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☐ Workshop ☐ Preliminary ☑ Full ☐ New ● Revised ☐ Addendum

Please tick or fill out information in all gray boxes

Title: Short title: Oman Drilling Project
Long title: Scientific Drilling in the Samail Ophiolite, Sultanate of Oman

Proponent(s): Lead proponents: Peter B. Kelemen, Jürg M. Matter, Damon A. Teagle
Other Principal Investigators: Raeid Abed, Ali Al Rajhi, Shoji Arai, Wolfgang

Keywords: *(5 or less)* (1) mid-ocean ridge processes, (2) subduction

Location: Sultanate of

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Permission to post abstract on ICDP Web site: ☒ Yes ☐ No

Abstract: *(400 words or less)*

The Samail ophiolite in Oman and the United Arab Emirates (UAE) is the world's largest, best-exposed, and most-studied subaerial block of oceanic crust and upper mantle. In an ongoing dialogue between geological studies of the ophiolite and seagoing investigations along modern oceanic ridges, observations from Oman and the UAE are central to scientific understanding of oceanic plates formed at spreading centers. Observations of mantle peridotites overlying the subduction zone thrust, which carried the ophiolite onto the Arabian continental margin, reveals an unexpected reservoir of carbon, derived from subducted sediments and precipitated as carbonate minerals in the mantle wedge. This could form an important, hitherto unrecognized part of the global carbon cycle. And, following on ground-breaking work in the 1980's, there has been a recent surge of interest in the Samail ophiolite as the ideal site for studies of weathering in mantle peridotite, together with the subsurface biosphere fueled by microbial catalysis of low temperature alteration reactions. Such studies will contribute to understanding of microbial ecosystems in extreme environments and the origin of life.

Following a successful workshop in September 2012, our international team of 38 investigators proposes a comprehensive drilling program in the Samail ophiolite in the Sultanate of Oman. Via observations on core, geophysical logging, fluid sampling, hydrological measurements, and microbiological sampling in a series of diamond- and rotary-drilled boreholes, we will address long-standing, unresolved questions regarding melt and solid transport in the mantle beneath oceanic spreading ridges, mass transfer between the oceans and the crust via hydrothermal alteration, and recycling of volatile components in subduction zones. We will undertake frontier exploration of subsurface weathering processes in mantle peridotite, natural mechanisms of carbon dioxide uptake from surface waters and the atmosphere via alteration and weathering, and the nature of the subsurface biosphere in peridotite undergoing alteration and weathering.

Societally relevant aspects of our project include the involvement and training of university students in earth science research, including numerous students from Sultan Qaboos University in Oman. Studies of the natural system of mineral carbonation in peridotite will contribute to design of engineered systems for geological carbon dioxide capture and solid storage. More generally, our studies of alteration will contribute to fundamental understanding of the mechanisms of reaction-driven cracking: chemical reactions that cause subsurface cracking, enhancing permeability and reactive surface area, in a positive feedback mechanism. The results of these studies could enhance geothermal power generation and extraction of unconventional hydrocarbon resources.

Scientific Objectives: (*250 words or less*)

(1) Quantify the nature and timing of solid upwelling beneath a spreading ridge using crystal shape and lattice preferred orientation data systematically collected on core from the periphery of a mantle diapir.
(2) Quantify the nature and structural relationships of melt transport features in the shallow mantle, to evaluate mechanisms that focus transport from a melting region 100's of kilometers wide into a zone 2 kilometers wide where igneous oceanic crust is formed.
(3) Quantify chemical variability deformation structures in the crust-mantle transition zone and plutonic lower crust, to determine the depth of crystallization, the nature of ductile flow, and mechanisms of melt transport.
(4) Quantify hydrothermal alteration and cooling of the plutonic lower crust using mineral compositions, diffusion profiles, and stable isotopes to determine the importance of hydrothermal convection in heat and mass transfer.
(5) Investigate processes in the critical "dike-gabbro transition" via study of cross-cutting igneous relationships, metamorphic mineral assemblages, and geochemical alteration.
(6) Quantify mass transfer from subducted sediments into overlying peridotite at the "leading edge of the mantle wedge" via petrologic and geochemical studies, with special focus on carbon cycling.
(7) Systematic and detailed study of ongoing, subsurface alteration of mantle peridotite, including fluid compositions, flow rates and hydrology, characterization of fracture and vein spacing, studies of mineral assemblages formed by carbonation, hydration (serpentinization) and oxidation and resulting mass transfer, and characterization of the subsurface microbial biosphere that derives energy from catalysis of low temperature alteration in this unique and fundamentally important environment.

Summary of Support Requested from ICDP

Requested ICDP funds: *(in US$)*	US$1,948,332	Estimated Total Project Budget *(ICDP funds plus other sources)*:	US$3,898,665
Planned Start:	permitting, matching fund proposals: 2014-15 drilling: Nov 2014 or 15	Estimated Duration in Month *(On-site operations only)*:	4 years
Requested Operational Support:	Drill Engineering *(Please contact ICDPs Operational Support Group if required)*		
	Downhole Logging *(Please contact ICDPs OSG if required)*		
	Field Lab Equipment *(Please contact ICDPs OSG if required)*		
	Training Course *(Please contact ICDPs OSG if required)*		

Details such as a Budget Plan, Management Plan, and Drilling Plan to be provided as attachment to the Proposal. OSG contact: U. Harms (ulrich@gfz-potsdam.de), Phone: +49 331 288 1085

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
DEPARTMENT OF EARTH & ENVIRONMENTAL SCIENCES
LAMONT DOHERTY EARTH OBSERVATORY

January 9, 2014

Prof. Brian Horsfield
Dr. Uli Harms
International Continental Drilling Program
GFZ Potsdam

Dear Brian and Uli,

With this letter, please find our revised proposal for the Oman Drilling Project.

In this cover letter, as you suggested at our meeting in Potsdam in October, we offer a brief summary of the revisions we made, in the context of the reviews of our 2013 proposal.

Our primary focus in revising the proposal was to cut the overall cost of the Project by prioritizing our planned holes, and then eliminating all but the most essential targets. In doing this, we wished to respect the input of the participants in the 2012 Oman Drilling Workshop, and follow the advice of reviewers who generally praised the broad, multi-disciplinary nature of the proposal and the proponent group. Thus, we retained *all* of the scientific goals identified at the workshop and in the 2013 proposal, and simply reduced the number of holes, and target depths, that were designed to address a specific subset of goals. With some trepidation, we also reduced the funds allocated for project management, and for project coordination meetings. We dropped our plan to purchase a (much-needed) XRF core scanner for the core description lab onboard the Joides Resolution (JR). We now plan to seek funds for the core scanner via the Qatar Foundation, with the idea of installing it at Sultan Qaboos University in Oman rather than on the JR. In any case, this equipment purchase is no longer a part of the ICDP proposal budget.

As a result, this revised proposal reflects the outcome of a substantial prioritization process, as requested by reviewers. We now plan a total of 3050 meters of diamond drilling and 2000 meters of rotary drilling, compared to last year's proposed 5450 and 3450 meters, respectively. This and other priority decisions reduced the overall cost to $3,896,665 from $6,775,596, and our request to ICDP from $3M to $1,948,332.

We added an important, though short, section addressing the nature of existing seismic data, which demonstrate that internal structure within the Samail ophiolite cannot be imaged by seismic reflection or refraction. Additional seismic experiments aimed at site characterization for this project would be a waste of time and money.

