.)
In this example the transformation of blueschist to eclogite is driven by the change in bulk composition through interaction with the Ca-rich fluid, not by differences in lithostatic pressure or ambient temperature. The eclogite formed where the reactive fluid infiltrated the precursor blueschist. The progress of the reaction, manifested by the replacement of glaucophane by omphacite, as well as the progressive change in the bulk composition of the rock are dependent on the distance to the fluid conduit.

The fluid phase may play two roles in a metamorphic reaction. First, by providing a dissolution–transport–precipitation mechanism for an essentially isochemical reaction, it acts as a catalyst that plays only a kinetic role. On the other hand, the fluid can also affect the thermodynamics of a reaction by changing the chemical potential of so-called “mobile” components, and hence can affect the bulk composition of the system.

This is further illustrated by the case where a subducting slab becomes partly dismembered; then, some eclogite is exhumed and becomes (re)hydrated, and transforms back into blueschist (e.g. van der Straaten et al. 2008; Miller et al. 2009). Figure 3 shows part of an eclogitised pillow lava that has been transformed into blueschist along a pillow rim during retrograde metamorphism. Field observations and petrologic data indicate migration of a free fluid phase into the pillow interiors, forming a reaction zone. The interfaces between the precursor eclogite and the product blueschist (Fig. 3a, d) show a well-defined reaction front. At higher magnification, the parts that are almost completely converted to blueschist illustrate the replacement character of the transformation. Figure 3b shows the replacement of omphacite by glaucophane, caught in the act, with only small patches of omphacite left in the core. Mass-balance calculations for this reaction front and zone, using immobile trace elements as a reference frame, show an overall mass loss and a corresponding volume loss during the eclogite-to-blueschist transformation. During transformation, the rock gained Mg, Ni and Co and lost Si and Ca, implying that the fluid was in equilibrium with rocks of peridotitic composition prior to infiltration (van der Straaten et al. 2008).

Since the precursor eclogite had a lower water content than the blueschist, fluids had to be involved. Furthermore, the chemical changes across the reaction interface demonstrate that this was not an isochemical reaction. The interaction between the eclogite and the infiltrating fluid caused a significant mass loss to the fluid phase, resulting in an overall volume loss that allowed fluid infiltration and diffusion to proceed.

**THE REPLACEMENT OF ROCKS IN THE UPPER CONTINENTAL CRUST**

In our case study from the upper continental crust, we examine how fluid can change a rock composition, producing pseudomorphs of initial minerals and retaining the overall texture. We also show that replacement processes that reproduce natural textures can be achieved in very short times in laboratory hydrothermal experiments.

In the Bamble sector of southeastern Norway, outcrops of albite and unaltered granite and gabbro allow detailed studies of reaction mechanisms (Fig. 4a). Albite is estimated to have taken place at 350–450°C and 2–4 kbar (Nijland and Touret 2001).

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**FIGURE 3** Eclogite-to-blueschist transformation (van der Straaten et al. 2008). (A) Field image showing an eclogite pillow lava relict (green) that is partly replaced by blueschist (blue). The dashed line highlights the former outline of the pillow structure. (B) Back-scattered scanning electron micrograph showing the replacement of omphacite (Omp) by glaucophane (Glau), along sharp and irregular interfaces. (C) Thin section image showing the reaction interface, (D) A simplified representation of B showing the blue rock (blueschist) replacing the green rock (eclogite) along an irregular interface.
Individual grains of plagioclase feldspar in the protolith (composition ~An$_{20}$) were pseudomorphically replaced by albite (Engvik et al. 2008) (Fig. 4a). The reaction interface lies within each partially replaced single crystal and proceeded both through the solid mineral and along micro-fractures. The micro-structure shows a number of characteristic features of mineral replacement reactions:

- **Isovolumetric replacement**, i.e. the external dimensions of the parent plagioclase grains are preserved;
- A sharp reaction front, indicating that volume (lattice) diffusion played an insignificant or minor role in the reaction;
- Porosity (assumed to be interconnected) developed in the albite product, which allowed fluid and mass transfer by diffusion through the pores in albite to and from the reaction front;
- Preservation of the crystallographic orientation of the feldspar across the reaction interface.

Hydrothermal experiments on feldspar–alkali chloride equilibria have been carried out for many years (e.g. Orville 1972; Moody et al. 1985), but the replacement mechanisms have only recently been clarified (Labotka et al. 2004; Niedermeier et al. 2009; Hövelmann et al. 2010). The albitionisation reaction shown in a natural example from the Bamble sector (Fig. 4a) was reproduced experimentally in a hydrothermal reaction (600°C, 2 kbars, 18 days) between plagioclase (composition ~An$_{22}$) and an aqueous solution containing Na and Si (Hövelmann et al. 2010). Figure 4c is a cross section through a partially replaced crystal. Replacement takes place at the rim as well as along fractures. Quantitative compositional data indicate the loss of Ca, Al, K and trace elements to the fluid phase. If the experimental solution is enriched in $^{18}$O, this isotope can be used as a tracer for oxygen exchange during the replacement. Raman spectroscopy confirms that the $^{18}$O is incorporated into the silicate framework of the albite; thus, all elements are exchanged in this dissolution–precipitation process (Hövelmann et al. 2010).

An important issue arises from an interpretation of images such as Figures 4b and c. Partial replacement is one of the micro-structural criteria considered to be reliable indicators of a metamorphic reaction in P–T space, with the implication that the parent and product phases represent a ‘frozen-in’ stable coexistence at the reaction boundary (Vernon et al. 2008). However, in the case of the albitionisation reaction, the parent plagioclase and product albite clearly are not an equilibrium pair, and the interface between them represents the reaction between the plagioclase and an Na, Si-bearing fluid, with which it is out of equilibrium. The partial dissolution of plagioclase in this fluid generates an interfacial solution supersaturated with respect to albite, and equilibrium, if it exists at all, would be between this solution and the precipitating albite.

**INTERFACE–COUPLED DISSOLUTION–PRECIPITATION**

The examples above show that one mineral can be replaced by another in the presence of a fluid with an appropriate composition. A large number of experiments of salt systems, oxides, sulphides and silicates show that, at temperatures too low for solid-state diffusion to be effective on the observed length scales, micro-structures are produced by coupled dissolution and precipitation at a reaction interface (Putnis 2009).

When a fluid interacts with a mineral with which it is out of equilibrium, dissolution begins. At the fluid–mineral interface, even the dissolution of a few monolayers of the parent may result in a new fluid composition that is supersaturated with respect to a more stable phase. The precipitation of this phase on the surface of the parent phase depends on the kinetics of nucleation. If the parent and...
potential product phase have some common crystallographic relationships, this favours epitaxial nucleation. In the case of a feldspar replaced by a feldspar, the parent and product share the same orientation across the reaction interface.

Where there is a lower degree of lattice matching, the product phase is likely to be polycrystalline with no obvious epitaxy. Nucleation of the product is also favoured if there is a high value of supersaturation at the fluid–mineral interface (i.e. a low solubility of the product phase). Dissolution and precipitation may be very closely coupled, resulting in an exact pseudomorph preserving nano-scale features of the parent, or they can become spatially separated, depending on whether the overall reaction is dissolution controlled (the first case), or precipitation controlled (the second case) (Xia et al. 2009).

Once the reaction interface between the parent and product phase is established, its propagation through the parent depends on the continued availability of pathways for fluid transport to and from this interface. The generation of porosity in the parent phase is therefore an integral requirement for the reaction to continue beyond producing a superficial layer. The generation of porosity depends on two factors: the change in the molar volume of the solid phases, and the relative solubilities of the solid phases in the fluid phase. The second factor determines how much of the parent is dissolved relative to how much of the product is precipitated, and it can outweigh the first factor (i.e. a porosity can still be generated) if there is an overall molar volume increase. This is discussed in more detail in Putnis (2009).

The hydrothermal replacement of albite by K-feldspar in an aqueous solution of KCl is a good example of an interface-coupled dissolution–precipitation reaction (Labotka et al. 2004; Niedermeier et al. 2009). Figure 5 shows partial replacement in an experimental sample, with a sharp reaction interface between the parent albite and the product K-feldspar. The diffraction contrast in the TEM image mosaic shows that the K-feldspar is defect rich and suggests nano-channels normal to the interface. Nano-pores in the product phase have also been imaged in a TEM study of albite-albitised plagioclase (Engvik et al. 2008). Diffraction patterns in both cases confirm that the crystallographic orientations are preserved when feldspar is replaced by feldspar.

In metamorphic reactions the replacement of one mineral by another need not be pseudomorphic, and as in the examples given by Carmichael (1969) the dissolution of one phase may not be spatially coupled to the precipitation of a product. The degree of spatial coupling depends on the relative rates of dissolution, diffusive transport through the fluid, and precipitation (Xia et al. 2009).

**FLUID TRANSPORT THROUGH ROCKS**

The mechanisms of fluid transport in metamorphic rocks have been widely discussed in the literature (e.g. Oliver and Bons 2001; Ague 2003). However, the low permeability of metamorphic rocks measured in the laboratory is not consistent with the estimates of time-integrated fluid fluxes inferred from metamorphic reactions (Ingebritsen and Manning 2003; Jamtveit et al. 2008). This suggests that permeability must be enhanced during metamorphism.

A number of fluid-transport pathways have been proposed: (1) pre-existing as the intrinsic rock porosity (e.g. grain boundaries), (2) created by deformation (e.g. grain-scale dilatancy), or (3) transport by the fluid event itself (hydraulic fracturing from fluid overpressure during devol-
2. In a dissolution–precipitation reaction, the partitioning of trace elements between parent and product phases may be influenced more by the nature and transport properties of the interfacial fluid than by any intrinsic closed-system equilibrium partitioning coefficient. In an open system, diffusion and advection in the fluid determine how much of the trace element content of the parent may be incorporated into the product. Fluid–mineral partition coefficients are valid, but the effective concentration of a specific element in solution has to be carefully evaluated.

3. When solid-state diffusion is not the principal mechanism for re-equilibration and when fluid composition rather than temperature is the driving force for metamorphic change, the concept of a “closure temperature” — used in isotope geochronology to determine when a mineral is effectively closed to further element exchange by solid-state diffusion — requires re-evaluation. Recognition that both temperature-dependent and fluid-dependent processes may operate during re-equilibration opens the possibility of dating both the thermal history and the “hygrometric” history of a rock (Villa 2006).

4. Experiments on mineral-replacement reactions indicate that, under hydrothermal conditions, reactions are very fast on a laboratory timescale and instantaneous on a geological timescale. This suggests that metamorphic reactions involving fluids may be fast even under conditions where the fluid and parent rock are not far from being in equilibrium.

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The Mechanics of Metamorphic Fluid Expulsion

James A. D. Connolly*

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Metamorphic devolatilization generates fluid and grain-scale porosity. Evidence for high fluid pressure indicates that devolatilization occurs under poorly drained conditions. Under such conditions, fluid expulsion is limited by the capacity of the reacted rocks to resist compaction or by the rate at which deformation modifies the permeability of the overlying rocks. In the former case, the compaction timescale must be greater than the metamorphic timescale, and flow patterns are dictated by details of rock permeability. The alternative is that compaction processes are fast relative to metamorphism. In this case, flow is compaction driven and accomplished by waves of fluid-filled porosity.

Keywords: metamorphism, devolatilization, fluid expulsion, compaction, porosity waves, permeability

INTRODUCTION

Typical crustal rocks lose 3–6% of their mass during regional metamorphic devolatilization, a process that generates fluid and porosity at the expense of the solid volume (Fig. 1). These fluids are of interest because of their role in crustal rock mechanics, mineralization, and the kinetics of other metamorphic reactions (Jamtveit and Austrheim 2010 this issue). The flow of fluid generated by devolatilization is determined by the rates at which (1) fluid is produced, (2) deformation accommodates the associated volumetric effects, and (3) fluid is drained from the reacting rock. The classical view of metamorphism involving lithostatically pressured fluids implies a perfect balance among these rates and allows fluid flow in only one direction, toward the Earth’s surface (Walther and Orville 1982). Such a balance is not only a mechanical impossibility (Connolly 1997a), but is at odds with studies that demonstrate a significant lateral component to metamorphic fluid flow (Ferry and Gerdes 1998). This paper outlines the relationship between fluid generation and expulsion and considers its implications for metamorphic flow patterns.

Phase equilibria (Holdaway and Goodge 1990), fluid inclusions (McCuaig and Kerrich 1998), and deformation styles (Etheridge et al. 1984) testify that metamorphic fluid pressures are above the hydrostatic values common in the upper crust (Zoback and Townend 2008). That these pressures are, at least sometimes, quantitatively lithostatic is demonstrated by nonvolcanic tremors in both subduction zone and continental settings (Peng et al. 2008; Scarpa et al. 2008). Because rocks have low tensile strength (less than ~5 MPa), hydrofracture provides an essentially instantaneous mechanism for regulating supralithostatic fluid pressures (Sibson 1992). The mechanism for generating high fluid pressure is more complex, but admits two limiting cases: the rock pores are collapsed, or devolatilization pressurizes the porosity of a rigid rock. The low grain-scale porosity of pristine metamorphic rocks (Norton and Knapp 1977), geophysically observable density changes during metamorphism (Hetényi et al. 2007), and isotopic evidence that grain-scale fluid–rock interaction occurs on brief timescales ($10^7–10^5$ years; van Haren et al. 1996; Graham et al. 1998) attest to efficient metamorphic compaction, but do not necessarily require that compaction occurs on the timescale of individual reactions.

Metamorphic fluid expulsion is a two-phase flow process whereby downward flow of the rock matrix (i.e. compaction) squeezes fluid upward. This process is controlled by both the rheologic properties that govern the flow of the solid matrix and the hydraulic properties that govern the flow of the fluid through the matrix. These properties are poorly constrained by laboratory data. To complement these data, this paper begins by examining order of magnitude constraints on crustal hydrology and rheology; these constraints follow from reasonable suppositions about the rate of metamorphism and the depth in the crust at which the dominant mode of deformation in response to tectonic stress changes from brittle to ductile. The paper then develops a conceptual, one-dimensional model of fluid expulsion towards the Earth’s surface, and concludes with discussion of a numerical model that illustrates the nature of lateral fluid flow in compacting rocks.

REGIONAL METAMORPHIC RATES

Prograde regional metamorphism is the wagging tail of a geodynamic dog. Unlike retrograde hydration and near-surface processes, the rates and scales of prograde devolatilization are controlled by the energy input arising from the large-scale geodynamic processes responsible for continental collision and thickened continental crust (England and Thompson 1984; Connolly and Thompson 1989). Because the tectonics of thickening are rapid relative to heat conduction, the thickened crust is undercooled relative to the steady-state geotherm necessary to conduct mantle heat flow. Subsequent heating as the geotherm relaxes toward the steady state, in combination with isostasy, results in clockwise pressure–temperature paths (Fig. 1) for the metamorphic process. Heat conduction constrains the metamorphic timescale, $\tau_{\text{m}}$, to be $-L^2/\kappa$, where $L$ is the crustal thickness and $\kappa$ is the thermal diffusivity.
Water content of average pelitic sediment (Plank and Langmuir 1998) as a function of temperature and pressure, computed assuming equilibrium with a pure H₂O fluid. More than half of the initial mineral-bound water content (7.6 wt%) is lost during diagenesis. The pelitic sediment contains 3 wt% CO₂, which is not accounted for in the model because decarbonation is sensitive to fluid–rock interaction (Ferry and Gerdes 1998; Connolly 2005). The red and blue lines indicate hot (20°C/km) and cold (10°C/km) metamorphic geotherms, respectively. The yellow-red-blue curve depicts the typical clockwise depth–temperature path followed by rocks during collision-belt metamorphism (England and Thompson 1984). The tectonically controlled, prograde, burial segment (yellow) is rapid (~1 My); thermal relaxation, in conjunction with isostatic rebound after burial (red) is slower (~10–100 My) and causes most prograde metamorphism; retrograde cooling (blue) does not affect the prograde mineral assemblage provided compaction isolates the rock from grain-scale interaction with fluids released by deeper metamorphism (Connolly and Thompson 1989). The increase in water content at temperature >600°C is due to melting that occurs because the model assumes water saturation; this melting does not occur if the water released by low-temperature processes is expelled.

where \( \kappa \) represents thermal diffusivity (~10⁻⁶ m²/s for crustal rocks) and \( l_c \) represents crustal thickness. Thus a tectonic event that doubles crustal water thickness to ~70 km is expected to generate metamorphism on a 100 My timescale. For an initial continental geotherm of ~15°C/km, peak conditions of Barrovian metamorphism (\( T \approx 600–700°C \) at 20–30 km depth) imply heating rates of ~3°C/My. In turn, these heating rates imply that metamorphic reaction fronts advance through the crust at ~200 m/My.