We added a brief clarification of how understanding of natural mineral carbonation is relevant to proposed design of engineered systems for CO_2 capture and storage (CCS). A reviewer wondered how useful natural data could be, given the goal – in some proposed, engineered systems – to dramatically enhance reaction rates using CO_2-rich fluids and/or catalysts. Keeping in mind that our ICDP proposal is not aimed at designing CCS systems, we did not want to overemphasize this topic by adding a long discussion. Instead, we simply noted that one proposed method, CO_2 capture from hydrothermally circulating seawater, simply involves stimulation of convection via drilling and hydraulic fracture, and then will proceed by the same rate and reaction mechanisms as natural systems.

If we had the space and the inclination to add additional information on CCS, we would have described our hypothesis that the Cretaceous, higher temperature mineral carbonation system, near the basal thrust of the ophiolite during its emplacement, involved rapid reaction with CO2-rich fluids at ~ 100°C, and so is actually a close analogue to the rate and fluid composition for other, proposed CCS systems. The natural, carbonated peridotites in this setting probably formed very rapidly indeed.

In Appendix 5, in addition to modifying our plans for each site based on the prioritization process described above, we added (1) substantially more site survey data, (2) a short section on our observations of the depth to the water table in water monitoring wells near the proposed drill sites in Appendix 5, (3) a short section on accessibility of drill sites via existing gravel roads and tracks, and (4) a short section on contingencies that could affect core recovery and hole completion.

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In addition, we added a short section in Appendix 5 making clear that there are no "previously drilled cores … present at Lamont", as one reviewer suggested, and no cores from our target lithologies in the Samail ophiolite that are available anywhere else for that matter.

We were unclear on how to respond to a reviewer request for us to "develop a phased program". The timing of each part of the proposed project was and is given in the table in Section 10, on page 28. Once this project is complete, proponents may decide to submit a follow-up proposal for more extensive drilling, including objectives at some of the sites that were dropped during this revision process. However, we have not designed a formal plan for such a second phase.

Similarly, we were uncertain how to respond to reviewer advice that we "consider image logging" in boreholes. Use of an optical televiewer tool was and is included in Table 2 in Section 5.1, which describes our plans for geophysical wireline logging.

We were encouraged by the generally positive reviews of our previous proposal, and by your positive input at our meeting in October. As a result, we are optimistic that this revised proposal with meet with ICDP approval, so that we can move forward on the permitting and contracting process with our Omani partners in 2014. Another yearlong delay would likely damage our credibility with these partners. Thus, we hope that issues identified during the upcoming review process could be addressed via conditional approval of the proposal, followed by required modification to address any continuing problems.

In this context, an important development is that the Sloan Foundation solicited a proposal from me, for support of field projects related to their Deep Carbon Observatory. They suggested that the proposal include $350,000 in matching funds, to facilitate startup of the Oman Drilling Project. (See supporting letter from Craig Schiffries and Robert Hazen of the Deep Carbon Observatory, in Appendix 17). In this proposal, we decided to budget funds to drill one hole at the active alteration site, Site BA1, including equipment for geophysical logging and water sampling. Of course, the Sloan funds will be considered as part of the overall matching funds if and when the overall ICDP project is approved. Meanwhile, the Sloan proposal was submitted today, and we are optimistic that it will be approved by the end of February. We hope that this confirmed funding will provide a concrete starting point and catalyst to begin specific steps in the permitting process in Oman.

On behalf of Jürg Matter, Damon Teagle and myself, thank you in advance for your continuing advice and assistance with the Oman Drilling Project.

Sincerely,

Peter B. Kelemen
Arthur D. Storke Professor & Vice Chair
Dept. of Earth & Environmental Sciences

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1. Introduction

The Samail ophiolite, along the northern coast of the Sultanate of Oman and the easternmost United Arab Emirates, is the largest and best sub-aerial exposure of oceanic crust and upper mantle in the world. The term "ophiolite" is used to identify blocks of oceanic crust and upper mantle, formed at spreading ridges, and later exposed on land. Key features of ophiolites are seafloor lava flows ("pillow basalts"), a continuous layer of dikes intruding dikes ("sheeted dikes") attesting to genesis of the crust at a spreading center, a layer of plutonic igneous rocks ("cumulate gabbros") rich in Mg and Ca, formed by partial crystallization of the magmas subsequently erupted as lavas and dikes, and underlying mantle peridotites that underwent partial melting to form the magmas that, in turn, comprise igneous oceanic crust (Figure 1).

Scientific drilling in the Samail ophiolite will improve understanding of the spectrum of processes that create and modify the oceanic crust and shallow mantle from its primary setting on the ocean floor to its modern setting in the mountains of Oman. These processes involve mass and energy transfers between the mantle, crust, hydrosphere, atmosphere and biosphere over a range of temperatures from ~1350 to 20°C, depths from 20 km below the paleo-seafloor to the surface, and tectonic settings from spreading ridges and subduction zones to the modern subaerial hydrology and surficial weathering.

Decompression melting of upper mantle peridotite, rising to fill the gap created by rifting of the plates at mid-ocean spreading ridges, and the consequent eruption and intrusion magma to form new ocean crust, are the primary steps in the plate tectonic cycle. These processes have repaved more than 60% of Earth's surface in the last 200 million years and are the principal mechanism of mass and heat transport from the interior of Earth to the surface. Hydrothermal circulation of seawater-derived fluids, at the spreading ridges and on the vast, submarine ridge flanks, forms base metal deposits and buffers the chemical and isotopic composition of the oceans. Alteration by seawater-rock exchange adds volatiles and other chemical tracers to the oceanic crust. The extreme thermal and chemical gradients within oceanic plates provide fertile ecological niches for novel microbial communities. Following subduction of oceanic crust, volatiles and tracers are returned to the crust by fluid transport and arc volcanism, or recycled into the deep mantle.

Over the past decade there has been growing recognition of the importance of serpentinization (hydration) of upper mantle peridotite in global chemical and tectonic cycles. Reactions between seawater and the minerals comprising peridotite, olivine and pyroxene, transform dense, strong, anhydrous materials into weak, hydrated, low-density serpentinites. These reactions alter tectonics along oceanic spreading ridges and in subduction zones. The juxtaposition of mantle rocks with oxidized surface waters (seawater, ground water) provides a chemical environment of extreme contrasts resulting in strongly exothermic reactions that form high pH fluids, hydrogen, and abiotic hydrocarbons, potentially key ingredients for the origin of life on Earth, creating fertile environments for the development of unique microbial communities at present.

The discovery on the Mid-Atlantic Ridge of Lost City, a large hydrothermal carbonate mound hosted by serpentinized peridotes [*Kelley et al.*, 2001], combined with observations of fully carbonated peridotite in numerous ophiolites (e.g., "listvenites", well exposed in Oman), has highlighted the potential for engineered capture and storage of anthropogenic carbon dioxide by mineral carbonation in peridotite. The presence of listvenites in mantle peridotites thrust over sediments in Oman suggests the presence of hitherto unrecognized, globally significant reservoirs for carbon in the "leading edge of the mantle wedge" above subduction zones. Active hyperalkaline springs depositing travertine terraces in Oman attest to on-going serpentinization and “Lost City”-type reactions occurring in the Samail ophiolite today, providing opportunities to understand both ancient and modern mineral carbonation processes through drilling and sub-surface experimentation.

The Oman Drilling Project, proposed here, will harness information from drill core, geophysical logs, fluid and gas samples, hydrological tests, in situ experiments, and continued detailed field mapping to address the spectrum of multi-disciplinary and inter-related science questions that connect the deep mantle and the ancient ocean floor with modern hydrology and ongoing biogeochemical reactions in the mountains and wadis of the Samail ophiolite.

1.1 Development of the Oman Drilling Project

Scientific drilling focused on the formation and evolution of the Samail ophiolite at an oceanic spreading ridge was first proposed to the International Continental Drilling Program (ICDP) in 1998. Although ICDP offered $40,000 in workshop support, international events during and after 2001 suggested that the project should be postponed. However, our original goals remain compelling. They represent essential steps toward the Mantle to Moho (M2M) Project, proposed to the Integrated Oceanic Drilling Program (IODP), to drill a complete, intact section of oceanic crust and upper mantle in the Pacific (see Appendix 1). In addition, scientific developments over the past decade augmented our original plan, reflecting increasing interest in low temperature alteration and weathering, and the associated sub-surface biosphere supported by the chemical potential energy inherent in exposure of mantle peridotite at the Earth’s surface. This interest is motivated, in part, by the possibility of geological carbon capture and storage via engineered, accelerated mineral carbonation in Oman.

A workshop proposal to the ICDP in January 2011 led to the Workshop on Scientific Drilling in the Samail Ophiolite, held in Palisades, New York (September 2010), supported by ICDP ($50k), the Sloan Foundation’s Deep Carbon Observatory (DCO, $30k) and the US National Science Foundation (NSF, $10k). There were 77 attendees from 11 countries, including 20 early career scientists. This proposal presents the science goals and drilling plans refined by the participants in working group and plenary sessions. Appendix 2 provides more information. We submitted a full proposal to ICDP in January, 2013, which was declined with encouragement for us to revise and resubmit. Reviews focused on a need for prioritization of drilling objectives. This revised proposal, submitted in January 2014, reflects the requested prioritization, with a total of 3050 meters of diamond drilling and 2000 meters of rotary drilling, compared to last year’s proposed 5450 and 3450 meters, respectively. This and other priority decisions reduce the overall cost to $3,896,665 from $6,775,596, and our request to ICDP from $3M to $1,948,332.

1.2 Advancement of the ICDP Science Themes

The Oman Drilling Project will make fundamental progress toward the central ICDP objective of “understanding the composition, structure and evolution of the Earth's crust and the processes that continue to modify it.” The formation and evolution of oceanic plates (crust and shallow, residual mantle) is the major mechanism of thermal and chemical exchange between the Earth’s interior and the crust, oceans, atmosphere, and biosphere. We will substantially improve understanding of mid-ocean ridge mantle and crustal processes, and estimates of the chemical fluxes exchanged between the ocean plates and the oceans by high temperature hydrothermal alteration near spreading ridges, and later during low temperature weathering.

We will also address other, key ICDP priorities including the wise use of Earth's energy, mineral, and water resources and the critical interactions between the biosphere and the Earth's crust. Ocean floor hydrothermal systems, powered by the cooling and crystallization of the lower oceanic crust, have produced mineral deposits that have been sources of base metals since the birth of civilization, yet the deep source of these metals remains poorly known. In parallel, understanding natural mineral carbonation reactions during the obduction of the Samail ophiolite and on-going carbonation processes during weathering will yield essential information on the Earth's carbon cycle, and insight into design of engineered systems for permanent capture and storage of anthropogenic carbon dioxide. Hydrogen and abiotic hydrocarbons produced by exothermic serpentinization reactions provide vital energy and ingredients that should support an extensive subsurface biosphere, which so far is largely undiscovered. Although there are abundant geochemical indicators of microbial activity in ancient rocks, evidence of present-day, sub-surface biological activity in these environments remains elusive.

1.3 The Samail ophiolite and oceanic crust

In the early 1970's, it was recognized that the thickness and seismic properties of the igneous oceanic crust in the Samail ophiolite were similar to those of Pacific crust formed at intermediate- to fast-spreading ridges [*Christensen and Smewing*, 1981; *Glennie et al.*, 1973]. Since that time, the ophiolite has been recognized as the best place on Earth for sub-aerial, three dimensional study of oceanic crust. Indeed, the widely accepted paradigm for the structure of Pacific crust is based largely on observations in the ophiolite. This led to accelerating interest in studies in Oman and the UAE that can be applied to understanding ridge processes worldwide.

In more detail, the tectonic provenance of the ophiolite – and the extent to which specific features are representative of processes at "normal" mid-ocean ridges – are subjects of continuing debate. Because of this uncertainty, ophiolite studies must always be viewed as part of a dialectical conversation, inspired, supplemented and corrected based on direct observations of active spreading centers in a variety of tectonic environments. Four decades of research and discussion have affirmed the great value of combining data and inferences based on observations from Oman with geophysical surveys, dredging and drilling along active submarine spreading ridges. In the past, this dialectic mainly focused on igneous and metamorphic processes near the ridge axis. Recently, the discussion has broadened to include off axis alteration and weathering. Our proposed project follows in this fruitful tradition.

In this project, we will focus on study of processes common to all submarine spreading centers, and the subsequent evolution of oceanic crust and upper mantle rocks at and near the Earth's surface. Of course, every place is unique, and processes vary depending on local history and boundary conditions. This understanding will always be part of the data gathering and interpretation we propose. However, we seek understanding of the factors that shape the two thirds of the solid Earth surface composed of oceanic crust and upper mantle. Doing this requires a clear understanding of the local context, but we will not emphasize lines of inquiry that are primarily relevant to regional geology. There are many fascinating aspects of the geological history of the Samail ophiolite that will not be a primary focus of the proposed study.

1.4 Regional setting and geologic history of the Samail ophiolite

The Samail ophiolite is the largest, best-preserved, best-exposed, and most intensively studied block of oceanic crust and shallow mantle in the world. The ophiolite was gradually thrust onto the Arabian continental margin from about 95 to 80 million years ago. The desert climate of Oman limits surficial weathering and supports only sparse vegetation (unlike the ophiolites of Papua New Guinea and New Caledonia). Further, large regions of the Samail ophiolite preserve an intact stratigraphy, from pelagic and metalliferous sediments to pillow basalts, sheeted dikes, gabbroic plutonic rocks, and residual upper mantle peridotites that underwent partial melting to form the magmas that comprise the overlying igneous oceanic crust. During emplacement onto the Arabian continental margin, this stratigraphy was tilted and eroded, exposing sections extending from the paleo-seafloor to 10 or 20 km depth below the crust-mantle transition zone, in residual mantle peridotites. These cross-sectional exposures represent an exceptional, unique natural laboratory for studying crustal formation and evolution at submarine spreading centers, and low temperature alteration of mantle rocks exposed at the Earth's surface.

Ore deposits formed at the Samail spreading ridge have been mined in Oman for more than 5000 years, providing one of the key sources of copper for early civilization in the Middle East. The presence of chemically unusual rocks – now recognized as outcrops of the Earth's upper mantle – has been known in Oman since at least 1850.