Assuming a heat conduction–controlled timescale and steady-state vertical fluid expulsion, average metamorphic fluid fluxes are:

\[
q_m = \frac{w l_c}{\rho l \tau_m} = -\frac{w \kappa}{\rho l_i} \approx 10^{-12} \text{ m/s,} \quad (1)
\]

where fluid density, \( \rho_f \), is ~900 kg/m³, and volatile content, \( w \), is ~0.06 kg volatile/kg m³. The timescale for metamorphism in subduction zones and continental rifting is significantly shorter, ~10 My, but the kinematics of these settings is such that the fluid fluxes are of the same order of magnitude as for collision belts (Connolly 1997a, 2005). Time-averaged flux estimates derived from field studies are also in this range (Ferry and Gerdes 1998). In detail, variability of the devolatilization process is sufficient to assure that metamorphic fluid production occurs within horizons of intense reaction (Fig. 2) bounded by nonreacting rocks that presumably limit drainage. Equation (1) gives the time-averaged flux at the top of the metamorphic column, but unless all fluid production occurs at the base of the column, steady-state fluxes must be a strong function of depth (Fig. 2).

Petrologists periodically invoke advective heating by fluids (including melts) to explain anomalous heating relative to the classical model of England and Thompson (1984). The integrated fluid fluxes necessary to create significant thermal effects are comparable to the rock mass that is heated; thus it is implausible that such fluxes can be generated by the metamorphism itself unless fluid flow is focused (Connolly 1997b), but focused flow cannot explain pervasive heating. Thus, while heat advection models may prove correct, they leave open the troubling question of the flux source. Deficiencies in the England and Thompson model with regard to temperature (Lux et al. 1986) and exhumation (Amato et al. 1999) can be explained by mechanical effects, notably advective heating by the vertical displacement of blocks of crustal material and by both local and diffuse shear heating (Burg and Gerya 2005) without substantially changing the metamorphic timescale. Deficiencies with regard to rate are more problematic; most prominently, several lines of evidence suggest that the type section for Barrovian metamorphism evolved one to two orders of magnitude faster than predicted by the conductive timescale (Olive et al. 2000; Ague and Baxter 2007). This evidence may ultimately require new models for regional metamorphism.

**HYDRAULIC PROPERTIES: PERMEABILITY AND POROSITY**

Although the hydraulic properties of metamorphic fluids are reasonably well known and not strongly variable (Walther and Orville 1982), the permeability and porosity of metamorphic rocks are poorly constrained. Indeed, it is conceivable that diagenetic processes eliminate all hydraulic connectivity prior to metamorphism. Discounting this possibility, the permeability of metamorphic systems...
is usually derived by estimating the metamorphic fluid flux and pressure gradient (Manning and Ingebritsen 1999). These estimates mask a dependence on the rate of metamorphism, which determines the fluid flux. This problem is avoided if the hydraulic regime is characterized by the flux necessary to maintain lithostatic fluid pressure rather than permeability. This flux, \( q_{0} \), defines a background state from which it is possible to assess the effect of local perturbations caused by devolatilization. Although this state is somewhat arbitrary, background fluxes are unlikely to exceed the average metamorphic fluid flux, which is dependent on the rate of metamorphism. Because the magnitude of the average flux decays with depth, it is reasonable to expect that the background flux has similar depth dependence. For quantitative illustration here, this dependence is ignored and \( q_{0} \) is taken to be \(-10^{-13}\) m/s, a value comparable to the average flux expected in the upper half of a conductively heated metamorphic column (Fig. 2). The corresponding characteristic permeability, \( k_{w} \), is \(-10^{-20}\) m². While this permeability is low compared to permeabilities generally observed in situ in the upper crust \((10^{13}-10^{17}\) m²; Ferry and Gerdes 1998; Manning and Ingebritsen 1999), it is unexceptional when compared to the permeabilities of argillaceous sediments (Neuzil 1994).

To a good approximation, the background flux is a proxy for all hydraulic properties of a metamorphic system except porosity. The term porosity here includes any interconnected fluid-filled voids present on spatial scales that are much smaller than the scale for fluid flow. Thus, porosity includes both grain-scale porosity generated by densification during devolatilization and small-scale fractures induced by the consequent dilatational (i.e., volume changing) deformation. This porosity is critical to the dynamics of fluid expulsion because the hydraulic impact of metamorphic reactions is determined by how they influence permeability via porosity. Theoretical and empirical considerations indicate that permeability increases as the cubic or higher power of porosity (Norton and Knapp 1977; Neuzil 1994). This relationship implies that the percent-level porosities generated by devolatilization reactions lead to order of magnitude increases in the permeability of the reacted rocks provided initial porosities are small, i.e. \(<1\%\).

On the basis of isotopic diffusion profiles, Skelton et al. (2000) infer background porosities in the range \( q_{0} = 10^{-3} - 10^{-6}\). These are consistent with grain-scale porosities of \(10^{-3} - 10^{-6}\) measured in exhumed metamorphic rocks (Norton and Knapp 1977). An upper bound on premetamorphic porosities of \(10^{-2}\) is provided by the sensitivity of geophysical measurements, which generally do not indicate fluids in the lower crust except in active metamorphic settings.

### RHEOLOGY: THE BRITTLE–DUCTILE TRANSITION

Elevated fluid pressure is commonly attributed to compaction in the ductile lower crust. This association is tenuous because the classification of the crust into an upper brittle regime and a lower ductile regime is based on its response to tectonic stress, whereas compaction occurs in response to the difference between pore-fluid pressure and the mean stress. In fact, a compelling case can be made that the upper crust is characterized by hydrostatic pressures only because faulting maintains large-scale permeability (Zoback and Townsend 2001). The absence of faulting in the upper crust allows processes, which include compaction but can also include retrograde metamorphism and diagenetic processes, to eliminate large-scale hydraulic structures. In the absence of such structures, the effective permeability of the crust would be limited by the vanishingly small permeability of argillaceous sediments (Neuzil 1994).

Regardless of the significance of the brittle–ductile transition for fluid pressure, as temperature increases, thermally activated time-dependent compaction must become important. Current experimental models for compaction are so uncertain that they provide no practical constraints (Farver and Yund 2000). Given this situation, an alternative is to calibrate ductile rheology in terms of the compaction timescale \( (\tau_{B-D}) \), formally, the time required to decrease porosity by \(-36\%\) at the depth \( z_{B-D} \) (~15 km) and temperature \( T_{B-D} \) (~623 K) of the brittle–ductile transition. In this formulation, the coefficient of viscous creep is

\[
\eta = \tau_{B-D} \left( \frac{\Delta p g z_{B-D}}{\rho m} \right)^n \exp \left( \frac{-Q}{RT \left( T_{B-D} - T_{B-D} \right)} \right) \tag{2}
\]

where \( \Delta p \) is the difference between rock and fluid density (~1900 kg/m³), \( n \) is the stress exponent, and \( Q \) represents the activation energy for viscous creep (~270 kJ/mol, with \( n = 3 \)). From equation (2), for \( \tau_{B-D} = 1 \) My, the effective viscosity at the brittle–ductile transition is \(-10^{22}\) Pa·s and decays to \(-10^{14}\) Pa·s at 700°C.
THE COMPAC TIONS SCALES

At near-lithostatic fluid pressures, the stress that causes compaction cannot be related directly to depth; rather, time-dependent compaction processes develop on a natural length scale known as the compaction length (McKenzie 1984). For crustal rheology (Connolly and Podladchikov 2004), the compaction length is

$$\delta = n \sqrt{\frac{\eta \phi}{\phi_0 \mu}} \left( \frac{\phi_0}{\Delta P g} \right)^{\alpha},$$

where $\mu$ represents fluid viscosity. In essence, $\delta$ is the length scale over which pore fluids can move independently of compaction processes; thus it is intuitive that $\delta$ increases with rock bulk strength, $\eta/\phi_0$, and the ease with which fluid can flow through rock, $k/\mu$. Substituting equation (2) into equation (3), $\delta$ can be reformulated as

$$\delta = n \sqrt{\tau_{B-D} \phi_0^2} \left( \frac{\phi_0}{\Delta P g} \right)^{\alpha} \exp \left( \frac{Q}{RT} \frac{T - T_{B-D}}{T_{B-D}} \right).$$

Equation (4) is relatively insensitive to the parameter estimates discussed previously, but $\delta$ is a strong function of temperature, decreasing from $\sim 10^0$ to $\sim 1$ m as temperature increases from 350 to 700°C. This suggests that at moderate temperatures, compaction is likely to influence metamorphic flow patterns on observable spatial scales. The compaction timescale for poorly drained rocks, $\tau = \eta/\phi_0 (\Delta P g)^{\alpha} n$, is highly uncertain and only weakly related to the timescale for compaction at the brittle–ductile transition, $\tau_{B-D}$, but its temperature dependence from equations (2) and (4) indicates that metamorphic temperature variations are sufficient to cause a 10-fold increase in compaction rates with depth.

THE LIMITING FLOW REGIMES

Although it is widely accepted that fluid expulsion occurs during metamorphism, it is not widely appreciated that this process is mechanical and as strongly dependent on rheology. To illustrate this dependence, consider a minimal model for vertical flow in which (1) the fluid and rock are inelastic; (2) the rock compacts viscoelastically if the difference between the fluid pressure, $P_f$, and rock pressure, $P_r$, is less than the tensile strength, $\sigma_t$ ($\sim 5$ MPa); and (3) the rock dilates plastically, i.e. hydrofractures, if $P_r - P_f > \sigma_t$. The model can be simplified further by discounting the volume change associated with devolatilization. While this effect is often attributed mechanical importance, in poorly drained systems it is largely irrelevant (Connolly 1997a). Evidence for high fluid pressures during metamorphism requires that the metamorphic systems are poorly drained. Thus, the essence of devolatilization is to produce a permeable horizon surrounded by impermeable rocks through which negligible fluxes are sufficient to generate lithostatic fluid pressure. Within the reacting layer, even if devolatilization involves a net volume increase, fracturing maintains near-lithostatic conditions. Conservation of mass requires that in the absence of deformation the fluid flux must be equal to the drainage flux, $q_0$, throughout the column. By Darcy’s law, this flux is

$$q_0 = -k \left( \frac{\partial P_f}{\partial z} - \rho_f g \right),$$

if $\partial P_f/\partial z$ is the lithostatic gradient, $\rho_f g$. However, within the reacted zone permeability, $k$, is much greater than the permeability, $k_\circ$, of the overlying rocks. Therefore the last term in equation (5) must be small, which is only possible if $\partial P_f/\partial z$ is similar to the hydrostatic gradient, $\rho_f g$, regardless of the near-lithostatic, absolute pressure. This situation gives rise to a positive effective pressure gradient, $-\rho_f g$, that causes deformation (Fig. 3).

The manner in which viscous compaction is superimposed on the foregoing scenario can be represented by the cases where the compaction timescale, $\tau$, is much greater than, or comparable to, the metamorphic timescale, $\tau_{m}$ (Fig. 4). For a constant-volume devolatilization reaction, the mean fluid pressure within the rocks behind a reaction front is identical to the mean total pressure. Thus the upper and lower halves of the reacted interval are subject to negative (dilational) and positive (compactive) effective pressures. If $\tau \gg \tau_{m}$, the rocks remain rigid on the timescale of reaction until the vertical extent of the reaction is large enough, i.e. $2\sigma_t/\rho_f g < 500$ m, to cause micro- or macroscale fracturing at the top of the reacted rocks. Unless this produces fractures that breach the low-permeability barrier formed by the overlying rocks, fracturing acts as a homeostat that limits fluid pressure within the permeable zone as reaction progresses. Because the fracturing occurs at the top of the reacted rocks, the rock is considered reaction-proof the yield stress has been reached is to propagate fracture-generated porosity beyond the reaction front and decrease fluid pressure.

![Conceptual model of metamorphic devolatilization](image-url)

**Figure 3**: Conceptual model of metamorphic devolatilization. The reaction leaves a region of elevated porosity and permeability in its wake. Fluid flux is proportional to the permeability and the difference between the fluid pressure gradient and the hydrostatic gradient. In the absence of deformation, conservation of mass requires that this drainage flux must also be the flux within the reacted horizon with permeability $k \gg k_\circ$; this is possible only if the difference between the fluid pressure gradient and the hydrostatic gradient is small. However, this near-hydrostatic fluid pressure gradient within the reacted rocks gives rise to an effective pressure $P - P_f$ greater than $\rho_f g$, so that pore fluids become increasingly underpressured toward the lithostatic depth within the high-porosity zone and, conversely, increasingly overpressured toward the reaction front. The resultant effective pressures are the driving force for deformation and fluid expulsion.
pressure. The propagation rate is dependent on the fracture mechanism, but because fracture permeability is also a cubic function of porosity (Norton and Knapp 1977), it is unlikely that the fracture front propagates much more rapidly than the reaction front. The important feature of this limiting scenario is that metamorphic reactions generate a permeable horizon that has the potential to allow lateral fluid flow.

In the compaction scenario ($\tau_{c} \approx \tau_{a}$), compaction squeezes fluid upward from the base of the reaction zone, while dilational processes at the top of the zone create porosity beyond the reaction front. If $\delta \rho g > \sigma_{f}$, this dilation can be accomplished by fracturing, but regardless of the dilational mechanism, the rate of dilation is limited by the rate at which devolatilization and compaction at depth supply the fluid that causes dilation. The combined effect of these processes is to propagate porosity upward relative to the reaction front. Because the rate of compaction at the base of the porous zone must increase with its vertical extent, compaction isolates the porous zone from the reaction front once the vertical extent of the reacted rocks is $\sim \delta$. The porosity then propagates upward independently of the reaction as a solitary wave. The essential features of this mode of fluid flow are that fluid pressures oscillate by approximately $\delta \rho g$ about the lithostatic and that fluid pressure gradients oscillate between hydrostatic and lithostatic. Since both $\tau_{c}$ and $\delta$ are proportional to rock shear viscosity, the classical picture of metamorphism as an isobaric process is recovered at high temperature when $\eta$ is low, i.e. $\tau_{c} < \tau_{a}$ and $\delta \to 0$, but porosity waves slow and lengthen as they propagate upward into cool, upper crustal rocks (Connolly and Podladchikov 1998).

The primary effect of volume changes during devolatilization on the foregoing scenarios is to influence the mean fluid pressure within the reaction zone. Thus, the vertical extent of the reaction zone required to induce fracturing is smaller for a reaction with a positive isobaric volume change.

Compaction-driven fluid flow is widely appreciated in the context of both sedimentary basins and asthenospheric melt migration (Richter and McKenzie 1984; Connolly and Podladchikov 2000), and mathematical analysis has demonstrated that solitary porosity waves are a steady-state solution of the governing equations for fluid flow in compacting media (Barcilon and Lovera 1989). This analysis shows that the waves are stable provided the reaction-generated fluid flux is at least three times the flux that can be conducted through the unperturbed matrix, $g_{0}$. When this condition is not met, the transient evolution at the reaction front is unchanged, but the waves dissipate as they propagate into the overlying matrix (Connolly and Podladchikov 1998). An additional requirement for the development of waves is that the vertical extent of the permeable source zone must be $\sim \delta$. Both the localization of fluid production and the large resultant fluxes (Fig. 2) suggest that these requirements are met in metamorphic systems. Numerical analysis reveals that the one-dimensional waves just described decompose into elongate, tubelike waves in three dimensions (Connolly and Podladchikov 2007). Such waves, illustrated in the next section, do not substantially change the scales of compaction-driven fluid flow.

Chemical kinetic effects cause devolatilization at higher temperature than predicted by equilibrium models, but they do not fundamentally change the equilibrium picture because chemically limited rates are proportional to the free energy change, $\Delta G$, of devolatilization (Jamtveit and Austrheim 2010). To a good approximation (Dahlen 1992), $\Delta G$ is related to the displacement in temperature, $\Delta T$, and fluid pressure, $\Delta P_{f}$, from equilibrium conditions by

$$\Delta G = \Delta V \Delta P_{f} - \Delta S \Delta T,$$

where $\Delta S$ and $\Delta V$ represent the entropy and volume changes of devolatilization; typically $\Delta S = 3000 - 3500$ J/K and $\Delta V = -2 \times 10^{-5}$ to $+8 \times 10^{-4}$ J/Pa per kg$_{volatile}$. These values imply that increasing temperature rapidly increases chemically limited kinetics until the process becomes heat-supply limited. A variation in fluid pressure must be greater than 5 MPa to have the same effect as a 1°C change in temperature; thus during prograde metamorphism, the effect of fluid pressure is to modulate the thermally controlled devolatilization rates (Connolly 1997a). For reactions with a positive isobaric volume change, rates decrease with decreasing fluid pressure and, counterintuitively, increasing fluid pressure increases the reaction rates.