Geological mapping is comprehensive at 1:100,000, with some areas mapped at 1:25,000, and more than 1000 papers have been published on the Samail ophiolite and the regional geology of

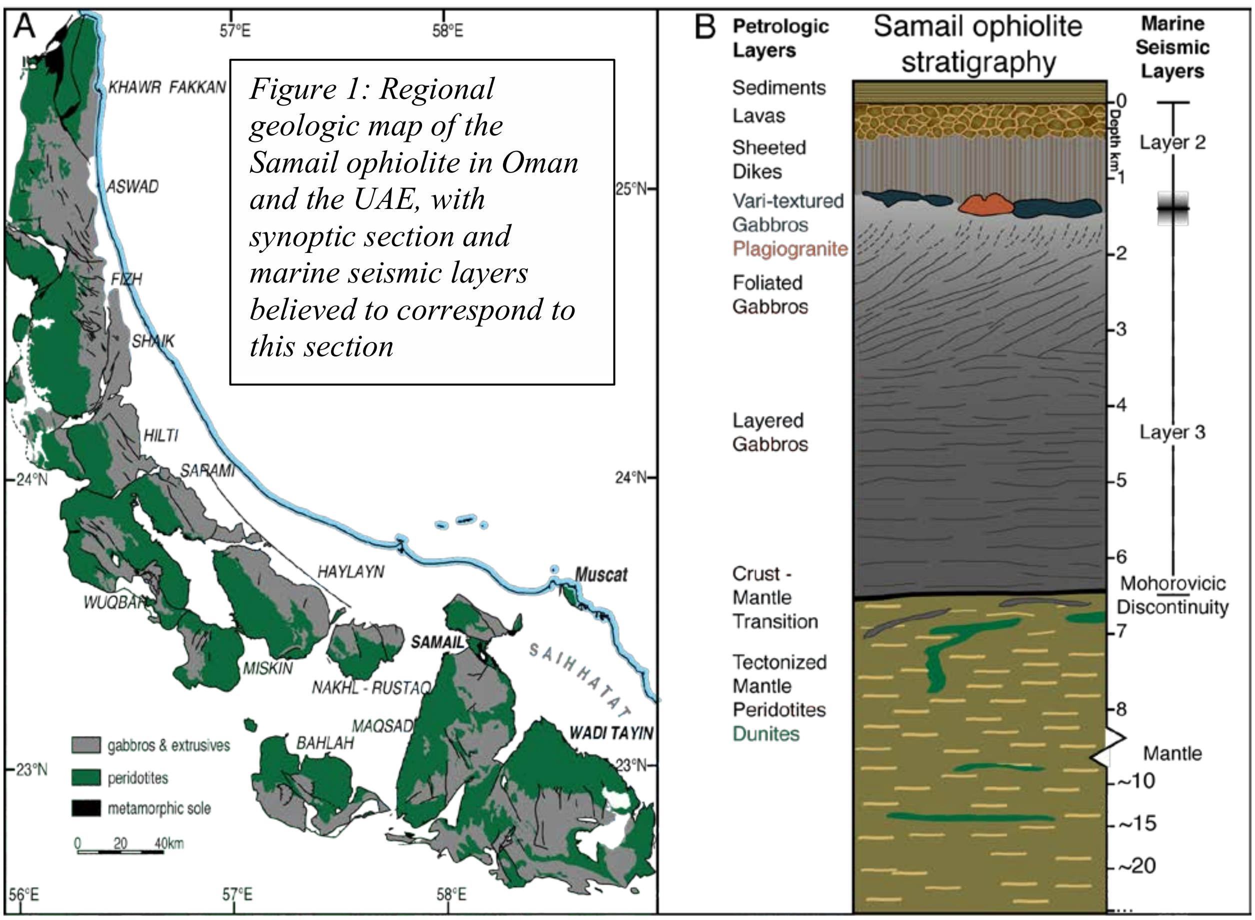

Figure 1: Regional geologic map of the Samail ophiolite in Oman and the UAE, with synoptic section and marine seismic layers believed to correspond to this section

the Oman mountains. Mapping and interpretation [*Lippard et al.*, 1986; *Nicolas et al.*, 2000] has subdivided the Samail ophiolite into approximately 15 “massifs”; spatially separated fragments of an initially elongate, continuous sheet of oceanic crust and upper mantle in extending for more than 350 km along strike in a SE-NW direction, roughly parallel to the strike of the sheeted dikes and thus to the spreading center at which the oceanic crust formed (Figure 1).

Geochemical investigations [e.g., *Koepke et al.*, 2009; *Pearce et al.*, 1981] indicate a polygenetic origin for the Samail ophiolite, with a first phase producing lavas and gabbros similar to typical “mid-ocean ridge basalts” (MORB) and related plutonic rocks. Later magmatic phases produced lavas that are highly depleted in incompatible trace elements, with affinities to lavas erupted in the early phases of western Pacific, subduction-related arc volcanism. These later lavas are related to distinctive, orthopyroxene-bearing pyroxenites and gabbronorites indicative of high SiO_2 contents in primitive magmas. Although debate continues, most workers agree that all of the Samail ophiolite lavas have geochemical affinities with lavas in subduction-related volcanic arcs, and that the spreading ridge that formed the crust was in the hanging wall of a subduction zone. However, the later stages of arc-related magmatism, intruding and disrupting the more MORB-like crust formed at the Samail spreading ridge, are more strongly developed in the northern ophiolite massifs [e.g., *MacLeod et al.*, 2013]. As a result, our proposed drilling will focus on the simpler, southernmost parts of the ophiolite, the Samail and Wadi Tayin massifs (Figure 1). Among all ophiolites worldwide, these massifs are the closest analogs to the Pacific crust and upper mantle that comprise a substantial fraction of the Earth’s tectonic plates.

Recent, precise U/Pb zircon ages have refined older radiometric dates. Spreading ridge magmatism extended from 96.25 to 95.50 Ma [*Rioux et al.*, 2012b; *Rioux et al.*, 2013; *Warren et al.*, 2005]. The zircon data combined with older $^{40}Ar/^{39}Ar$ ages on hornblende and micas indicate that metamorphism (and minor partial melting) along the basal thrust of the ophiolite had initiated by 94.9 Ma, giving a minimum age for the initiation of thrusting [*Rioux et al.*, 2013]. The striking overlap of igneous and metamorphic ages indicates that thrusting began near an active spreading center. Probably, the ophiolite was “obducted” – eventually onto the continental margin – because it was young and hot, with a density too low to be subducted.

Thrusting of the ophiolite, together with an underlying blanket of allocthonous, pelagic sediments (the Hawasina Group) continued until about 80 Ma. The ophiolite was subaerially exposed and eroded, and then unconformably covered by shallow marine sediments during a Late Cretaceous to Early Miocene transgression. Late Miocene – Early Pliocene tectonism formed spectacular anticlinoria cored by autochthonous Proterozoic to Mesozoic sediments of the Arabian continental margin that now separate the different ophiolite massifs. Cooling ages interpreted in terms of uplift and erosion yield Pliocene-Quaternary uplift rates averaging ~ 0.3 mm/yr. Although the ophiolite preserves many high temperature contacts, metamorphic parageneses and structural relationships formed at the submarine spreading center, some faulting and deformation in the massifs must have accompanied Miocene-Pliocene folding and uplift. Metamorphic temperatures remained below 100°C during this episode [*Poupeau et al.*, 1998]. Hence, the only higher temperature metamorphism affecting the ophiolite occurred at and near the spreading center and the nearby, newly initiated subduction zone.

Ophiolite massifs seaward of the Miocene-Pliocene anticlinoria dip offshore beneath a broad apron of fluvial conglomerates. Ophiolite massifs inboard of the watershed in the Oman mountains, including the Samail and Wadi Tayin massifs, are isolated klippe, overlying a variable thickness blanket of allocthonous Hawasina sediments, which in turn overlies the authochthonous Arabian margin sediments. Topographically corrected, Bouger gravity anomalies [*Ravaut et al.*, 1997] indicate that, at their approximate centers, the Samail and Wadi Tayin massifs are composed mainly of partially hydrated (serpentinized) residual mantle peridotite extending to depths greater than 5 km below the present-day erosional surface. These interpretations are consistent with large scale seismic reflection and refraction lines crossing the coast and the Oman mountains just NW of the Samail and Wadi Tayin massifs [*Al Lazki et al.*, 2002] and in the United Arab Emirates [*Callot et al.*, 2010; *Naville et al.*, 2010].

At this juncture, it is crucial to note that seismic surveys cannot detect structure within the ophiolite despite the obvious lithological boundaries within it. Seismic P-wave velocities (Vp) in the crust and mantle are variable and reach a maximum of ~ 5 km/s, due to extensive, multi-scale fracture networks, together with extensive alteration (serpentinization) of mantle peridotite. Even crucial lithological boundaries within the ophiolite, such as the crust-mantle transition, are not imaged. Indeed, sophisticated seismic techniques are needed simply to map the base of the ophiolite, where peridotite overlies limestone with Vp ~ 6 km/s [*Jardin et al.*, 2013; *Naville et al.*, 2010]. Smaller scale seismic surveys (100 m to 7 km) did not detect reflection or refraction boundaries, although site-specific, fracture-related anisotropy was different in peridotite and gabbro, allowing limited, local detection of the crust-mantle boundary [*Ildefonse et al.*, 2000]. Additional seismic surveys for the purpose of characterizing the lithologies in our proposed 250 to 600 m boreholes would be a waste of time and money.

The present day hydrology of the ophiolite was studied by Dewandel et al. [2005], with a focus on the mantle exposures and the crust (gabbro) – mantle transition zone. They estimated a permeability of 10^{-14} m^2 for the fractured mantle peridotite within a few hundred meters of the surface. In catchments underlain by peridotite, water in seasonal and perennial streams within "wadis" (canyons), and most ground water sampled in wells, originated as rainwater and was modified by surficial weathering of the peridotite to produce Mg-HCO_3 rich waters. Neal and Stanger [1985] documented the presence of alkaline springs (pH up to 12) in peridotite catchments, similar to previously studied alkaline springs in peridotite from the California Coast Ranges and other localities. These record ongoing serpentinization and mineral carbonation in subsurface, peridotite-hosted aquifers [*Kelemen and Matter*, 2008; *VanTongeren et al.*, 2008]. The fracture density, permeability, fluid fluxes, microbial communities and reaction rates in these subsurface environments remain almost entirely unknown.

2. Motivation and Goals of the Oman Drilling Project

The overarching goal of scientific drilling in the Samail ophiolite is to understand the full spectrum of processes that create and modify oceanic crust and shallow mantle, involving mass and energy transfer between the mantle, the crust, the hydrosphere, the atmosphere and the biosphere over a range of temperatures from ~ 1350 to 20°C, depths from the surface to 10 or 20 km below the paleo-seafloor, and tectonic settings from spreading ridges to the deep ocean to surficial weathering to subduction zones. Less comprehensive proposals would likely address a few of these processes. Indeed, some proposed drill sites are ideally suited to addressing specific issues. However, all sites will provide crucial data on multiple processes.

In this section, we provide overviews of our broad scientific objectives. In Section 2.5, we will illustrate how each drill site will address these objectives.

2.1 Igneous and metamorphic processes at oceanic spreading centers

The remarkable exposures of the Oman mountains, with close affinities to ocean lithosphere formed at intermediate to fast spreading rates, means that the Samail ophiolite has long been an inspiration and testing ground for hypotheses about processes at spreading centers. Many of these ideas remain at the forefront of ocean lithosphere investigations and include:

- ductile flow in the upper mantle (focused vs plate driven upwelling; Figure 2) [e.g., *Ceuleneer et al.*, 1996; *Nicolas and Violette*, 1982]
- melt extraction and transport in the mantle (cracks vs porous conduits) [e.g., *M. G. Braun and Kelemen*, 2002a; *Kelemen et al.*, 1995; *Nicolas*, 1986]
- accumulation of melt in the crust-mantle transition zone [e.g., *Boudier and Nicolas*, 1995; *Korenaga and Kelemen*, 1997]
- deformation of the lower crust (gabbro glacier vs sheeted sills; Figure 3) [e.g., *Kelemen et al.*, 1997; *Nicolas et al.*, 1988]
- near-ridge hydrothermal circulation and alteration (shallow vs deep; Figure 3) [e.g., *Bosch et al.*, 2004; *L Coogan et al.*, 2002; *Manning et al.*, 2000; *VanTongeren et al.*, 2008]
- melt transport, porosity and crystallization in lower crustal cumulates [e.g., *Korenaga and Kelemen*, 1998; *Nicolas and Ildefonse*, 1996]
- freezing, intrusion, stoping and metamorphism at the dike-gabbro transition (Figure 4) [e.g., *Boudier and Nicolas*, 2011; *France et al.*, 2009; *MacLeod and Rothery*, 1992; *MacLeod and Yaouancq*, 2000]

These topics have been addressed via seagoing research when possible, and in turn observations from the oceans have lead to refinement or modification of ideas about the ophiolite. However, ocean drilling is expensive and drilling intact ocean crust has proved slow and challenging. ODP Hole 1256D, the deepest hole into fast spreading Pacific crust [*Teagle et al.*, 2006; *Teagle et al.*, 2012; *Wilson et al.*, 2006], has taken four ocean drilling expeditions to penetrate only as far the dike-gabbro transition zone. Rotary coring and the difficulties of cleaning deep, uncased holes result in biased, low rates of core recovery, compromising attempts to quantitatively describe the oceanic basement [e.g., *Tominaga et al.*, 2009]. High rates of core recovery (approaching 100%) are routine for diamond-coring on-land. Core from the Samail ophiolite will provide an invaluable archive to test well-formed hypotheses in sections of the oceanic crust that remain inaccessible in the modern oceans.

Proposed investigations in drill core samples of the Oman mantle section include studies combining geochemistry to characterize mantle heterogeneity and crystallographic preferred orientations indicative of solid state mantle flow trajectories, and studies of the relative age and spatial relationships of melt transport features relevant to evaluating the nature and importance of "mantle diapirs" in Oman (Figure 2), and to understanding the mysterious processes by which partial melt from a region hundreds of kilometers wide in the mantle is focused into a two to four kilometer wide zone of crustal accretion along oceanic spreading ridges.

We will concentrate our investigations of the formation of the oceanic crust on the accretion of the lower oceanic crust, from the sheeted dike-gabbro to the crust-mantle transitions, as this is where the greatest knowledge gaps exist and ocean floor sampling has been least successful.