**LOOKING FOR LARGE LATERAL FLUXES**

There is little doubt that lateral fluid flow occurs in metamorphic rocks (Ferry and Gerdes 1998). Both lithological contrasts and reaction-generated porosities give rise to permeable horizons that promote lateral fluid flow, but in overpressured systems, large lateral fluxes can only be explained by the existence of local drains into the perme-
Numerical simulation of the influence of a permeable (10^{-17} m^2) shear zone on devolatilization-induced fluid flow for noncompacting (A, B) and compacting (C, D) scenarios. The plots of porosity, fluid pressure, and the magnitude of the vertical and horizontal components of the fluid flux are for a 24 km wide segment of the model spatial domain, which represents a 20 x 40 km crustal section. In the plots of vertical flux magnitude, large domains in which flow direction is predominantly downward are bounded by white curves; smaller domains of downward flow associated with individual porosity waves are not indicated. Prior to shear zone emplacement at \( t = 0 \), devolatilization proceeds for 100 ky, creating a ~100 m thick permeable horizon overlain by a fringe of fracture-generated porosity (as in Figure 4). At \( t = 10 \) ky, both scenarios are virtually identical, the surge of fluid into the shear zone causes extraordinary fluid pressures and fluxes, and the consequent lowering of fluid pressure within the reacted horizon locally accelerates devolatilization. The noncompacting scenario rapidly reaches a quasi-steady state in which negligible pressure gradients are adequate to drain fluid from both within and about the reacted layer. In contrast, for the compacting scenario, by \( t = 60 \) ky the active portion of the reaction front is drained by tubelike porosity waves and is completely isolated from the shear zone. By \( t = 110 \) ky, compaction has also eliminated the residual porosity in the inactive portion of the reaction zone; thus when dehydration resumes, the resulting flow is independent of the shear zone.

As anticipated by the one-dimensional scenario, in the noncompacting limit, a fringe of fracture-generated porosity develops above the reaction front (Fig. 5a), but other than this feature, the model has no important nonkinematic behavior. With time, the reaction creates an ever thicker permeable layer that conducts the reaction-generated fluid, as well as fluids from the rocks above and below, to the fracture zone (Fig. 5a). The pressure gradient within the layer necessary to drive lateral flow is insignificant, with the consequence that the reaction front propagates uniformly upward. With time, such a model evolves toward a steady state, in which fluid pressures are hydrostatic above the reaction front and essentially all flow is focused into the shear zone. The flow pattern in this model is unsurprising, and the main conclusion to be drawn from it is that the pattern is determined by uncertain initial conditions and kinematics.

In the compacting scenario, the shear zone drainage is less effective because compaction throttles lateral fluid flow and the shear zone must compete with drainage by tubelike porosity waves. The waves (Fig. 5c) develop with a spacing comparable to the model compaction length (\( \delta = 880 \) m), an effect that leads to focusing of reaction-generated fluxes. An unexpected feature of the flow pattern associated with the two-dimensional porosity waves is that the lateral and vertical fluxes are comparable. This convective pattern results because fluid is forced into the surrounding matrix by high pressures at the top of the wave and drawn back into the lower underpressured portion. This convective pattern is reminiscent of buoyancy-induced Rayleigh convection that develops in shallow hydrothermal systems (Norton and Knight 1977). However, dimensional analysis (Connolly 1997a) indicates that Rayleigh convection is unlikely in lower-crustal metamorphic settings, a conclusion also reached by more elaborate numerical modeling (Lyubetskaya and Ague 2009).

In the compacting model, drainage by the shear zone suppresses the development of porosity waves. The lateral extent of this near-instantaneous effect is quantitatively determined by the properties of the shear zone, but it decays rapidly as compaction seals the distal portions of...
the layer. This decay accelerates with time as the shear zone becomes a more effective drain for the portion of the layer with which it is in hydraulic contact. In the numerical simulation, these effects seal the shear zone from the reaction front within 60 ky (Fig. 5c), and by 110 ky compaction has eliminated essentially all hydraulic contact with the shear zone (Fig. 5d). This latter effect has the consequence that subsequent devolatilization-induced fluid flow occurs independently of the shear zone.

DISCUSSION

Regional metamorphism occurs in an ambiguous rheological regime between the brittle upper crust and the ductile mantle. This ambiguous position has allowed two schools of thought to develop concerning the nature of metamorphic fluid flow. The classical school holds that metamorphic rocks are perfectly plastic, i.e., inviscid, and that any fluid generated by devolatilization is squeezed out of rocks as rapidly as it is produced (Walther and Orville 1982; Connolly and Thompson 1989; Yardley 2009). According to this school, permeability is a dynamic property and fluid flow is upward. In contrast, the modern school selectively uses concepts from upper-crustal hydrology that presume implicitly, if not explicitly, that rocks are rigid or, at most, brittle (Walder and Nur 1984; Manning and Ingebritsen 1999; Lyubetskaya and Ague 2009). For the modern school, the details of crustal permeability determine fluid flow, and because these details are poorly known, almost anything is possible.

Field studies offer some support to both schools. In particular, evidence of significant lateral fluid flow (Ferry and Gerdes 1998; Skelton et al. 2000) is consistent with flow in rigid media, while evidence for short (10^2–10^3 y), grain-scale fluid–rock interaction (van Haren et al. 1996; Graham et al. 1998; Ague and Baxter 2007) during much longer metamorphic events suggests that reaction-generated, grain-scale permeability is sealed rapidly by compaction, a phenomenon that is also essential to prevent extensive retrograde metamorphism. These observations provide a compelling argument for recognizing in conceptual models of fluid flow that metamorphic rocks are neither inviscid nor rigid, but have finite strength. The surprising consequence of this finite strength is that the steady-state solutions for fluid flow in porous, compacting media require that fluid expulsion is channeled into waves of fluid-filled porosity. The waves develop on a characteristic length scale that is also the length scale for lateral fluid flow. In this context, porosity includes all hydraulically connected space present on a spatial scale << δ. Thus, porosity waves may be manifest as self-propagating domains of fluid-filled fractures. Because δ is proportional to rock viscosity and consequently decreases exponentially with increasing temperature, the flow regimes of the classical and modern schools are recovered at high and low temperatures.

The compaction-driven flow regime has been illustrated here under the assumptions that compaction is time-dependent, that compaction is largely time-independent, and that the far-field stress is isostatic. Near-surface sediments compact by time-independent plastic mechanisms that may well contribute to metamorphic porosity reduction. Fluid flow through porous media that compact dominantly by time-independent rheological mechanisms is also accomplished by porosity waves, but in contrast to the viscous case, the waves have no intrinsic length scale (Connolly and Podladchikov 1998). Fluid flow in compacting media is in the direction of low mean stress. In nonsisostatic systems, mean stress does not necessarily decay upward, an effect that could trap fluids beneath the tectonic brittle–ductile transition or draw fluids downward (Connolly and Podladchikov 2004). In the presence of far-field stress, the Mohr-Coulomb failure criterion implies that fracturing occurs at sublithostatic fluid pressures (Sibson 1992). This effect would reduce fluid pressures and influence fracture patterns but would not change the dynamics and scales of porosity waves limited by viscous compaction.

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Alteration of the Oceanic Lithosphere and Implications for Seafloor Processes

Wolfgang Bach1 and Gretchen L. Früh-Green2

1 Geoscience Department, University of Bremen
2 Institute of Geochemistry and Petrology, ETH Zurich

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Three-quarters of global magmatism and one-quarter of global heat loss are associated with tectonomagmatic and hydrothermal processes governing oceanic lithosphere accretion and the aging of the lithosphere from ridge to trench. Hydrothermal reactions between seawater and oceanic lithosphere under zeolite to granulite facies conditions are linked with magmatic and deformation processes, but they differ in nature depending on spreading rates. Fast-spreading ridges with frequent eruptions have telescoped metamorphic gradients and short-lived hydrothermal systems. Less magmatically robust, slow-spreading ridges are commonly cut by normal faults that expose ultramafic rocks on the seafloor and sustain long-lived hydrothermal systems with distinct vent fauna and fluid compositions.

Keywords: oceanic lithosphere, mid-ocean ridge, water–rock interaction, geochemical fluxes, hydrothermal systems

INTRODUCTION

Approximately 3 km² of new seafloor is created annually along the >60,000 km long global network of mid-ocean ridges and back-arc spreading centers. This crust interacts with seawater throughout much of its lifetime (the average age of oceanic crust is 60 million years). Fluid circulation within the crust is largely thermally driven and accounts for ¼ of the total global heat loss, or 11 terawatts (TW). Metamorphic conditions range from zeolite to granulite facies, and the amount of mass transferred varies from minimal to extensive. Hydrothermal circulation and interaction between seawater and the oceanic lithosphere are fundamental in controlling the composition of both seawater and the subducting oceanic plate. These processes play a critical role in regulating global heat and mass fluxes (German and Von Damm 2003). They also determine the geophysical and mineralogical properties of the oceanic lithosphere, with profound consequences for its mechanical behavior during aging and subduction. This is particularly relevant for volcanically starved mid-ocean ridge segments, where serpentinized mantle peridotite is exposed at the seafloor. The stability of serpentine and other hydrous phases determines the release of water in subduction zones. In submarine arc and back-arc hydrothermal settings located above subduction zones, silica- and volatile-rich magmas form as a consequence of the water flux into the mantle wedge. This, in turn, affects the composition of hydrothermal solutions, making arc-associated vent systems chemically and biologically distinct from their mid-ocean ridge counterparts. We discuss some of the principal processes controlling water–rock interaction in submarine hydrothermal systems and highlight some of the key differences in crustal architecture, magmatism, and deformation among various geotectonic settings.

STRUCTURE OF THE OCEANIC LITHOSPHERE

The results from numerous oceanographic investigations and the ocean drilling programs (ODP and IODP) over the past three decades have changed the long-held view that the entire oceanic crust is uniform in architecture and thickness, and they have led to the recognition of fundamental differences in crustal accretion and alteration processes related to spreading rates (Fig. 1). The principle of a uniform crust, characterized by a “layer-cake” structure of basalt, diabase (sheeted-dike complex), and gabbro, is based on early geophysical data and comparisons with ophiolites (i.e. sections of oceanic crust exposed on land). This concept is commonly referred to as the “Penrose ophiolite model” or “Penrose-type crust,” defined during a Penrose conference and published in Geotimes in 1972. The Penrose model is generally applicable for crust formed at fast-spreading ridges, such as the East Pacific Rise, where melt supply is able to keep up with extension at the divergent plate boundary (Fig. 1A, B). However, it cannot be applied to much of the crust formed at oceanic ridges spreading at less than 40 mm y⁻¹. This type of ridge comprises nearly 50% of the global mid-ocean ridge system and extends from the Arctic Ocean, along the entire Mid-Atlantic Ridge (MAR) and into the Indian Ocean (Southwest Indian Ridge, SWIR). At these slow-spreading ridges, melt supply does not always keep up with plate separation, which is accommodated by significant tectonic extension (Fig. 1C, D).

Ultraslow-spreading ridges, with spreading rates of <20 mm y⁻¹, have unique morphologies consisting of linked alvonic and volcanic accretionary segments, with large variations in crustal thickness along ridge segments. Differences in melt volumes and focusing of melts are reflected by discontinuous volcanic centers separated by long stretches of alvonic or melt-starved segments; in these settings, the principal unit of accretion appears to be emplacement of mantle blocks onto the seafloor (Dick et al. 2003). Similarly, slow-spreading ridges, such as the Mid-Atlantic Ridge, are characterized by rugged topographies, a high degree of segmentation, and considerable heterogeneities in crustal thickness, rock types, deformation, and degree of alteration, which reflect strong temporal and spatial variations.
Fast-Spreading Ridges (robust magma supply) (~11-16 cm/year)

- Across-axis
- Depth (km)
- Crystal mush zone
- Moho

Slow-Spreading Ridges (variations in magma budgets) (< 4 cm/year)

- Along-axis
- Depth (km)
- Segment center
- Asthenosphere
- Moho
- Lithosphere
- Strike-slip fault
- Oblique-slip fault

**Figure 1** Conceptual models of tectonomagmatic and alteration processes associated with differences in spreading rates and based on geophysical and petrological constraints. (A) Robust magmatism at fast-spreading ridges produces a relatively homogeneous, layered crust. Melts extracted from rising asthenosphere feed a narrow, sill-like melt lens, 1–2 km beneath the ridge axis. The melt lens grades downward into a partially crystallized mush zone, which is surrounded by a transitional zone of solidified but still hot gabbroic rock. Fluid circulation is limited to the crystallized upper crust, and focused fluid circulation (dark brown arrows) produces hydrothermal vent fields along the ridge axis. The relative volumes of melt and crystal mush vary along the ridge axis (B), especially near axis discontinuities (modified from Sinton and Detrick 1992). In contrast, slow-spreading ridges are characterized by variations in magmatic, tectonic, and alteration processes along ridge segments. (C) Layered crust forms where magma supply is high, but where magma budgets are lower, detachment faults develop during tectonic extension, exposing mantle-dominated lithosphere at the seafloor (modified from Boschi et al. 2006). Much of the magma rising through this mantle section crystallizes at depth and forms variably sized gabbroic bodies. Detachment faults may intersect the crystallizing magma bodies and their feeder dikes and can channel high-temperature fluids to feed large black smoker vent fields (dark brown arrows). Serpentinitization progresses as the mantle sections are uplifted and oceanic core complexes develop. Late normal faults and mass wasting can focus low-temperature, alkaline, hydrothermal fluids derived from serpentinitization reactions (blue arrows), as seen in the Lost City vent field located at the crest of the Atlantis Massif. (D) Along-strike variations in magma supply at slow-spreading ridges are reflected by segment centers with relatively continuous, layered magmatic crust that becomes thinner and discontinuous toward magma-poor segment ends. Ultramafic rocks and serpentinitization, with arrays of short strike-slip and oblique faults, are common at segment ends and contribute to a thick lithosphere, as interpreted from seismic data (modified from Cannat et al. 1995).

In tectonic and magmatic processes (Fig. 1C, D). In these environments, serpentinized mantle peridotite and lower-crustal plutonic rocks may represent 20–25% of the seafloor exposed through faulting (Cannat et al. 1995).

Recent studies have imaged broad, dome-like massifs with exceptional relief (>2.5 km) and with arched upper surfaces marked by distinctive corrugations and finer-scale striations parallel to the spreading direction. These dome-shaped massifs are referred to as oceanic core complexes, in analogy with metamorphic core complexes on the continents. They form along long-lived detachment (normal) faults during phases of extensive tectonic extension, commonly associated with asymmetric spreading. Detachment faults remove the basaltic upper crust and expose, in the footwalls of the faults, plutonic and upper-mantle sequences originally at depths of >6 km (Blackman et al. 2005 for a recent review).

Core complexes have been found in many places along the SWIR (Cannat et al. 2006) and MAR (Smith et al. 2008). For example, between 13° and 15°N on the MAR, 45 potential core complexes, some less than 25 km apart, are scattered along two segments (Smith et al. 2008). The modern view of oceanic crust at slow-spreading ridges is that some portions of segments may consist of more uniform, Penrose-like crust, with characteristic abyssal hill morphologies, while other portions of the segments are highly heterogeneous, with attenuated or missing volcanic crust and with gabbroic intrusions trapped in partially serpentinized lithospheric mantle (Fig. 1C, D). The depth and spatial extent of serpentinization of oceanic peridotites have direct implications for the interpretation of seismic velocities and may influence where geophysicists place the Mohorovičić discontinuity (Moho). In these environments, the Moho may not represent the crust–mantle boundary but may be a serpentinitization front.