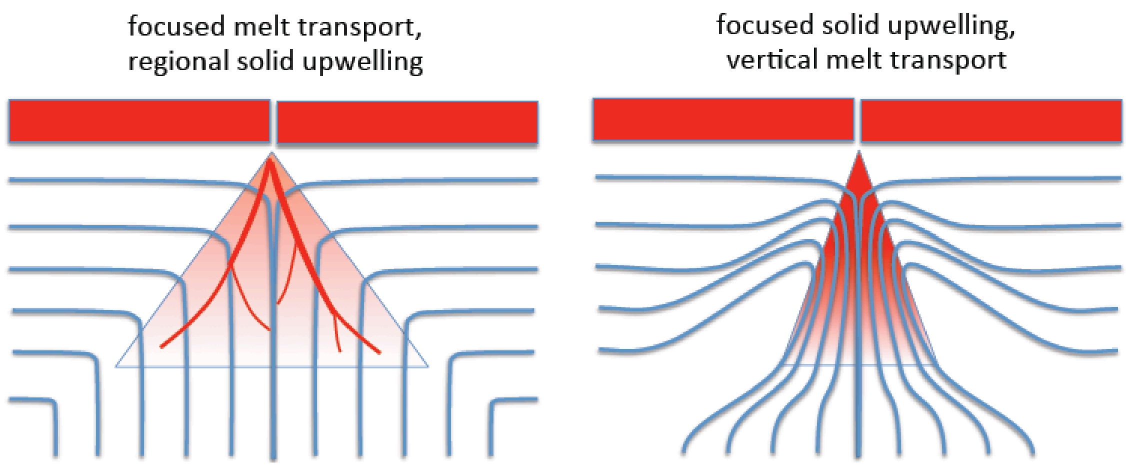

Figure 2: *The magmas from which oceanic crust crystallizes form via partial melting of the mantle as it rises and decompresses beneath spreading centers, driven by the divergence of the tectonic plates. The mechanism that drives focusing of the partial melts, to form igneous oceanic crust over a narrow region, just a few kilometers wide at the spreading center, is not well understood. Is this due to coalescing melt transport within a wide region of solid mantle upwelling, or to highly focused solid upwelling? Study of melt transport veins and solid deformation structures in the Samail ophiolite mantle will resolve this.*

Analyses of drill core from the Oman lower crust will be used to address well-posed, long-standing, unresolved questions. These include the extent of porous flow versus magmatic injection in dikes and sills, the extent of solid-state versus crystal mush deformation of the lower crust and its variation with depth, the modification of lower crust composition via hydrothermal alteration, the transition from relatively coarse gabbros to fine-grained sheeted dikes, and the role of fluids in controlling the nature and rate of cooling of the lower crust. These processes are the primary controls on heat and mass input from the mantle to the oceans, but their extent and interplay remain controversial after decades of discussion. Study of chemical variation with depth, the extent of crystallographic preferred orientation, and zoning within minerals indicative of cooling rates over a variety of different temperature intervals, should provide clear resolution of these questions, or at least comprehensive constraints on remaining hypotheses.

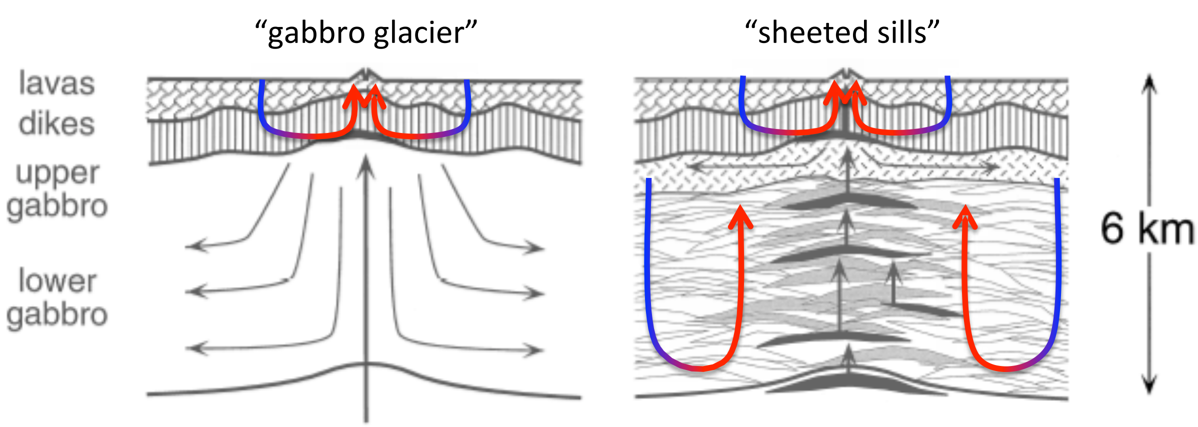

Figure 3: *Lower oceanic crust crystallizes from subsurface magma beneath spreading centers, forming gabbros. The site of crystallization is poorly known. Does it occur in a "shallow melt lens", after which gabbros undergo ductile flow downward and outward (left), or do gabbros crystallize from stacked melt lenses throughout the crust (right)? Study of chemical variation and crystal orientation in the lower crust*

of the Samail ophiolite will resolve this question. Crystallization of gabbro in a shallow melt lens requires rapid removal of heat by hydrothermal convection in the upper crust. Crystallization of gabbro at a range of depths requires hydrothermal circulation down to the base of the crust. Measurement of mineral zoning in Oman gabbros, interpreted in terms of cooling rates, will resolve which process was predominant. Figure modified from Kelemen et al. [1997] .

Figure 4: *Gabbros intruding blocks of hydrothermally altered sheeted dikes in the Wadi Gideah section of the Wadi Tayin massif. Study dike-gabbro transitions will provide essential information heat and mass transfer between oceanic lower crust, upper crust, and the oceans. From France et al. [2009].*

2.2 Mass transfer into the shallow mantle above subduction zones

A close correspondence between 96 to 95 Ma igneous ages in the crust, and the oldest ages of metamorphic rocks along the basal thrust (ca. 95-94 Ma), indicates that thrusting of the ophiolite over adjacent oceanic crust and nearby sedimentary rocks began during or immediately after initial formation of igneous crust [*Rioux et al.*, 2012a; *Rioux et al.*, 2013]. Metamorphic rocks emplaced along the basal thrust, between overlying peridotite and underlying metasediments, record hot subduction zone conditions up to 800-900°C, 650-900 MPa [*Ghent and Stout*, 1981; *Hacker and Gnos*, 1997]. In some localities, at much shallower depths and lower temperatures, hanging wall peridotites underwent 100% carbonation at ~100°C, to form “listvenites”, rocks composed entirely of magnesite + quartz + chromite [*Falk*, 2013; *Falk and Kelemen*, 2013; *Kelemen et al.*, 2011; *Streit et al.*, 2012] (Figure 5). Sr isotope ratios in listvenites are elevated relative to seawater, like those in metasediments below the basal thrust. Based on a Rb/Sr mineral isochron from a fuchsite-bearing sample yields 97 ± 17 Ma (2 σ), the listvenites formed by metasomatic introduction of CO_2-bearing fluids from underlying metasediments during emplacement of the ophiolite. Thus, the “leading edge of the mantle wedge” may be a globally important, hitherto unappreciated reservoir for carbon [*Kelemen et al.*, 2013a; b].

Drilling and outcrop studies of the thrust contact between metasediments and overlying mantle peridotites (Figure 6), will allow direct study of chemical and physical processes of mass transfer in a subduction zone. Ideas and observations can be quantified via detailed 1D geochemical and structural transects in drill core(s), combined with mapping of the surrounding 3D geology.

Of particular interest will be identifying the footwall source(s) of carbon-rich fluids, the mechanical processes of fluid migration, the diffuse or localized nature of hanging wall alteration, the overall balance of low temperature mass transfer, the pressure and temperature range over which mass transfer was active, and the extent to which Oman observations can be extrapolated to subduction zones worldwide. Observations there will be interpreted in the context provided by investigations of other settings, especially along active subduction zones in different stages of evolution.