**Detachment Faulting and Channeled Fluid Flow**

Oceanic core complexes and their exposed detachment faults represent tectonic windows that provide access to deep-seated rocks and allow studies of mantle flow, melt generation and migration, strain localization, and alteration. In heterogeneous sections of the oceanic litho-
Serpentinization Processes

Lithosphere consisting predominantly of mantle-derived rocks constitutes a highly reactive chemical and thermal system, in which interaction with seawater has significant geophysical, geochemical, and biological consequences for the global marine system and for subduction zone processes. Serpentinization involves hydration of olivine and pyroxene, the dominant minerals in the oceanic mantle, and typically incorporates >10 wt% H₂O into the rocks. Hydration reactions are accompanied by a decrease in bulk density that implies a 20–30% increase in volume and by changes in mineralogy and rheology, all of which directly affect the strength and physical properties of the mantle, the magnetic and gravity signatures, and the seismic velocities. Serpentinization processes also have major consequences for long-term, global geochemical fluxes by acting as a sink for H₂O, Cl, B, U, S, and C and as a source of Ca for hydrothermal fluids (Früh-Green et al. 2004). Seafloor weathering of serpentine acts as a source of Mg for the oceans, as brucite dissolves away (Snow and Dick 1995).

Since the earliest experimental studies of serpentines and studies of Alpine peridotites and ultramafic rocks in ophiolites, it has been known that serpentinization generates H₂-rich fluids and native metals. Hydrogen is released and magnetite produced during olivine hydration. Serpentinization involves solid solutions and metastable reactions governed by local variations in the concentrations of elements such as Si, Mg, Fe, Ca, and C (Allen and Seyfried 2003). Thermodynamic constraints on phase equilibria predict that serpentinization will commence once the shallow-mantle sequences have cooled below 400–425°C, when olivine breakdown produces thermodynamically stable serpentine + magnetite, or below ~350°C, when the serpentine + brucite + magnetite assemblage becomes stable (Früh-Green et al. 2004; McCollom and Bach 2009). Commonly, reduction leads to the formation of FeNi alloys in serpentinites, and a number of studies indicate that these alloys may act as catalysts for the reduction of CO or CO₂ to form abiotic methane (CH₄) and other hydrocarbons. The production of H₂ and CH₄ during serpentinization is important in sustaining diverse microbial communities in subsurface and near-vent environments and may be significant for the existence of a deep biosphere (Kelley et al. 2005).

The products and sequence of serpentinization reactions depend on the depth, temperature, and degree of seawater penetration into the lithosphere and are influenced by bulk protolith composition, the presence or absence of magmatic intrusions and trapped gabbroic melts, and structure (e.g. detachment faults, cataclastic fault zones). The mineral assemblages and textures of oceanic serpentinite typically record progressive, static hydration reactions that take place over a wide range of temperatures, lithospheric depths, fluid compositions, and redox conditions. The bulk volume of alteration is recorded by pseudomorphic mesh textures replacing olivine and bastite textures replacing pyroxene. Serpentinization is also accompanied by multiple generations of veins with a variety of vein-filling minerals, morphologies, and textures that document local differences in formation mechanisms, stress regimes, and fluid infiltration (Andreani et al. 2007). Recent studies of serpentine associated with detachment faults and core complexes indicate that serpentinization reactions in the footwall may initiate at depths of 4–6 km (Andreani et al. 2007). The early stages of high-temperature seawater–mantle–gabbro interaction can also result in the replacement of serpentine by talc–tremolite–chlorite assemblages to form fault rocks characteristic of detachment faults (Boschi et al. 2006). Progressive serpentinization reactions and veining continue until exposure on the seafloor. Pervasive serpentinization is likely to be restricted to the shallow lithosphere at depths of <2 km, where brittle fractures facilitate convection of seawater-derived fluids and enhance advective mass transport.

AXIAL HYDROTHERMAL SYSTEMS

During crustal accretion, the balance between magmatic heat input and hydrothermal cooling is determined by a complex interplay among magmatic, tectonic, and hydrothermal processes, in which hydrothermal convection of seawater plays an important role. Circulation is controlled by magmatic diking at fast-spreading ridges, but may be tied more to extensional faults at slow-spreading ridges (Wilcock and Delaney 1996). Hydrothermal systems on the seafloor tend to be small and short-lived at fast-spreading ridges, while they are large and long-lived at slow-spreading ridges. These differences are expressed in the style of seawater–rock interaction that can be observed in deep drill holes penetrating the oceanic crust and in ophiolites. Crust produced at fast-spreading ridges commonly shows progressive, static alteration controlled by fractures and microcracks, while in crust produced by slow spreading, alteration is more heterogeneous and extensive and is tied to brittle or brittle deformation in normal faults or to serpentinization processes in peridotite-dominated domains (Alt 1995; Escartín et al. 2003).

The nature of the magmatic–hydrothermal interface in the oceanic crust is poorly known, and we do not yet understand the mechanism by which heat is mined to drive mid-ocean ridge hydrothermal systems. It is commonly assumed that the maximum temperature in axial hydrothermal convection cells is between 420 and 450°C because of the rapid increase in the specific volume of the fluid above 400°C.

Hydrothermal alteration and mineralization patterns in oceanic crust share similarities and differences with ophiolite crust. In both settings, a conceptual model that divides a hydrothermal system into a recharge zone, a reaction (or root) zone, and a discharge (or upflow) zone may be applicable (Alt 1995). Another commonality is the formation of large sulfide deposits within the upper crust and at the seafloor from heating of circulating seawater by crystallizing magmas and leaching of metals from the basement (e.g. Humphris and Cann 2000). In ophiolites, however, the leaching zones near the sheeted dike–gabbro transition and in the deep upflow zones show abundant epidote (base metal–depleted and Ca-metasomatized rock), a rock type that has not yet been recovered from in situ mid-ocean ridge sections (e.g. Alt 1995). It also appears that...
greenschist facies metamorphism is more pervasive in the sheeted dikes and upper gabbros in ophiolites than in oceanic crust. The presence of epidote and changes in Sr and O isotope compositions provide evidence that fluid fluxes were greater in ophiolite sections. Gillis and Banerjee (2000) have suggested that alteration patterns and styles in most ophiolite sections resemble forearc crust more than mid-ocean ridge crust. The upper greenschist to lower amphibolite facies mineral assemblages found in the basal parts of the sheeted-dike complex in the deepest drill hole in oceanic crust (ODP Hole 504B in the eastern equatorial Pacific) are consistent with thermodynamic predictions of mineral assemblages in the root zones of hydrothermal vent fluids (Bowers et al. 1985). The chemical composition of hydrothermal vent fluids implies temperatures of fluid–rock interaction around 420 to 440°C (Seyfried et al. 1991). The conceptual model, therefore, is that black smoker vent fluids rise from the root zones to the seafloor fairly rapidly and undergo cooling (adiabatic and conductive) by a few tens of degrees.

**TAG Hydrothermal Mound**

One of the largest and best-studied seafloor hydrothermal systems is the TAG hydrothermal mound at 26°N on the MAR (Humphris et al. 1995). In 1994, the Ocean Drilling Program drilled several holes into the 200 m diameter and 50 m high sulfide mound, which hosts active black and white smoker complexes. Drilling revealed a complex internal stratigraphy, a dominance of breccias, and a distinct mineralogical zonation, all of which are very similar to features in massive sulfide deposits in ophiolites, such as the Troodos massif on Cyprus (Humphris et al. 1995). The upflow zone of hydrothermal fluids is zoned vertically and horizontally, with extensive, massive, brecciated pyrite ore at the top of the deposits, grading progressively downwards into silica–anhydrite breccias, which overlie a lowermost silica–pyrite–chlorite zone (Fig. 2). The chlorite zone develops where upwelling hydrothermal solution mixes with seawater that has been entrained into the upflow zone. In the shallow and permeable parts of the system, mixing between hot hydrothermal fluids and seawater leads to precipitation of anhydrite and pyrite. Anhydrite plays a major role in the construction of the deposits. It is precipitated through conductive heating of small amounts of entrained seawater, forming a structural framework during periods of high-temperature activity; these are followed by periods of inactivity during which anhydrite dissolves and causes the structure to collapse (Humphris et al. 1995). TAG is one of the largest sulfide deposits known in the oceans (4 million tons of sulfide with 30,000–60,000 tons of Cu) and is similar in size to ancient sulfide deposits in ophiolites.

**Serpentinite-Hosted Systems**

Five active hydrothermal systems hosted in serpentinized peridotite with interspersed gabbro have been discovered along the northern MAR. They are located close to ridge discontinuities and segment ends and are known as the Rainbow (36°N), Logatchev (15°N), Ashadze (13°N), Saldanha (36°N), and Lost City (30°N) fields. These hydrothermal systems vary in venting temperature, fluid composition, and type of hydrothermal deposit, but they are all characterized by high concentrations of H₂ and CH₄ attributed to seawater interaction with ultramafic rocks (Charlou et al. 2002; Kelley et al. 2005). The Rainbow, Logatchev, and Ashadze fields are high-temperature (black smoker) systems, in which sulfides are deposited from low-pH and low-temperature fluids (Fig. 3a). The heat output from Rainbow has been estimated at 1–5 GW (Thurnherr and Richards 2001), making it the vent field with the largest heat flux yet discovered. High heat and fluid output, as well as the formation of sulfide deposits and high CO₂ concentrations in the fluids, suggest that hydrothermal circulation in these high-temperature systems is likely driven by yet-to-be-detected crystallizing magma bodies within the lithospheric mantle.

The Lost City hydrothermal field is located on 1–1.5-million-year-old serpentinized mantle rocks, 15 km west of the MAR axis, and is distinctly different from all other known marine hydrothermal systems (Fig. 3B). At Lost City, carbonate–brucite structures up to 60 m high have formed where clear, high-pH (9–11) fluids exit onto the seafloor from faults in serpentine-dominated basement rocks. The fluids are up to 91°C and are depleted in metals and CO₂, but they have high concentrations of H₂ and CH₄ (and other low-molecular-weight hydrocarbons), which serve as important energy sources for anaerobic microorganisms within the porous chimney walls (Kelley et al. 2005; Proskurowski et al. 2008). Stable isotope and radiocarbon measurements on methane venting at Lost City have demonstrated that the methane is derived abiotically from mantle CO₂ and not from seawater bicarbonate. This implies that seawater bicarbonate carried in recharge fluids is largely removed, presumably by carbonate precipitation before the abiogenic reactions that form methane occur (Proskurowski et al. 2008).

Low- to moderate-temperature serpentinization reactions play a key role in the production of high-pH fluids. Therefore, they have important consequences for the sequestration of CO₂ from seawater—an area of research that has stimulated considerable interest in the industrial and scientific communities.
OCEAN–CRUST EXCHANGE

From the heat and geochemical budgets, one can determine that about 1–4 TW of heat are exchanged between the ridges and the oceans (Sleep 1991; Elderfield and Schultz 1996). This axial heat flux is only a small fraction of the total oceanic hydrothermal heat flux of 11 TW. The remaining heat is transported off-axis in ridge-flank crust up to roughly 65 million years in age. The hydrothermal systems associated with these hydrologically active ridge flanks are low temperature (<65°C), producing lower zeolite–facies alteration in the rocks.

The budget of Mg—a major cation in seawater—can be explained only by considering both types of hydrothermal circulation (Mottl and Wheat 1994). Mg is lost from seawater during interaction with oceanic crust at all temperatures, but removal becomes essentially complete at temperatures above 100°C. Several 10^{13} kg of seawater are fluxed through on-axis hydrothermal systems per year. The fluids become enriched in Ca, SiO₂, alkalis, base metals, and sulfide but depleted in Mg, U, P, and sulfate. In general, oceanic crust is either a source or a sink for the elements dissolved in the oceans. Carbon dioxide, for example, is added to the oceans by magmatic degassing along mid-ocean ridges, but ridge-flank alteration removes CO₂ at about the same order of magnitude (1–2×10^{12} moles/y; Alt and Teagle 1999). Likewise, alkali elements are leached from the rocks by seawater-derived fluids in high-temperature, axial, hydrothermal processes, while in low-temperature ridge-flank systems, they are transferred from the circulating seawater to the oceanic crust. The net effect is that oceanic crust is a prominent sink for alkali elements, as well as other elements, like boron and uranium. Hydrous minerals (smectites, zeolites) and carbonates form in these ridge-flank systems and slowly seal the crust, which also becomes increasingly insulated from the ocean by the accumulation of sediments. Sediments and alteration minerals provide an important source of water and CO₂ in subduction zones.

SEAFLOOR VENTS AND LIFE

The discovery of hydrothermal vents in the deep sea more than 30 years ago led to the recognition that geological processes along mid-ocean ridges support rich and diverse chemosynthetic ecosystems at the seafloor. In contrast to the ocean surface, water column, and marine sediments, where essentially all life depends directly or indirectly on photosynthetic energy, vent communities are fuelled by chemical energy from the deep Earth (Fig. 3A). Magma degassing and reactions between seawater and lithosphere support chemosynthetic ecosystems in many submarine geontectonic settings, such as mid-ocean ridges, intraplate volcanoes, forearcs, back-arc basins, submarine arc volcanoes, continental margins, and ridge flanks (Fig. 4). What all these environments have in common is high energy potential in the form of redox disequilibria.

Chemosynthetic microorganisms that derive metabolic energy from the enzymatic catalysis of redox reactions are the basis of the food web in the deep oceans (Fig. 4). These organisms harness energy through electron transfer from a reduced to an oxidized chemical compound for their metabolic needs. They thrive wherever reduced compounds, released by magma degassing or water–rock interactions,
and oxidants mix, whether within the oceanic crust, at the seafloor, or in particle plumes originating from vent sites. Microorganisms can also mine energy from oxidizing solids such as rocks, volcanic glass, and sulfide minerals deposited at hydrothermal vents. Even at sites remote from spreading axes and thermal vents, chemosynthesis plays a role in bare-rock systems in the deep ocean (Edwards et al. 2005).

Geochemical energy is also released where $H_2$ is generated by hydrolysis during the reaction of water with reduced Fe (or other metals) in basaltic glass or in Fe-rich minerals such as olivine. Dissolved $H_2$ generated in this way can be combined with $CO_2$ and $SO_2$ by methanogens and sulfate reducers. In serpentinizing environments, such as at Lost City, microbial communities of archaea and bacteria are supported by such hydrogen-rich vent fluids (Kelley et al. 2005), and these systems provide insight into early metabolic pathways on Earth (Martin et al. 2008). Vent microorganisms can use this geochemical energy in a wide range of aerobic and anaerobic processes, many of which have not yet been fully explored.

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Carbon dioxide is produced by metamorphic reactions in orogenic belts and high-heat-flow systems. Part of this carbon is ultimately released to the atmosphere, but the long timescale of regional metamorphism implies that the short-term effects on the environment are minor. However, contact metamorphism around igneous sill intrusions in organic-rich sedimentary basins has the potential to generate huge volumes of CH$_4$ and CO$_2$, and these gases are rapidly released to the atmosphere through vertical pipe structures. The high flux and volume of greenhouse gases produced in this way suggest that contact metamorphic processes could have a first-order influence on global warming and mass extinctions.

**Keywords:** metamorphic carbon degassing, contact metamorphism, large igneous provinces, volcanic basins, rapid environmental changes

**INTRODUCTION**

Carbon-bearing fluids are constantly seeping from the lithosphere to the Earth’s surface and into the atmosphere (e.g. Kerrick 2001; Morner and Etiöpe 2002). In some places, such as young mountain ranges and high-heat-flow zones, the seepage is more intense than in others. In these settings, fluid expulsion at the Earth’s surface is a reflection of metamorphism taking place many kilometers below the surface. Hot springs and mud pots are familiar surface manifestations of metamorphic fluid production. The processes behind the production of C-rich volatiles include reactions that transform carbonates, feldspar, and quartz into amphibole, epidote, pyroxene, garnet, and CO$_2$ (e.g. Kerrick et al. 1991). Key questions include: How much CO$_2$ can be generated and released by metamorphic processes? And how fast? Can the degassing trigger rapid global warming and make an impact on life on Earth?

Pioneering work by Derrill M. Kerrick and coworkers in the 1990s attempted to link Cenozoic greenhouse events (see Zachos et al. 2001) to large-scale CO$_2$ degassing caused by prograde metamorphism of carbonate-bearing rocks (Kerrick et al. 1995; Nesbitt et al. 1995). It was proposed that regional metamorphism and contact metamorphism around plutons in western North America in the Eocene released large amounts of metamorphic CO$_2$, with an areaintegrated CO$_2$ flux of about 3 × 10$^{18}$ mol Myr$^{-1}$ (equivalent to 0.13 gigatons (Gt) per year) and that the degassing could have contributed to Eocene greenhouse conditions (Nesbitt et al. 1995; Kerrick and Caldeira 1998). Such abundant CO$_2$ degassing would have exceeded CO$_2$ consumption by silicate weathering (Kerrick and Caldeira 1993). An Early Cenozoic climatic effect of CO$_2$ degassing by Himalayan regional metamorphism was however discarded (Kerrick and Caldeira 1999), but new data suggest that present-day regional metamorphism is a net supplier of CO$_2$ to the atmosphere (Becker et al. 2008; Evans et al. 2008).

The relatively short duration of Cenozoic greenhouse gas–driven events, which lasted less than 200,000 years, relative to the long duration of orogenesis is a major challenge for the hypothesis that metamorphic CO$_2$ has affected climate. Several rapid global warming events and mass extinctions are known from the geological record, including the Paleocene-Eocene thermal maximum (PETM; 55 million years [Ma]), the Toarcian (183 Ma), the end-Permian (252 Ma), and the Triassic-Jurassic (200 Ma) (e.g. Wignall 2001; Courtillot and Renne 2003). The triggering mechanisms of these events are poorly understood. Gas hydrate dissociation, sluggish ocean circulation and anoxia, CO$_2$ degassing of lava, and CH$_4$ degassing during metamorphism are among the hypotheses that have been proposed (e.g. Wignall 2001; Cohen et al. 2007; Knoll et al. 2007). However, the temporal correlations among these environmental events, the formation of large igneous provinces (LIPs), and contact metamorphism in sedimentary basins intruded by LIP magmas (Table 1) suggest a causal relationship.

**VOLCANIC BASINS AND LIPS**

Contact metamorphism in sedimentary basins occurs when hot and partly molten igneous intrusions heat the country rocks. These sedimentary basins are called volcanic basins. The igneous intrusions are often basaltic and emplaced during LIP formation. Volcanic basins are common along volcanic rifted margins and on cratons (Fig. 1). The intrusions commonly form sheet-like sills and dikes. Sills are commonly sandwiched between sedimentary sequences and can be more than 350 m thick. Because sedimentary basins are among the main crustal reservoirs of organic and inorganic carbon (e.g. IPCC 2001), they have a huge potential for CH$_4$ and CO$_2$ generation. A link between contact metamorphism and the PETM was proposed in 2004, based on detailed seismic imaging and borehole studies in the Voring and Møre basins, offshore Norway (Svensen et al. 2004). This hypothesis provided a new framework for investigating the environmental consequences of metamorphism. The cornerstone of the theory is that gas is rapidly generated from heated organic material in metamorphic aureoles and is subsequently released to the atmosphere as greenhouse gas. Recent results have provided strong evidence that a similar explanation applies

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* Center for Physics of Geological Processes (PGP), University of Oslo  
P.O. Box 1048 Blindern, N-03176 Oslo, Norway  
E-mail: hensven@fys.uio.no
to other climate events, including the Toarcian (Lower Jurassic), the Triassic-Jurassic, the end-Permian, and the end-Guadalupian (e.g. McElwain et al. 2005; Beerling et al. 2007; Svensen et al. 2007, 2009; Retallack and Jahren 2008; Ganino and Arndt 2009). This hypothesis is supported by geological constraints (e.g. observed contact aureoles, sill intrusions, and vertical pipe structures) as well as the fact that metamorphism of organic carbon leads to generation of $^{12}C$-enriched $CH_4$, which better explains the available geochemical data than the emission of $^{12}C$-depleted mantle $CO_2$ as a result of the degassing of LIP lava.

**CONTACT METAMORPHISM AND CARBON DEGASSING**

Vast volumes of sedimentary rocks are heated in volcanic basins following sill emplacement (Fig. 1; Table 2). Sill intrusions can extend laterally over several hundred kilometers, with thicknesses commonly in the 50–200-meter range, and they can dominate the geology of sedimentary basins (Fig. 2a). A single sill could fill a volume of 5,000 to 20,000 km$^3$. Considering that the thickness of the metamorphic aureole on each side of the sill is commonly about the same as the sill thickness, the volume of heated sediments could be as much as 40,000 km$^3$. Because the contact aureoles reach peak metamorphic conditions (typically 400–500°C) shortly after sill emplacement (tens to hundreds of years), the metamorphic reactions and associated fluid production are also very fast. If only 1 wt% of the organic carbon in shale or siltstone is transformed into gaseous carbon compounds, the gas production potential associated with a 5,000–20,000 km$^3$ sill is 230–920 Gt C (corresponding to a greenhouse gas equivalent of 310–1200 Gt methane, $CH_4$). This means that a single melt batch injected into an organic-rich sedimentary basin can generate sufficient methane to cause global warming (Svensen et al. 2004, 2007).

In volcanic basins, there is abundant evidence for rapid injection of the aureole-generated gases into the atmosphere. When sedimentary rocks are heated by magma, decomposition of organic matter, mineral dehydration (generating $H_2O$ and $CO_2$), and pore fluid expansion or boiling occur on a timescale of years. The resulting over-pressure can lead to hydrofracturing and the formation of breccia pipes and hydrothermal vent complexes (e.g. Jamtveit et al. 2004). In the Karoo Basin, South Africa, hydrothermal vent complexes commonly formed in the uppermost 400–500 meters of the basin (Fig. 2). In addition, numerous breccia pipes are rooted in contact aureoles in black shale at deeper levels in the basin (Svensen et al. 2007). Baked grey shales that have lost their organic carbon remain in the pipes (Fig. 3). Vent structures and breccia pipes are characteristic features of many volcanic basins, including the Voring and More basins, the Faroe-Shetland

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**Table 1 MAJOR VOLCANIC BASINS, LARGE IGNEOUS PROVINCES (LIPS), AND ENVIRONMENTAL CHANGES**

<table>
<thead>
<tr>
<th>Volcanic basin</th>
<th>LIP</th>
<th>Sill age (Ma)</th>
<th>Event</th>
<th>Pipe structures</th>
<th>CIE</th>
<th>Mass extinction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voring and More (Norway)</td>
<td>Northeast Atlantic</td>
<td>55.6</td>
<td>PETM</td>
<td>yes</td>
<td>yes</td>
<td>minor</td>
</tr>
<tr>
<td>Karoo (South Africa)</td>
<td>Karoo-Ferrar</td>
<td>182.6</td>
<td>Triassic-Jurassic boundary</td>
<td>yes</td>
<td>yes</td>
<td>minor</td>
</tr>
<tr>
<td>Amazonas (Brazil)</td>
<td>CAMP</td>
<td>~200</td>
<td>Triassic-Jurassic boundary</td>
<td>yes</td>
<td>yes</td>
<td>major</td>
</tr>
<tr>
<td>Solimoes (Brazil)</td>
<td>CAMP</td>
<td>~200</td>
<td>Triassic-Jurassic boundary</td>
<td>yes</td>
<td>yes</td>
<td>major</td>
</tr>
<tr>
<td>Tunguska (Russia)</td>
<td>Siberian Traps</td>
<td>~252</td>
<td>Permian-Triassic boundary</td>
<td>yes</td>
<td>yes</td>
<td>major</td>
</tr>
<tr>
<td>Sichuan (China)</td>
<td>Emeishan Traps</td>
<td>~261</td>
<td>End-Guadalupian</td>
<td>?</td>
<td>?</td>
<td>major</td>
</tr>
</tbody>
</table>

Abbreviations: PETM = Paleocene-Eocene thermal maximum; CAMP = Central Atlantic Magmatic Province; CIE = carbon isotope excursion.

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**Figure 1** Distribution of large igneous provinces (LIPS; basalt lava flows in red) and volcanic basins. Sedimentary basins injected by sills and dikes (i.e. volcanic basins) mentioned in the text are outlined with heavy lines. Other major volcanic basins are indicated by black filled circles.
In the Siberian Tunguska Basin, spectacular pipes with up to 1.6 km wide subaerial explosion craters formed during the latest Permian. A schematic cross section of a volcanic basin with pipe structures is shown in Figure 4. In marine settings, such as the Voring Basin, the craters can be more than 10 km in diameter (Planke et al. 2005).

SEDIMENT COMPOSITION AND ENVIRONMENTAL EFFECTS

The chemical composition of the sedimentary rocks heated by igneous intrusions has a profound influence on the metamorphic fluid composition (e.g. Svensen et al. 2004, 2009; Ganino and Arndt 2009). An overview of the sediment types heated in various volcanic basins is given in Table 2. For example, organic-rich shale generates CH₄ during contact metamorphism, whereas coal generates fluids enriched in CO₂. Both generate water by dehydration. Because many sedimentary basins contained hydrogen-rich kerogen and oil and gas accumulations at the time of sill emplacement, petroleum-derived gases such as CH₄ and C₂H₆ may dominate the metamorphic fluid. If limestones or dolostones are heated, the generated fluid is dominated by ¹³C-enriched CO₂, but if organic matter or graphite is present, the fluid contains ¹³C-depleted CH₄. Evaporites with anhydrite and rock salt can generate SO₂ and HCl, and if organic matter or petroleum is present, CH₄ and halocarbons such as CH₃Cl (methyl chloride) and CH₃Br can also form. Halocarbon generation was recently confirmed by experiments in which natural rock salt from the Tunguska Basin in eastern Siberia was heated to 275°C, to simulate contact metamorphism (Svensen et al. 2009).

In eastern Siberia, a major sill-emplacement event took place at the end of the Permian, when thick sills were injected throughout the basin. Mass-balance calculations suggest that 10,000–30,000 Gt C could have been generated during contact metamorphism of organic matter, accompanied by 4,500–13,000 Gt CH₃Cl (Svensen et al. 2009). The presence of hundreds of pipe structures rooted in evaporitic rocks suggests that the gases were released to the atmosphere. Thus the end-Permian global warming event could have been triggered by aureole degassing. Recent atmospheric modeling showed that >1000 Gt of methyl chloride are required to cause significant stratospheric warming.

### Table 2: Key Facts about Volcanic Basins

<table>
<thead>
<tr>
<th>Volcanic basin</th>
<th>Area with sills (x 1000 km²)</th>
<th>Sills in black shale</th>
<th>Sills in evaporite</th>
<th>Sills in carbonates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voring and More (Norway)</td>
<td>85</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Karoo (South Africa)</td>
<td>390</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Amazons (Brazil)</td>
<td>200</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Solimoes (Brazil)</td>
<td>600</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Tunguska (Russia)</td>
<td>2000</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Sichuan (China)</td>
<td>200</td>
<td>?</td>
<td>?</td>
<td>yes</td>
</tr>
</tbody>
</table>

### Figures

**Figure 2** Sills and pipes in the Karoo Basin, South Africa. (A) The Golden Valley sill complex with its saucer-shaped intrusions (see Polteau et al. 2008). The dolerite sills are about 100 meters thick and were emplaced in sandstones and mudstones. Sill intrusions are associated with all the hills in the background. Photo: Sverre Planke (B) Breccia pipes in the Loriesfontein area in the western part of the basin. The pipes are seen as black dots with circular, light grey alteration haloes. A dirt road in the lower half of the image gives the scale. (C) The Witkop III hydrothermal vent complex (Svensen et al. 2006) represents an infilled crater formed in the Lower Palaeozoic paleosurface by degassing of fluids released during contact metamorphism deeper in the basin.

**Figure 3** Photograph of drill core showing contact metamorphism of black shale in a breccia pipe in the Calvinia area, western Karoo Basin (Svensen et al. 2007). The original shale was black, and contact metamorphism transformed the organic matter into gas, causing a change in color to grey. Secondary bleaching (white) in the sample was caused by reaction with hydrothermal fluids within the breccia and the precipitation of sulfides.

**Figure 4** Schematic cross section of a sill intrusion with an associated contact aureole and hydrothermal vent complex.
CONTACT VERSUS REGIONAL METAMORPHISM

Regional metamorphism is unlikely to cause short-term global climate changes for two main reasons: (1) The timescale of orogeny and crustal extension is long, typically >5 million years, whereas the relevant climatic events occur on a timescale of a few hundred thousand years or less. (2) Regional metamorphism of carbonates generates 13C-depleted CO2, whereas available geological data show that the carbon responsible for Eocene global warming was enriched in 13C (e.g., Dickens et al. 1997; Zachos et al. 2001). Contact metamorphism in volcanic basins is a far more likely mechanism for transferring greenhouse gases to the atmosphere on a short timescale. This scenario provides causal connections between flow processes taking place in the deep interior of the Earth, heat transfer to the shallow crust by rising magma bodies, associated contact metamorphism of carbon-bearing sedimentary rocks, release of massive volumes of greenhouse gases, and associated climate change. In this sequence of events, contact metamorphism represents a critical link that even connects the biosphere to the bowels of the Earth.

ACKNOWLEDGMENTS

This study was supported by a Centre of Excellence Grant to PGP and by a Young Outstanding Researcher grant and a PetroMaks to H. Svensen, all from the Norwegian Research Council. We thank Sverre Planke for introducing us to volcanic basins and for providing Figures 1 and 2A, and Luc Chevallier, Alexander G. Polozov, Yuri Y. Podladchikov, Stephane Polteau, and Ingrid Aarnes for collaboration aimed at a better characterization and understanding of metamorphic and hydrothermal processes in volcanic basins. We also thank Susan L. S. Stipp and Michael R. Rampino for reviews.

REFERENCES


LETTER FROM THE PRESIDENT

Dear members of the DMG,

I would like to draw your attention to an important political decision of the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), which might also be of interest to members of other mineralogical societies. The Senate of the DFG recently adopted new regulations to counteract various negative aspects of the flood of publications in research. The new regulations require that (1) researchers submitting proposals and reports to the DFG list only a limited number of eminent publications, and (2) more emphasis be given to the description of the research project. In order to highlight the most important papers on publications lists, applicants will, for example, be restricted to citing a maximum of five publications. Those who do not comply with the new rules will have their proposals and reports returned with a request for revision. The new regulations will be effective as of July 1, 2010.

With this policy change, the DFG resolves to put more emphasis on the quality instead of the quantity of publications and to counteract the general trend of relying heavily on quantitative measurements, such as the h-index of scientists and the impact factor of journals. The new regulations should diminish some of the pressure on scientists to publish as many papers as possible and encourage the publication of fewer but more substantial papers. In my opinion the DFG has taken a courageous step towards more reasonable publication and review policies, and I heartily recommend support of this initiative.

Yours sincerely,
Falko Langenhorst, President

CALL FOR NOMINATIONS FOR THE 2010 PAUL-RAMDOHR AWARD

The Paul-Ramdohr Award (www.dmg-home.de/Paul_Ramdohr.html) will honor young (less than 33 years of age) graduate students who give outstanding presentations (poster or talk) on their master's or PhD research at the upcoming annual DMG meeting in Münster (www.conventus.de/dmg2010/). Nominations for the Ramdohr Award should include the curriculum vitae and publications list of the candidate as well as information about the master's or PhD thesis. Please submit nominations by September 17, 2010, to Timm John, Institute of Mineralogy, University of Münster, Corrensstrasse 24, D-48149 Münster, Germany (e-mail: timm.john@uni-muenster.de).
Prague, the City of a Hundred Spires and the capital of the Czech Republic, will be hosting the 21st annual V. M. Goldschmidt Conference between August 14 and 19, 2011. One thousand years ago Prague was the third-largest European city, and today it has established itself as the fourth-largest tourist destination on the Old Continent (following Paris, London and Rome).

Meeting preparations are in full swing. The conference will take place in the Prague Congress Center, overlooking the historical town quarters, and the 1100-year-old Royal Castle. Once you enter the Congress Center, conveniently located near an underground station, you will be able to reach any of the 20 lecture halls, the poster sessions and the exhibitors' area in less than a minute. The smoothly operating public transport system will take you to the conference venue in less than 30 minutes, regardless of the location of your hotel or student dormitory. Budget accommodation has been negotiated at student dormitories for over 1600 conference participants.

Half-day city sightseeing tours and two-day pre- and post-conference field trips will visit some of the nation's 12 protected UNESCO World Heritage castles and country houses, as well as cities like Cesky Krumlov and Telc, and natural preserve areas.

The scientific program will be a well-balanced mix of high- and low-temperature geochemistry, and biogeochemistry and environmental themes. The Scientific Program Committee of the 21st Goldschmidt Conference, along with the local organising team, look forward to welcoming you all to a stimulating and rewarding gathering in Prague in 2011. In addition to being the geographical centre of Europe, for one week in the middle of August 2011, Prague will hopefully also become the scientific heart of Europe.

Martin Novak
Goldschmidt2011
The EAG awarded the Werner Stumm Medal for advances in low-temperature geochemistry and/or processes at the mineral-water interface. William Casey has been recognized for greatly improving our understanding of reactions between aqueous fluids and mineral surfaces through the use of novel atomic-scale techniques, including atomic force microscopy, elastic recoil detection, Rutherford backscattering, and NMR spectroscopy. Much of his recent work has centered on studying large aqueous clusters, which mimic the behavior of mineral surfaces. He is currently a professor of geology and chemistry at the University of California, Davis. More information about William Casey can be obtained at www.eag.eu.com/WilliamCasey.html.