Figure 5: *Fully carbonated lenses (magnesite + quartz + chromian spinel) within partially serpentinized mantle peridotite, near the base of the mantle section of the Samail ophiolite, where peridotites were thrust over metasediments. The lenses are parallel to the basal thrust. The thinner lower lens is about 10 meters thick, the thicker upper lens is about 200 meters thick. Together, they contain about 1 billion tons of CO_2 in solid carbonate minerals. P. Kelemen photo.*

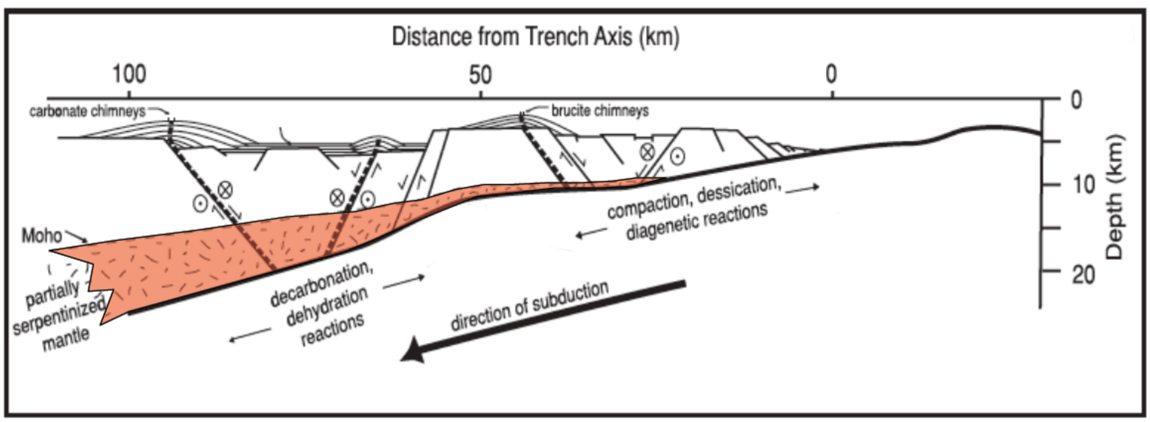

Figure 6: *Modified from Oakley et al. [2007]. Red area indicates approximate position of the Samail mantle section during thrusting over the metamorphic sole and metasediments of the Hawasina Group. Study of alteration of hanging wall peridotites and footwall metasediments will provide an essential complement to studies of mass transfer in subduction zones worldwide.*

2.3 Modern mineral carbonation, serpentinization, hydrology and subsurface biosphere in mantle peridotite

There is increasing recognition that investigating ongoing alteration of peridotite, and the related, subsurface microbial ecosystem in the Samail ophiolite, holds as much promise – for contributing to fundamental understanding of global processes – as studying the Cretaceous formation and evolution of oceanic plates in Oman. Alteration of mantle peridotite – via serpentinization (hydration), carbonation and oxidation – is an essential process in Earth dynamics. Almost everyone has seen altered peridotites – whether they know it or not – as a popular ornamental stone used for building facades and kitchen counters, soapstone amulets and monumental statues. Mineral parageneses in altered peridotite comprise part of the canon of metamorphic petrology. Unlike most iconic metamorphic processes, occuring in obscurity, deep in the Earth, peridotite alteration is ongoing and accessible, occurring at appreciable rates near the surface. For example, in their classic paper Barnes & O'Neil [1969] estimated that dissolved Ca in one alkaline spring was extracted from 10^3 to 10^4 tons/yr of peridotite.

And no wonder. At low pressures, say at 2 kb, mantle peridotite is unstable in the presence of water below ~ 700°C, unstable in the presence of CO_2-rich fluids below ~ 500°C, and unstable at any temperature in the high oxygen fugacity that prevails near the Earth's surface. Below 200°C, the energy density (free energy per unit mass) for peridotite hydration and carbonation is ~ 500 kJ/kg, about 1% of the energy density in liquid hydrocarbon fuels [*Kelemen and Hirth*, 2012]. Where plate tectonics, coupled with erosion, exposes fresh peridotite on the surface, as in the Samail ophiolite, this creates a chemical potential gradient that is unparalleled on Earth in magnitude and extent, like a giant battery, which then proceeds to burn itself out.

The energy from this chemical dynamo drives many of the fundamental processes that shape the Earth. Hydration followed by subduction, supplies huge volumes of water to drive arc volcanism, and maintains or even increases the hydrogen content of the Earth's mantle over time. Peridotite alteration controls the rheology of oceanic plates and subduction zones, causes forearc uplift, and lubricates the mantle. It is essential in the global water and carbon cycles. It produces some of the most reduced fluids on the surface of the Earth, and generates steep compositional gradients that are exploited by chemosynthetic organisms. It has been invoked as an essential ingredient in the origin of life, because it creates ideal conditions (low Eh, FeNi metal catalysts) for abiotic synthesis of organic compounds. Enhanced peridotite carbonation could play a significant role in CO_2 storage, or even a practical and inexpensive route to geological CO_2 capture.

Tectonic uplift and erosion of the Samail ophiolite has brought a vast mass of mantle rocks into the modern weathering domain, providing a unique opportunity to investigate the active serpentinization of mantle peridotite [e.g. , *Clark and Fontes*, 1990; *Kelemen and Matter*, 2008; *Kelemen et al.*, 2011; *Paukert et al.*, 2012; *Streit et al.*, 2012]. The reaction of groundwaters with peridotite at low temperatures forms pH~8, Mg-HCO_3-rich, oxidized fluids in the near surface (Type I fluids in Figure 7; following Barnes and O'Neil [1969], Neal and Stanger, [1985], Bruni et al. [2002], and Dewandel et al., [*Dewandel et al.*, 2005]. When isolated from the atmosphere at depth (>50 m?), Type I fluids continue to react with peridotite to produce pH 12, Ca-OH-rich, highly reduced fluids with no dissolved C or Mg (Type II fluids). This reaction produces very large volumes of serpentine and Mg-carbonate minerals in the subsurface but these deposits have never been sampled in situ. Calcite travertine deposits are precipitated when Type II fluids emerge in springs and react with the atmosphere. Reduced fluids at depths become saturated with the FeNi alloy awaruite. The modern peridotite alteration system in Oman produces oxygen fugacity gradients ranging from bars to nanobars, and pH gradients from 6 to 12. However, the location of the reactions and sub-surface mineral precipitation zones, the fluid residence times, the length scales of fluid flow and chemical gradients, and the sources of essential chemical components (e.g., Ca) remain poorly established.

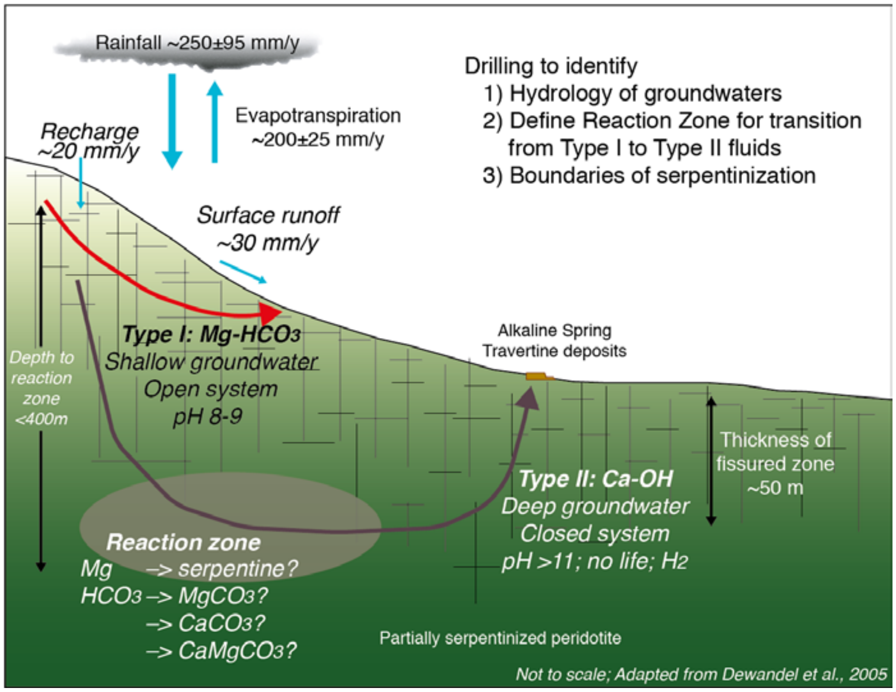

Figure 7: Schematic diagram showing the chemical evolution of groundwaters fluids during reaction with mantle peridotites, [adapted from Dewandel et al., 2005]..