Charles H. Langmuir is the 2010 recipient of the Urey Medal, awarded by the European Association of Geochemistry for his outstanding contributions to our understanding of the geochemistry of terrestrial basalts. He has shown great intuition in formulating elegant and insightful models for the genesis of magmas at mid-ocean ridges and in arc and back-arc settings. More information about Charles Langmuir is available at www.people.fas.harvard.edu/~langmuir/homepage.html.

This year’s Houtermans Medal was awarded to Karim Benzerara (Institut de Minéralogie et de Physique des Milieux Condensés, Paris), a highly talented young scientist working at the interface between mineralogy and microbiology. Karim has studied a range of problems, reflected in more than 30 peer-reviewed publications in top journals. For example, he has clearly demonstrated that, at least in some instances, so-called nanobacteria are a complex association of minerals and proteins. Using the best microscopy tools, he has shown that carbonate minerals from microbialites, such as stromatolites, are mostly formed on extracellular polysaccharide substances produced by the cells, rather than directly at cell surfaces. For more information about Karim, go to www.ipgg.fr/pages/1611.php.

The French Igneous and Metamorphic Petrology Group promotes its activities in coordination with the SFMC. One of the first activities of the GPE is to bring together researchers working in a broad spectrum of igneous, metamorphic, and structural petrology, including the study of natural and synthetic samples, field projects, etc. The main aim of the group is to provide information to members via a mail distribution list, a website, and an annual scientific meeting. While the website is under construction, more information about GPE and its activities can be obtained from Michel Grégoire, the initiator of the group (michel.gregoire@dtpt.obs-mip.fr).

The Society will hold two training days in Paris, France (Pierre and Marie Curie University) on November 30 and December 1, 2010. These days will be devoted to reviewing a wide range of technical tools and, in the spirit of the previous sessions held in 2000, 2002, and 2004, will be open to a large audience of PhD students, engineers, and researchers. Each invited speaker will present one or two analytical methods suitable for the study of minerals and/or fluids. The speakers will show how parameters determined at molecular or nanometer scales can provide important constraints for understanding global processes. The organizing committee comprises Anne-Line Auzende (Anne-Line.Auzende@impmc.upmc.fr), Marc Blanchard and Etienne Balan. Further information can be obtained at http://sfmc-fr.org.

This year’s Houtermans Medal was awarded to Karim Benzerara (Institut de Minéralogie et de Physique des Milieux Condensés, Paris), a highly talented young scientist working at the interface between mineralogy and microbiology. Karim has studied a range of problems, reflected in more than 30 peer-reviewed publications in top journals. For example, he has clearly demonstrated that, at least in some instances, so-called nanobacteria are a complex association of minerals and proteins. Using the best microscopy tools, he has shown that carbonate minerals from microbialites, such as stromatolites, are mostly formed on extracellular polysaccharide substances produced by the cells, rather than directly at cell surfaces. For more information about Karim, go to www.ipgg.fr/pages/1611.php.

The SFMC gets a new website! The Society is pleased to invite you to visit its fully redesigned website at www.sfmc-fr.org. The new architecture of this dynamic website, built using the user-friendly SPIP CMS publishing system, will allow more efficient updates and enrichments. New links to mineralogical databases, job offers, meetings, and information related to the new SFMC working groups (“Synchrotron” and “Igneous Petrology”) will be posted on the site. Contributions from the mineralogical community are welcome, and people wishing to post information are invited to contact Étienne Balan, Anne-Line Auzende, or Bertrand Devouard (sfmc@ccr.jussieu.fr).

The RST Earth sciences meeting will be held in Bordeaux on October 25–29, 2010. This joint FFG-SGF-SFMC meeting occurs every two years and brings together about 600 scientists from various fields in the Earth sciences. The meeting will be held on the Talence campus of the École Nationale Supérieure d’Électronique, Informatique & Radiocommunications of Bordeaux (ENSEIRB). RST offers to students and senior scientists the opportunity to present their most recent work. More than 600 oral communications and 200 posters will be presented to academic and industrial geoscientists. Nine thematic sessions will be offered: Earth observation, geophysics and physical geology, geohazards; Sedimentary basins, characterization of deposits, processes, hydrocarbon-bearing rocks; Geological fluids; Mineralogy and mineral resources; Paleoenvironments, paleoclimates; Erosion and sedimentary transport from continent to ocean; Geodynamics, tectonics, magmatism; Education, valorization, applications of geosciences; Transverse sessions. Seven fieldtrips (pre- and postmeeting) are proposed. Information is available on the website www.rst2010.epoc.u-bordeaux1.fr.
MSA has a close association with the Geological Society of America, particularly at the GSA Annual Meeting, which is MSA’s annual meeting as well and where MSA holds its awards luncheon, awardee lectures, annual business meeting, and a joint reception with the Geochemical Society. As an “associated society” of GSA, MSA sponsors technical sessions, and our representatives (currently Jim Beard and Phil Brown) are members of the Joint Technical Program Committee, which organizes the session schedule. Last fall, GSA established its Mineralogy, Geochemistry, Petrology, and Volcanology (MGPV) Division, which now has over 800 members, many of whom are also MSA members. The new MGPV Division is already stimulating more activity and interest in MSA fields at GSA meetings. This is apparent in the list of technical sessions announced for Denver, which includes 49 sessions that fit into one or more of the MSA fields (mineralogy, crystallography, geochemistry, petrology), making it a good meeting for MSA members to attend.

One highlight of the meeting this year will be a Pardee Symposium on Mineral Evolution. This event is being organized by Bob Hazen and will feature as speakers the authors of articles on this topic that appeared in the February 2010 issue of Elements. This will be a great opportunity to bring Elements to the attention of a broader community and may serve as a model for future Elements-based symposia at GSA and other meetings.

Two technical sessions will honor MSA awardees: T57, “Frontiers in Experimental Petrology: In Honor of Robert C. Newton, Recipient of the 2010 Roebling Medal,” organized by Craig Manning, John Ferry, and David Jenkins. And T102, “Structure, Properties, and Geochemistry of Nanoparticles, Nanoclusters, and Nanocomposites in Biogeochemical Systems: In Honor of Benjamin Gilbert, Recipient of the 2010 MSA Award,” organized by Glenn Waychunas and Jill Banfield. In addition, the Roebling Medal and MSA Award lectures will be delivered by the recipients themselves.


It’s time to make your plans for Denver 2010. The GSA abstract deadline is 10 August. I look forward to seeing many of you at the meeting. When you register, be sure to get a ticket to the joint MSA-GS reception, which will now be cosponsored by the MGPV Division of GSA. And remember to submit the paper you create from your GSA presentation or poster to American Mineralogist!

John Brady, jbrady@smith.edu
2010 MSA President
2010–2011 MSA Distinguished Lecturers

The Mineralogical Society of America is pleased to announce its Distinguished Lecturers and their lectures for 2010–2011:

David Dobson
- How Juicy Is the Earth’s Inner Core? Reconciling Mineral Physics and Seismological Observations
- Deforming the Earth: Runny Solids in the Deep Mantle

Craig E. Manning
- In Deep Water: New Insights into Geologic Fluids in the Deep Crust and Upper Mantle
- How Efficient is Earth’s Volatile Recycling Program?

Terry Ann Plank
- Are the Oceans Shrinking? The Subduction Zone Water Cycle
- Hot and Cold Slabs: New Constraints from Mineral–Fluid Thermometers

The schedule of the Lecturers’ tours will be posted on the MSA website (www.minsocam.org). Check to see if they may be at a location near you. MSA expresses its appreciation to these individuals for undertaking such a service to our science.

IN MEMORIAM

Michael Seal (Member – 1964)
Kenzo Yagi (Member – 1940)
Gordon L. Davis (Life Fellow – 1949)
Eric J. Essene (Senior Fellow – 1975)
Peter B. Nalle (Senior Member – 1942)

Elements
June 2010

Mineralogical Society of America and Geochemical Society

Short Course Announcement

DIFFUSION IN MINERALS AND MELTS

December 11–12, 2010
Napa Valley Marriott Hotel & Spa
Napa, CA, USA
(before Fall AGU Meeting)

Convenors

Youxue Zhang
University of Michigan

Daniele Cherniak
Rensselaer Polytechnic Institute

The short course will focus on diffusion of all elements in minerals and melts at high to moderate temperatures. Topics include: theoretical background on diffusion, experimental methods and analytical techniques in diffusion studies, and summary and assessment of diffusion data in minerals and melts.

More information and registration: www.minsocam.org

The Geological Society of America
Reaching New Peaks in Geoscience
31 Oct. – 3 Nov. 2010
Colorado Convention Center
Denver, Colorado, USA
Abstract Deadline: 10 August 2010

www.geosociety.org

VOTE
2010 MSA ELECTIONS
THE PRESIDENT’S CORNER

Earlier this year, the Executive Committee of CMS was very pleased to grant Jim Aronson of Dartmouth College permission to make a DVD of a video of the Pioneer Lecture delivered in 1993 by Linus Pauling at the annual meeting of the Society in San Diego (USA). Jim wanted to make copies of the DVD for use in teaching an advanced undergraduate course to his students. I did not participate in the 1993 meeting myself but I have often heard it mentioned at the Society’s annual meetings as this Pioneer Lecture is clearly etched in the memory of those who heard it. The Pioneer Lecturer is chosen by the local organizers of the Society’s annual meetings, and it was Dick Berry who invited Linus Pauling to deliver the 1993 lecture. It was an inspired choice and the lecture clearly inspired those who heard it – many felt privileged to have heard this wonderful scientist deliver what turned out to be his last public lecture as he died the following year. I am sure that you will find Jim’s article on these CMS news pages interesting, and it is gratifying to know that today’s geology students can still be fascinated by a lecture delivered by a 92-year-old pioneering scientist at a CMS meeting 17 years ago.

Anyone wishing to purchase a DVD of this wonderful lecture can order it using the link https://cms.clays.org/publications.html. The lecture is the last item listed under “Audio Visuals.”

Derek Bain, President, The Clay Minerals Society
The Macaulay Institute, Aberdeen, UK
d.bain@macaulay.ac.uk

LINUS PAULING – AN INSPIRATION

I just finished teaching a brand new course in Earth sciences at Dartmouth College, which I called Mineralogy and Earth Processes. Our goal was to examine the transformations of minerals that occur in various Earth processes, such as weathering, diagenesis, and metamorphism. The course culminated this March with a 5-day traverse across the central Appalachians, where we viewed in their natural geological context practically every rock type and most minerals that we discussed in class.

We used the phyllosilicates for in-depth study of their mineral chemistry and structure, and showed how we (and nature!) can build each crystal structure of a protein (hemoglobin); and to Pauling (Peace prize)—all of them followed in the footsteps of Pauling, who possessed an uncanny knack for fitting atoms of a certain size, valence, and bonding mode into crystal structures using mental and real physical models.

One highlight of my course was to show the class my copy of The Clay Minerals Society’s 1993 video of Linus Pauling’s last public lecture. It was with great admiration that I could say it was The Clay Minerals Society who invited him to their annual meeting in San Diego to be their featured banquet speaker and deliver the Pioneer Lecture. What a fabulous idea, and how appropriate to match the Society with the speaker. He was 92 years old and here he was coming to our Society, which could basically trace its roots to his initial crystal-structure discoveries at Caltech (we learn on the video about his personal very humble beginnings at the Oregon School of Agriculture). Here was this extremely vigorous gentleman with a wonderful sense of humor looking pretty much as I remembered him when I was a graduate student at Caltech 50 years ago. The class got the impression that the honor was mutual, and he appreciated going back to his own roots in delivering this talk. The first quarter of the video was on Society business, which I fast-forwarded, but not without pointing out the intimate nature of the Pioneer Lecture is clearly etched in the memory of those who heard it. The Pioneer Lecturer is chosen by the local organizers of the Society’s annual meetings, and it was Dick Berry who invited Linus Pauling to deliver the 1993 lecture. It was an inspired choice and the lecture clearly inspired those who heard it – many felt privileged to have heard this wonderful scientist deliver what turned out to be his last public lecture as he died the following year. I am sure that you will find Jim’s article on these CMS news pages interesting, and it is gratifying to know that today’s geology students can still be fascinated by a lecture delivered by a 92-year-old pioneering scientist at a CMS meeting 17 years ago.

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Derek Bain, President, The Clay Minerals Society
The Macaulay Institute, Aberdeen, UK
d.bain@macaulay.ac.uk

LINUS PAULING – AN INSPIRATION

I just finished teaching a brand new course in Earth sciences at Dartmouth College, which I called Mineralogy and Earth Processes. Our goal was to examine the transformations of minerals that occur in various Earth processes, such as weathering, diagenesis, and metamorphism. The course culminated this March with a 5-day traverse across the central Appalachians, where we viewed in their natural geological context practically every rock type and most minerals that we discussed in class.

We used the phyllosilicates for in-depth study of their mineral chemistry and structure, and showed how we (and nature!) can build each crystal structure of a protein (hemoglobin); and to Pauling (Peace prize)—all of them followed in the footsteps of Pauling, who possessed an uncanny knack for fitting atoms of a certain size, valence, and bonding mode into crystal structures using mental and real physical models.

One highlight of my course was to show the class my copy of The Clay Minerals Society’s 1993 video of Linus Pauling’s last public lecture. It was with great admiration that I could say it was The Clay Minerals Society who invited him to their annual meeting in San Diego to be their featured banquet speaker and deliver the Pioneer Lecture. What a fabulous idea, and how appropriate to match the Society with the speaker. He was 92 years old and here he was coming to our Society, which could basically trace its roots to his initial crystal-structure discoveries at Caltech (we learn on the video about his personal very humble beginnings at the Oregon School of Agriculture). Here was this extremely vigorous gentleman with a wonderful sense of humor looking pretty much as I remembered him when I was a graduate student at Caltech 50 years ago. The class got the impression that the honor was mutual, and he appreciated going back to his own roots in delivering this talk. The first quarter of the video was on Society business, which I fast-forwarded, but not without pointing out the intimate nature of the special, welcoming society. The first part of Dr. Pauling’s talk was about his determinations of some of the first crystal structures of inorganic compounds—it was a major effort for him to grow sufficiently large, near-perfect crystals of these compounds. The latter part of the video focused on his determinations of the structure of the micas, about which the students were now pretty good experts. Dr. Pauling showed slides, many of them hand-composed, overhead-type drawings. If there was any sense of his age, it was that he himself could not see his own slides. Notably he used multiple “I-beam” TO and TOT columns in his slides as short-hand cartoons to symbolize the various phyllosilicate structures, just as we did in class. We wondered out loud if he was the one who invented that.

It was particularly gratifying to point out to these budding Dartmouth geologists that among the several CMS officers sitting up front beside Dr. Pauling at the podium was the distinguished clay mineralogist Dennis Eberl, who about 45 years ago sat as a Dartmouth undergraduate, possibly in that very classroom. And the gentleman next to Dr. Pauling on the right of the podium was Dennis Eberl’s Dartmouth professor, Bob Reynolds. I could point to Bob’s photo on display alongside the photos of all the Dartmouth professors of the past.

Looking back, we owe a great deal of thanks to those past CMS officers who planned the 1993 meeting, and in particular to Dick Berry, the meeting organizer, who had such bold insight inviting Dr. Pauling. It was an opportunity for us to thank Dr. Pauling for all he gave us through his pioneering discoveries. Watching the video, it gave me pleasure to see his vigor and genuine enjoyment in being at the annual meeting of our CMS.

Jim Aronson, Dartmouth College
Hanover, USA
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CONTINUOUS/Fast-Track Publication

Readers of and authors in Clays and Clay Minerals will be interested to know that we have now deployed an early-publication system for the electronic version of our journal (on both the GSW and Ingenta platforms). In practice, this means that shortly after a paper is accepted, it will be published online and will no longer have to wait, sometimes for six months, while a suitable paper issue is being prepared. In addition, the editorial team is working very hard to reduce review times. Everyone can help with this by turning reviews around in the agreed three-week time frame. Login to the online journals through the CMS website: www.clays.org/JOURNAL/CCMgsw.html.
FROM THE PRESIDENT

One of the core mission activities of IAGC is to sponsor scientific meetings and to contribute to the organization of technical sessions at conferences and symposia of other societies. In this context, 2010 is shaping up to be a busy year for IAGC.

IAGC members are involved at various levels in the 2010 Goldschmidt Conference. Yousif Kharaka is co-convener for theme area 09, Geochemistry of Energy Systems. In theme area 13, Hydrogeochemistry of Earth Surface Processes, Avner Vengosh is co-organizer of the session “Application of Isotopic Approaches to Tracing Contaminant Sources, Transport and Transformations,” and David Long, Berry Lyons, Russell Harmon, LeeAnn Munk, and Sarah Fortner are co-organizers of the session “Solute and Sediment Geochemistry of Fluviatile Systems Past and Present.” In theme area 14, Weathering Interactions in Critical Zone Processes, Tom Bullen is co-chair of the session “Isotope Tracers of Critical Zone Processes and Function.” IAGC members will be keynote speakers in four technical sessions: Sigurdur Gislason in the session “Geochemistry of CO₂ Sequestration: Theory, Modeling, and Field and Laboratory Results”; Susan Brantley in “Lithologic and Erosional Influences on Critical Zone Processes”; Tom Bullen in “Application of Isotopic Approaches to Tracing Contaminant Sources, Transport, and Transformations”; and Kenneth Stollenwerk in “Sustainable Management of Safe Aquifers in Areas Affected by High Groundwater Arsenic.”

Under the direction of Thomas Kretzschmar, the Water–Rock Interaction Working Group will hold the 13th Symposium on Water–Rock Interaction in the world heritage city of Guanajuato, Mexico, on 16–20 August. Information is available at the website http://wri13.cicese.mx/. The IAGC awards ceremony for 2010 will be held as a part of WRI-13.

IAGC will also organize five technical sessions at the Geological Society of America annual meeting, scheduled for 31 October to 3 November, in Denver, Colorado. Robert Seal and LeeAnn Munk are co-conveners of the session “Environmental Geochemistry for Modern Mining,” which will focus on baseline characterization, geochemical characteristics of mine wastestones, ecological and human health effects associated with mine waste and drainage, pit lake geochemistry, and case studies. Kirk Nordstrom is co-convenor of the session “Neutral Mine Drainage: Release, Transport, and Attenuation of Metals and Trace Elements in Circumneutral Mining Environments,” which will examine the geochemistry, mineralogy, and microbiology of metals and trace elements in mining-impacted environments characterized by circumneutral-pH conditions. Russell Harmon will co-chair the session “Geochemical Behavior and Reactivity of Nanostructures in Natural Systems,” which will focus on understanding geochemical reactions and mass transfers at the nanometer scale, especially the formation of nanostructures (e.g. particles, films, and pores) in geologic materials and their effects on geochemical processes. LeeAnn Munk, David T. Long, and W. Berry Lyons are co-conveners, for the 13th consecutive year, of the IAGC-organized session “Sources, Transport, and Fate of Trace and Toxic Elements in the Environment.” This session will include research dealing with trace and potentially toxic elements in the environment, together with applied research topics on trace elements in water, sediment, and rocks with respect to their sources, transport, and fate. Yousif Kharaka is co-convenor of the session “Geochemistry of Geologic Sequestration of CO₂: Understanding Gas–Water–Mineral Interactions over Wide Temporal and Spatial Ranges.” Abstracts may be submitted until 10 August at www.geosociety.org/meetings/2010/sessions/topical.asp.

Russell Harmon, IAGC President

INTRODUCING THE KHARAKA AWARD

The International Association of GeoChemistry is pleased to announce that Dr. Mike Edmunds, Research Director of the Oxford Centre for Water Research, has been selected to receive its highest honour, the Vernadsky Medal. This honour is bestowed biennially on a single person for a distinguished record of scientific accomplishments in geochemistry over the course of his or her career. The award will be presented at the 2010 IAGC awards ceremony, which will be held during the Water–Rock XIII Symposium in Guanajuato, Mexico.

Mike earned his PhD in geochemistry at the University of Liverpool, where he studied the genesis of garnet in polymetamorphic rocks. In 1966, accepting the challenge to move into the growing discipline of hydrogeology, he joined the British Geological Survey, where he held an Individual Merit research position until his recent retirement. During this time, Mike established the BGS hydrogeochemical laboratories and developed what over the years would become recognized as a ‘world-class’ research programme. While at BGS, he developed new methodologies and approaches for the study of hydrogeochemical processes, conducted research that applied innovative trace element and isotope approaches to important hydrological problems, and led several notable palaeohydrological studies.

Mike’s early research was centred in the UK, where he focused on understanding water–rock interaction processes within important aquifers, assessing the hydrological impacts of acid rain and understanding the groundwater geochemistry of geothermal areas. Mike’s BGS work also took him to Russia, Africa and the Middle East, where he developed multi-tracer approaches using trace elements and environmental isotopes. Working mainly in the large sedimentary basins of Libya and the Sahara, he began

VERNADSKY MEDAL TO W. MIKE EDMUNDS

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The global economic problems have put government-supported science budgets at risk. After years of comparative growth, cuts are already with us as the UK research councils tighten their belts, making difficult decisions, for instance, about which facilities and major projects to support. What is clear is that in the future there will be even more focus on near-market research and knowledge-transfer activities, aimed at stimulating economic development. How will this affect mineralogical research and how much (more) will fundamental research suffer? Traditional applied mineralogy research areas, such as environmental mineralogy covering pollution and remediation, will continue to be supported. But where should mineralogists be turning their attention for new funding? The need for more and more imaginative ways to extract raw materials will require people who understand the nature, structures and properties of minerals. The field of novel materials, such as bio-minerals and nano-materials, is fertile ground for applied research, and mineralogists can provide a perspective that materials chemists may be missing. One area where mineralogy will play a pivotal role is in the development of a repository for the safe geological disposal of radioactive wastes — this is now policy in the UK, although several other countries, such as Belgium, France and the USA, have longer track records in this area. Geological disposal is saturated with mineralogical challenges. The performance of high-level waste forms such as glasses and Zr-resistates is being well researched, but there remains a plethora of issues relating to the range of complex legacy waste forms. The evolution and interactions of clays and cements in intermediate-level waste containers, backfills and construction materials are of critical importance. And an understanding of a large number of mineral interactions involving actinides in the host lithology will be needed if the safety case is to be accepted. Some of these topics remain on hold as the UK has yet to decide ‘where’ and in what lithology the repository will go. However, we can hope, at this time of fiscal austerity, that the necessity for high-quality research in this area will lead the government to provide mineralogists with some optimism for their research futures.

R. A. D. Pattrick, President

IAGC Cont’d from page 190

NUCLEAR WASTE MANAGEMENT: RESEARCH CHALLENGES FOR THE FUTURE
28–29 September 2010
Venue: Cambridge
Following on from Richard Pattrick’s comments, online registration for this exciting meeting is now open. Go to www.minersoc.org/pages/meetings/nuclear/nuclear.html for information.

Management of the UK’s nuclear waste presents a major challenge to current and future generations of scientists and technologists, and to existing infrastructure and institutional arrangements. Young researchers entering the field now and over the next four decades will need to build and communicate an integrated understanding of the multi-scale processes involved in the processing, packaging, disposal and regulation of a wide variety of materials designated as nuclear waste. The context of this work is evolving rapidly — the Radioactive Waste Management Directorate of the NDA (Nuclear Decommissioning Authority) has now published its R&D strategy, and CoRWM (the Committee on Radioactive Waste Management) has issued its reports to the UK government on R&D and on the geological disposal programme.

This conference will address key questions for the next generation of nuclear waste researchers. What are the emerging research priorities, and what progress is being made? How are those in historically distinct disciplines to work together to address new challenges? What skills are required for research and delivery of a geological disposal programme, and how can funding and implementation bodies be configured to encourage talented scientists to build long-term careers in this area?

The dual focus — on cutting-edge research and the need to build communities to meet new skills needs — is intended to attract a diverse audience, especially those in the early stages of their careers, not only from universities and research institutes, but also from industry, government, regulatory bodies and other institutions.

The Hallimond Lecturer will be Rod Ewing of the University of Michigan. Other invited speakers include Andy Felmy, Pacific Northwest National Labs, USA; Francis Livens, Manchester; B. Kienzler, Karlsruhe; and Scott Painter, Los Alamos National Laboratory, New Mexico.

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Have you joined the Mineralogical Society fan page on Facebook yet? Please do so now to receive regular updates on Society activities.

And Finally
In March of this year, the Society held its Annual General Meeting, the meeting where the Society’s Annual Report is presented and where other formalities, such as the recording of new members’ names, are observed. Dr Peter Sabine was present this year and noted that the last time he had attended an AGM was in 1953! He joined the Society in 1945. It was a firm reminder that we, the current crew, merely carry the torch.

Mike has been one of the pioneers in the use of the vadose zone to investigate recharge estimation, climate history and water-rock interaction. He has some 230 scientific publications to his credit. Most recently his research has included an investigation of baseline geochemistry in relation to the Water Framework Directive and another European consortium study on palaeohydrology of aquifers across Europe. His arid- and semi-arid-zone studies continue to expand in Africa and most recently China.

In 1999 Mike received the Whitaker Medal of the Geological Society of London and in 2009 the Meinzer Award of the Geological Society of America for his achievements in these areas. Additionally, he was a founding member of IAGC’s Working Group on Water–Rock Interaction and its chairman from 1986 to 1997. His international career includes work with IAEA, UNESCO and NGOs in the promotion of geochemical studies for groundwater improvement in developing countries.

Mike is currently Visiting Professor in Hydrogeology at the Oxford University Centre for the Environment, where he teaches and continues research in groundwater quality and water management and, as Research Director of the centre, promotes links between science and policy.
2010 AWARDS

The Mineralogical Association of Canada presented its 2010 awards at its annual luncheon on May 11, 2010, during the GeoCanada 2010 Conference in Calgary. We reproduce excerpts of citations here.

**Martin A. Peacock Medal to Brian Fryer**

The Peacock Medal, formerly the Past Presidents’ Medal, is the highest honor bestowed by the Mineralogical Association of Canada. This year, it was awarded to Dr. Brian Fryer of the University of Windsor for his outstanding contributions to the mineral sciences in Canada. Among Brian’s major contributions to science are the introduction and development of inductively coupled plasma mass spectroscopy (ICP–MS) to analyze practically all metals involved in natural processes at concentration levels never before realized. Brian led a team of researchers at Memorial University who recognized that the capabilities of ICP–MS could make it the analytical tool of the future in the Earth and biological sciences. In a series of landmark papers beginning in 1987, Brian and his group demonstrated that ICP–MS could successfully be used to analyze the concentration of elements in complex materials and that it could be applied in U–Pb geochronology. In 1990, they married a laser and microscope to the ICP–MS apparatus and showed how complex solid samples could be analyzed in situ using the laser as a sampling tool at spatial resolutions hitherto only possible with much more expensive and technologically challenging instruments, such as the ion microscope. Brian has not only developed new techniques for analyzing complex materials with ICP–MS, but also used these techniques to contribute to our understanding of how Newfoundland was tectonically assembled, how trace elements such as platinum and palladium could be used to trace natural processes, how trace elements are partitioned among various mineralogical, biological, and aqueous phases in natural systems, and, most recently, how trace metals can be used to indicate sources of pollutants in the Great Lakes.

**Hawley Medal to David London for the best paper published in The Canadian Mineralogist in 2009**


In his manuscript “The origin of primary textures in granitic pegmatites,” David London presents a model for the development of textural domains in granitic pegmatites. He also addresses three fundamental questions about pegmatites by cleverly combining existing results and observations with new and exciting experimental data. Although some of the model is not new, he presents extensive lab experiments to support existing models and new key evidence from data on the interactions of fluxes (B, P, and F) with haplogranitic melt. This paper presents an interesting and well-told story that captivates the reader, but it is also an original and comprehensive study, making it worthy of the distinguished Hawley Medal.

**Young Scientist Award to Sarah Gleeson**

The Young Scientist Award is presented to a young scientist who has made a significant international research contribution in a promising start to a scientific career. The 2010 award was presented to Dr. Sarah Gleeson of the University of Alberta for her significant and internationally recognized research contributions in fluid geochemistry and mineral deposits. Beginning with her PhD thesis on the geochemical evolution of mineralizing brines in southern Cornwall, she has enhanced our understanding of the geochemistry and evolution of hydrothermal systems, including those involved in the formation of mineral deposits. Sarah applies a range of geological and geochemical techniques to decipher the evolution of paleofluid flow in crustal rocks on a range of scales. Her combination of mapping, petrography, and geochemical and stable isotope techniques has resulted in a series of publications that elucidate the processes that control fluid–rock interactions in a multitude of base metal deposits and in regional crustal processes. She has refined techniques for the analysis of fluid inclusions, the only way to sample fluids directly, and has developed novel strategies for tracing fluids using halogens and chlorine isotopes in both mineralizing and nonmineralizing systems. Her research efforts in the field of mineral deposits have been recognized by the Society of Economic Geologists, which awarded her the Waldemar Lindgren Award for 2007, and by the Mineral Deposits Division of the Geological Association of Canada, which awarded her the William Harvey Gross Award for 2010.

**INCOMING VICE PRESIDENT AND COUNCILORS**

At its recent meeting, MAC Council welcomed incoming vice president Lee Groat and incoming councilors Andrew Conly and Ian Coulson. Special thanks go to outgoing past president Kurt Kyser for his commitment to the welfare of the Association during his six-year cycle on the Executive, and to outgoing councilors Michele DeVWolfe and Sarah Gleeson.

**Lee A. Groat, Incoming Vice President**

Lee Groat grew up in Kingston, Ontario, and graduated from Queen’s University with a BSc (honours, geology) in 1982. From there he went to the University of Manitoba, graduating with a PhD degree in 1988. In 1988–1989, he was a NATO Postdoctoral Fellow at Cambridge University. He moved to the University of British Columbia in July 1989. In 1999 he was awarded the Young Scientist Award of the Mineralogical Association of Canada. Throughout the 1990s, he was at various times an associate editor for both The Canadian Mineralogist and American Mineralogist, and from 2001 to 2006 he was editor of American Mineralogist. In 2002 he was awarded a Killam Prize for Excellence in Teaching. In 2003 he was elected a fellow of the Mineralogical Society of America. He is currently a professor in the Department of Earth and Ocean Sciences and director of the Integrated Sciences Program at UBC. His main areas of research are the geology of gem deposits, granitic pegmatites, and the crystal chemistry of minerals. Through his former students, he has strong ties with the exploration, mining, and environmental industries in Vancouver.
Councilors 2010–2013

Andrew Conly received his HBSc and MSc degrees in geology from Carleton University and obtained his PhD degree in geology from the University of Toronto. In 2003, he joined the Department of Geology at Lakehead University and in 2008 was promoted to associate professor. Andrew is also the director of the Lakehead University Mineralogy and Experimental Laboratory. Andrew is the Regional Vice President – North America for the Society for Geology Applied to Mineral Deposits. He previously served as the chair of the Mineral Deposits Division of the Geological Association of Canada and as a director of the Geology Society of the Canadian Institute of Mining, Metallurgy and Petroleum. Andrew’s primary research interests include experimental investigations into the source of metals in hydrothermal mineral deposits and the application of stable isotopes to mineral-forming systems. Andrew’s research recently expanded to the investigation of acid mine drainage and the remediation of contaminated waters and mine waste associated with the former Steep Rock iron mine, and to the study of natural and synthetic, highly metalliferous manganese oxide minerals.

Ian M. Coulson is an associate professor of volcanology and igneous petrology at the University of Regina, Saskatchewan. He studied at the University of Portsmouth and the University of Birmingham in the UK, before moving to Canada in 1998 to work as a postdoctoral fellow at the University of British Columbia with Kelly Russell and Greg Dipple, and later at Queen’s University. Ian’s interest in volcanism and mineralogy/petrology has led him to work extensively in Italy, Greenland, and the Canadian Cordillera. He is now involved in collaborative studies of several active volcanoes in the Andes of Colombia. Combining diffusion profiles in minerals, analytical petrography and geochemistry, this work is helping to constrain eruption timescales, which provide insight into periods of magma chamber replenishment and their eruption. Ian is a fellow of the Geological Society and is currently an associate editor of The Canadian Mineralogist.

WEB-BASED MINERALOGICAL RESOURCES

The Mineralogical Association of Canada offers on its website an opportunity to contribute information of interest, but whose nature or scope is more appropriate to a website format than to an international journal. Members of the MAC community are invited to contribute relevant information, like reports of new assemblages of minerals at well-known localities, and basic information and mineral lists for various mineral localities in Canada. There are currently two publications available on the website: one providing general mineral statistics and the other entitled Catalogue of Mineral Species Found in Canada. The latter, maintained by László Horváth, is a useful source of information about minerals found in Canada. Updated recently in December 2009 as Revision 6 (2009), this catalogue, published as a PDF file, now lists 1492 confirmed mineral species (including IMA-approved but unpublished species) and 79 unnamed minerals. While succinct, the information presented for each mineral species is quite complete as it indicates whether the species is a Canadian type-locality mineral, the reference to the original description or to a significant publication describing the occurrence, and, if possible, to the locality. The mineralological community is asked to contribute to this project by sending unpublished information to Mr. Horváth. The catalogue is located at the following address: www.mineralogicalassociation.ca/doc/catcanmin.pdf.

François Létourneau, Saint-Nicolas, Québec

Interested in Metamorphism?
We Have Publications for You!

Order online at www.mineralogicalassociation.ca
**CHANGES IN IMA COUNCIL**

Founded in 1958, the International Mineralogical Association is the world's largest organization promoting mineralogy. Its membership comprises 39 national mineralogical societies or groups. Individuals are associated with IMA and take part in IMA decision making through these national societies. IMA itself is affiliated with the International Union of Geological Sciences (IUGS).

The IMA supports the activities of 11 commissions and working groups, which are involved in a wide range of subjects. Examples are the Commission on New Minerals and Mineral Nomenclature, the Commission on Ore Mineralogy, the Working Group on Environmental Mineralogy and Geochemistry, and the Commission on Museums. The commissions and working groups are active in organising meetings and sessions at various conferences worldwide, including at the quadrennial IMA conference to be held in Budapest, Hungary, in August 2010. In addition to the scientific presentations, one or two business meetings will be held at the Budapest conference. This meeting will be an ideal opportunity for members to express what they would like IMA to do and to become involved in IMA activities. Delegates from each member society attend the business meetings. This year a number of changes to the Constitution and By-laws of the Association will be proposed by Council. Various new members of Council will be elected. Maryse Ohnenstetter, IMA general secretary, will stand down in Budapest after nine years of excellent work on behalf of IMA (doesn't time fly when you are having fun, Maryse?). Ian Parsons will finally come to the end of his term of office – as vice president, president and past president (I calculate that as 12 years!). Three Council members – Kari Kojonen (Finland), Marcello Mellini (Italy) and Nikolai Yushkin (Russia) – have also come to the end of their eight-year terms of office, and we thank them very much for their work. President Takamitsu Yamanaka finishes his four-year term (thank you very much Takamitsu) and becomes past president, and vice president Ekkehart Tillmanns takes over as president. Several commission and working group officers will also be due for election/re-election this year.

So Budapest, August 2010, will be the opportunity for new people with new ideas to join the IMA Council. According to IMA statutes, Council must nominate new councillors ten weeks before the business meeting in Budapest. The IMA has rules that ensure a good geographical representation on Council, and this restricts election of members residing in Austria, Canada, China and Germany to some of the Council positions. Anywhere else in the world is fine. If you are a member of one of IMA's member societies, are enthusiastic about IMA and think you could contribute to IMA management, you are welcome to contact President Takamitsu Yamanaka (t.yamanaka@kce.biglobe.ne.jp), Vice President Ekkehart Tillmanns (ekkehart.tillmanns@univie.ac.at), General Secretary Maryse Ohnenstetter (ohnen@crpg.cnrs-nancy.fr), Treasurer Bob Downs (downs@geo.arizona.edu) or Communication Officer Frances Wall (f.wall@exeter.ac.uk).

For more information visit www.ima-mineralogy.org.

**NEW MEMBERS JOIN IMA MEDAL COMMITTEE**

We welcome Monika Koch-Mueller (Potsdam, Germany) and Kazushige Tomoeoka (Kobe, Japan) as new members of the IMA Medal Committee. They replace Masaki Akaogi and Catherine McCammon, who have reached the end of their terms of office. The Medal Committee chairman is now Walter Maresch (walter.maresch@rub.de), who has taken over this year from fellow councillor Marcello Mellini. The IMA expresses its sincere thanks to the outgoing chairman and committee members.

The continuing committee members are Christian Chopin, Barb Dutrow, Herta Effenberger, Roberta Oberti, Igor Pekov and Mark Welch. Last, as reported in last December’s *Elements*, Frank Hawthorne is the latest winner of the IMA Medal and will receive his award at IMA2010 in Budapest.

**Frances Wall**
IMA Communication Officer

**RECORD-BREAKING IMA CONFERENCE**

IMA2010, “Bonds and Bridges”, the quadrennial conference of the International Mineralogical Association, looks set to break all previous records and become the largest-ever IMA general meeting. Over 1600 abstracts have been received for 80 sessions organised into 14 themes. The conference will be held on 21–27 August in the historic city of Budapest, Hungary. Registered participants are from 74 countries, including 22 Asian and 11 African countries. This excellent geographic coverage, which reflects IMA’s wish for a wide international participation, is in part the result of grants given by the conference to help attendance. Grant awardees range from students and young scientists to ‘not-so-young’ (retired) scientists who will add their experience to the conference discussions. If you would like to come and join in, registration is still open, and day rates are available if you can only attend part of the conference. Details can be found on the website www.ima2010.hu.

**ATTEND THE ELEMENTS PLENARY LECTURES!**

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For more information visit www.ima-mineralogy.org.
"METAMORPHIC EXTRAVAGANZA" IN CALGARY

A “metamorphic extravaganza” was held in Calgary between May 8 and 16, 2010, in association with the GeoCanada 2010 meeting. Sponsored by the Mineralogical Association of Canada, it consisted of three events:

- a two-day premeeting short course on the “Theriak-Domino” phase equilibrium modeling software, presented by its developer, Christian de Capitani of the University of Basel, Switzerland
- a two-day special session entitled “Interplay between Thermodynamics, Kinetics and Deformation in Metamorphism”
- a four-day field trip to metamorphic localities in southeastern British Columbia entitled “Metamorphism and Tectonics in the Southern Purcell Anticlinorium and Kootenay Arc, Southeastern British Columbia”

The Theriak-Domino short course, organized by Dave Pattison and Fred Gaidies, was held at the Department of Geoscience, University of Calgary. It was attended by 35 geoscientists, over half of whom were students (see photo). Christian de Capitani (“Capi,” as he is known by many) led attendees through the calculation of pressure–temperature isochemical phase diagram sections (often referred to as “pseudosections”) for different bulk compositions; various types of isolines (e.g. isopleths, modal and density contours) on these sections; log-activity diagrams; temperature–log-activity diagrams; binary and ternary diagrams; “pixel maps” allowing rapid visualization of hundreds of compositional and physical parameters in a given phase diagram section; and a number of specialized applications available in the software. The attendees were enthusiastic about the rapidity, flexibility, and ease of use of the software, and by the possibilities it affords to experiment with different chemical systems and bulk compositions. A senior attendee after the first day said, “I am filled with joy,” and after the second day said, “I wish I were starting my career in metamorphic petrology over again.” Attendees got a taste of Canada’s national spring ritual when they gathered for a lively group meal at a pub with televisions on all sides showing the Stanley Cup playoffs (ice hockey for the uninitiated).

The two-day special session, “Interplay between Thermodynamics, Kinetics and Deformation in Metamorphism,” was organized by Dave Pattison, Fred Gaidies, and Ed Ghent. It was the largest individual session at the GeoCanada 2010 meeting, a pleasant surprise given that it was a metamorphic session held within a generalist geoscience meeting in the center of Canada’s hydrocarbon industry. Twenty-eight talks and eight posters were presented by individuals from eleven countries. The geographic diversity was represented by the three invited speakers: Rainer Abart from the University of Vienna (“Chemical mass transfer in polycrystals and polycrystalline aggregates”), Dave Hirsch from Western Washington University (“An experimental inquiry into gos

The four-day postmeeting field trip, “Metamorphism and Tectonics in the Southern Purcell Anticlinorium and Kootenay Arc, Southeastern British Columbia,” led by Dave Pattison, David Moynihan, and Chris McFarlane, took 27 participants across the leading edge of the Canadian Cordilleran orogen, through the famous Rocky Mountain fold and thrust belt, and into the metamorphic–magentic orogenic hinterland, the southern Omineca belt. The trip took the group through the towns of Cranbrook, Creston, and Nelson. A theme of the trip was the varying character of, and interfaces between, Barrovian-type and Buchan-type metamorphic domains ranging in age from Mesoproterozoic to Cretaceous. Participants saw this beautiful part of British Columbia at its finest, under sunny skies and pleasant temperatures. The diverse backgrounds of the participants (see photo) made for excellent outcrop discussions.

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David Pattison, University of Calgary

February 27–March 3 The Minerals Metals & Materials Society (TMS) Annual Meeting, San Diego, CA, USA. E-mail: mtgserv@tms.org; web page: www.tms.org/meetings


March 7–11 42nd Lunar and Planetary Science Conference, The Woodlands, TX, USA. Web page: www.lpi.usra.edu/meetings

March 21–25 Chapman Conference on Climates, Past Landscapes and Civilizations, Santa Fe, NM, USA. E-mail: chapman-climatesociety@agu.org; web page: www.agu.org/meetings/chapman/2010/eCall

March 27–31 241st American Chemical Society (ACS) National Meeting & Exposition, Anaheim, CA, USA. Web page: www.acs.org

April 10–13 AAPG Annual Convention & Exhibition, Houston, TX, USA. Web page: www.aapg.org/meetings


May 2–6 Congreso Geologico Argentino, Neuquén, Republic of Argentina. E-mail: info@congresogeologico.org.ar; web page: www.congresogeologico.org.ar

May 15–19 12th European Workshop on Modern Developments and Applications in Microbeam Analysis, Angers, France. Web page: www.emas-web.net


May 22–27 IAMAS-V: 5th Meeting of the International Union of Microbeam Analysis Societies, Incheon, South Korea. E-mail: ssang@ samsung.com


June 21–24 The Mineralogical Society’s Annual Meeting: Frontiers in Environmental Geoscience, University of Aberystwyth, Wales, UK. Details: N. Pearce, e-mail: nip@aber.ac.uk; web page: www.minsoc.org/pages/meetings/frontiers-2011/frontiers-2011.html


June 27–July 7 XXVth International Union of Geodesy and Geophysics (IUGG)–IAVCEI General Assembly, Melbourne, Australia. E-mail: ray.casin@sci.monash.edu.au; www.iugg2011.com

July 4–9 Seventh Hutton Symposium on Granites and Related Rocks, Avila, Spain. E-mail: hutton@rug.es; web page: www.seventh-hutton-meeting.org/Welcome.html


July 20–27 International Union for Quaternary Research (INQUA) XXVIII Congress, Bern, Switzerland. Website: www.inqua.tcd.ie/ice/congress.html


July 30–31 MSA and GS Short Course: Applied Mineralogy of Cement and Concrete, Trondheim, Norway. Details: Maarten A.T.M. Broekmans, e-mail: maarten.broekmans@ngu.no; web page: www.minsocam.org/MSA/SC

August 1–5 10th ICAM International Congress for Applied Mineralogy, Trondheim, Norway. Details: Maarten A.T.M. Broekmans, e-mail: maarten.broekmans@ngu.no; website: www.icam2011.org


August 8–12 74th Annual Meeting of the Meteoritical Society, Greenwich, England. Details: Gretchen Benedix, e-mail: gbenedix@nmm.ac.uk

August 14–19 2011 Goldschmidt Conference, Prague, Czech Republic. E-mail: helpdesk@goldschmidt2011.org; web page: www.goldschmidt2011.org


August 19–23 244th ACS National Meeting & Exhibition, Philadelphia, PA, USA. Web page: www.acs.org


August 28–September 2 242nd American Chemical Society (ACS) National Meeting & Exhibition, Denver, CO, USA. Web page: www.acs.org


September 4–7 7th European Conference on Mineralogy and Spectroscopy (ECMS 2011), Potsdam, Germany. Details: Prof. Dr. Monika Koch-Mueller; e-mail: mkochgfz-potsdam.de; web page: www.physchemgeo.com/ECMS/index.html

September 20–24 GEODEMED2011 – 4th Hemispheric Conference on Medical Geology, Bari, Italy. Details: Piero Fiore, e-mail: fiore@imaa.cnr.it; web page: www.geomeded2011.it

October 9–12 Geological Society of America Annual Meeting, Minneapolis, MN, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/index.htm

October 16–20 Materials Science & Technology 2011 Conference and Exhibition – MS&T’10 combined with the ACRS’113rd Annual Meeting, Columbus, OH, USA. Web page: www.tms.org/meetings/meetings.asp

November 21–24 Conference on Arsenic in Groundwater in South Asia, Hanoi, Vietnam. E-mail: vietacetd35@yahoo.com; web page: vietas.erd.tu.dk
The lure of place names

For reasons of social history, the number of places on planet Earth with Scottish names is out of all proportion to the population and land area of the little country in which I live. How places on distant continents obtained their names is a matter of endless fascination to me, one that could lead to an almost unending series of Parting Shots, a temptation I will avoid. But sometimes I visit the New World and find that the contrast between what I see there and what I know back home is so marked that I’m driven to peer into Google and ferret out the connection.

Take, for example, the magnificent, wealthy Canadian city of Calgary. There it stands, at the foot of the Kicking Horse Pass, which takes the Canadian Pacific and the Trans-Canada Highway west through the Rocky Mountains, facing out to the east over the immense plains of central Canada and the USA. With a population of more than a million and great riches based on oil and gas, it is a riot of skyscrapers and mirror glass.

I know the original Calgary. It is a cluster of a few houses at the head of Calgary Bay on the northwest coast of the island of Mull off the west coast of Highland Scotland. It is simply achingly beautiful. Near-silent apart from the seabirds, the turquoise sea laps gently onto a snow-white beach of shell sand, fringed by grass-covered dunes nibbled to a perfect green carpet by sheep – a terrain known as machair in Gaelic. The name ‘Calgary’ probably comes from the Gaelic cala gherraidh (which is pronounced ‘calgary’, more-or-less) and means ‘the beach of the pasture’. (As usual in such matters this is disputed by some, who favour a Norse origin.) The distant headland has basalt trap topography, because most of Mull is a lava pile extruded at about 60 Ma, when the North Atlantic began to open. The lava was erupted from fissures and from a central volcano whose inner structures are exposed some 20 km to the south. The concept of two worldwide basaltic magma types, which dominated much petrological thinking from the 1930s, grew out E. B. Bailey’s mapping of the Mull volcano. The Calgary lavas are of the classic ‘plateau magma type’, olivine and alkali olivine basalts, while those from the central volcano, the ‘non-porphyritic central type’, are predominantly tholeiitic.

So how did this exquisite, lonely bay come to give its name to a shining metropolis in Alberta? The romantic ideal is that some family of dispossessed crofters found its way across the vast spaces of Canada, and at this location decided to put down its roots. In a rush of homesickness, they named their new home- stead Calgary. The real story is rather different.

The only large building near Calgary Bay is a vast, turreted and castellated, pseudo-gothic mansion built in 1817 by a Captain MacAskill and now called ‘Calgary Castle’. At that time the bay could be reached only by sea, and you do wonder whom he was trying to impress! In 1876, the Commissioner of the North-West Mounted Police (which later became the Royal Canadian Mounted Police), James Macleod, stayed in the house. The NWMP had been set up in 1873 by Queen Victoria to bring law and order to, and assert sovereignty over, the Northwest Territories, and they established Fort Brisebois where Calgary Mark 2 now stands. Macleod liked Calgary Bay. Can I imagine him striding the machair in his red tunic and boy-scout hat? When he returned to Canada he renamed his new fort ‘Fort Calgary’. So, it was the Mounties who brought Calgary to Calgary!

Ian Parsons
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Course registration through the Society of Economic Geologists only via e-mail at seg@segweb.org or by phone +1.720.981.7882.

Conveners: Bob Seal & Kirk Nordstrom

Instructors: Bob Seal, USGS; Kirk Nordstrom, USGS; Dirk Van Zyl, University of British Columbia; Carol Russell, USEPA; Rod Eggert, Colorado School of Mines; Kathy Smith, USGS; David Nimick, USGS; Geoff Plummer, USGS; Graeme Spiers, Laurentian University; John Besser, USGS; Heather Jamieson, Queen’s University; Kim Lapakko, Minnesota Dept. of Natural Resources; David Blower, University of Waterloo; Devin Castensky, SUNY-Oswego; Chris Gammons, Montana Tech; Craig Johnson, USGS; Tanya Gallegos, USGS; Kate Campbell, USGS.

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• Vapors, brines, sulfides, and mines: Understanding metal mobility in magma-hydrothermal systems and their supergene successors; Jacob Lowenstern, USGS; Adam Simon, University of Nevada, Las Vegas; Charles Alpers, USGS

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