Pioneering studies of peridotite-hosted alkaline springs [*Neal and Stanger*, 1985] and bedrock hydrology [*Dewandel et al.*, 2005] in the ophiolite are now commonly-cited foundations for research on weathering of Oman peridotites, focused primarily on mineral hydration (serpentinization), mineral carbonation, and generation of H_2 and CH_4 [e.g., *Boudier et al.*, 2010; *Kelemen et al.*, 2011; *Oeser et al.*, 2012]. Closed-system interpretation of ^{14}C data yields ages of 0 to > 50 kyr for carbonate veins in serpentinized peridotites with an average of about 26 yr, and a similar range in ages of travertine terraces at alkaline springs [*Clark and Fontes*, 1990; *Kelemen and Matter*, 2008; *Kelemen et al.*, 2011; *Mervine et al.*, 2013] consistent with mineral thermometry indicating near-surface crystallization at 20 to 60°C [*Streit et al.*, 2012], and with observations of alkaline spring water [*Paukert et al.*, 2012], demonstrating that subsurface serpentinization and mineral carbonation are active, ongoing processes in Oman. Perhaps this is not surprising, given the huge reservoir of chemical potential energy represented by outcrops of peridotite far from equilibrium with the high fO_2, fH_2O and fCO_2 in the atmosphere and surface waters.

On the other hand, active alteration in Oman, continuing over 10's of thousands of years in specific sites, poses something of a puzzle. In igneous and metamorphic rocks, fluid porosity and permeability may be negligibly small, so retrograde processes are supply limited. Furthermore, fluids enhance diffusion and so act as catalysts for recystallization. Prograde reactions produce fluids, in a positive feedback, while retrograde reactions may consume all available fluid long before recrystallization is complete. Finally, in an initially open system, retrograde reactions may increase the solid volume. This may fill porosity, destroy permeable flow networks, and armor reactive surfaces, limiting fluid supply and slowing reaction rates. Thus, rocks overcome by these limitations often contain a hodge-podge of disequilibrium mineral assemblages formed by incipient, but arrested, retrograde metamorphism. Commonly peridotites in outcrop are 10 to 60% hydrated, with abundant relicts of the original, mantle minerals.

However, 100% hydrated peridotites, known as serpentinites, are common. Less familiar, but of increasing scientific interest, are "listvenites", 100% carbonated peridotites composed of, magnesite + quartz. How do these form, when retrogression is self-limiting? Two end-member explanations have been offered. Many metamorphic petrologists consider that such reactions occur at constant volume, in which expansion due to decreasing solid density is balanced by dissolution and export of chemical components in a fluid. However, with notable exceptions, most studies of serpentinites, and our work on listvenites in Oman, suggest that alteration was nearly isochemical except for addition of H_2O and/or CO_2.

Alternatively, increasing stress due to volume expansion in an elastically confined volume may cause fractures, which in turn increase or at least maintain permeability and reactive surface area, in a positive feedback mechanism that allows retrograde reactions to proceed to completion [*Iyer et al.*, 2008; *Jamtveit et al.*, 2009; *Kelemen and Hirth*, 2012; *MacDonald and Fyfe*, 1985]. This, and other similar processes involving regulation of permeability via (bio) chemical feedbacks, forms a central hypothesis motivating our proposed drilling of actively altering peridotite.

In some subsurface locations, extreme chemical gradients in altering peridotite are present on a centimeter to millimeter scale, for example in the wall rock surrounding a crack with percolating groundwater. The presence of these gradients has important consequences for the subsurface biosphere and possibly the origin of life. Chemosynthetic organisms thrive in geochemical gradients, where they can catalyze spontaneous reactions resulting from disequilibrium, and make a metabolic "profit". The peridotite alteration environment could be one of the best habitats on Earth for chemosynthetic organisms. Microbial communities in these settings may provide analogs for subsurface life on the early Earth and/or on other less differentiated planets, where surface rocks retain a near chondritic composition. The combination of low fO2, reduced carbon species, and the presence of FeNi metal alloys in serpentinizing peridotite, promotes abiotic synthesis of complex hydrocarbon species [e.g., *McCollom et al.*, 2010].

Deep biosphere habitats are generated during serpentinization because reduced conditions are reached that can lead to the production of H_2 via reduction of H_2O, ideal for sulfate reduction, methane generation, and abiotic or biotic organic synthesis [*Shock and Canovas*, 2010]. Sulfate reduction to form sulfide minerals, and autotrophic methanogenesis, in which microbes gain energy from the reduction of dissolved inorganic carbon, are enabled by serpentinization.

Sulfur and carbon additions and isotopic shifts in ocean floor and ophiolitic peridotites provide abundant evidence for microbial activity during serpentinization [e.g., *Alt et al.*, 2013; *Alt and Shanks*, 1998; 2011; *Alt et al.*, 2007; *Delacour et al.*, 2008; *Schwartzenbach et al.*, 2012]. Also, organic matter derived from biomolecules associated with hydrogarnets in serpentinized peridotites from the Mid-Atlantic Ridge [*Ménéz et al.*, 2012] supports the argument that altered ultramafic rocks host microbial communities that are intimately involved in geochemical exchanges between the mantle and seawater. However, so far studies of active, subsurface peridotite alteration environments have found very little life (D. Cardace, M. Schrenk, A. Templeton, I. Tiago, pers. comm. 2012). Are there nutrient limitations, or toxic constituents? Perhaps investigators have been looking in the wrong places, where alkaline Type II waters have already equilibrated with peridotite, rather than in the reaction zone where Type I waters are converted to Type II. Alternatively, perhaps this energetic but geochemically extreme environment is inaccessible along almost all available evolutionary pathways?

Low temperature alteration and weathering of the Samail ophiolite today is very similar to processes on the seafloor, and in other ophiolites. Thus, high pH alkaline spring waters in peridotite catchments in Oman are very similar in composition to those from the peridotite-hosted Lost City hydrothermal vents on the Atlantic seafloor. There are important differences, which should be emphasized and quantified in all work on this topic, but the general processes of far-from-equilibrium interaction between exposed mantle rocks, the hydrosphere, the atmosphere, and the biosphere, are very similar. Alkaline springs in Samail are also similar to those in other ophiolites, with the best known examples in the California Coast Ranges, the Ligurian ophiolites, and New Caledonia [e.g., *Barnes et al.*, 1978]. However, the arid climate of Oman has enabled the preservation of dozens of extensive travertine terraces formed by these springs, and of carbonate veins – formed in the subsurface and later exposed by erosion – that have been largely dissolved away from surface outcrops in colder areas with more precipitation.

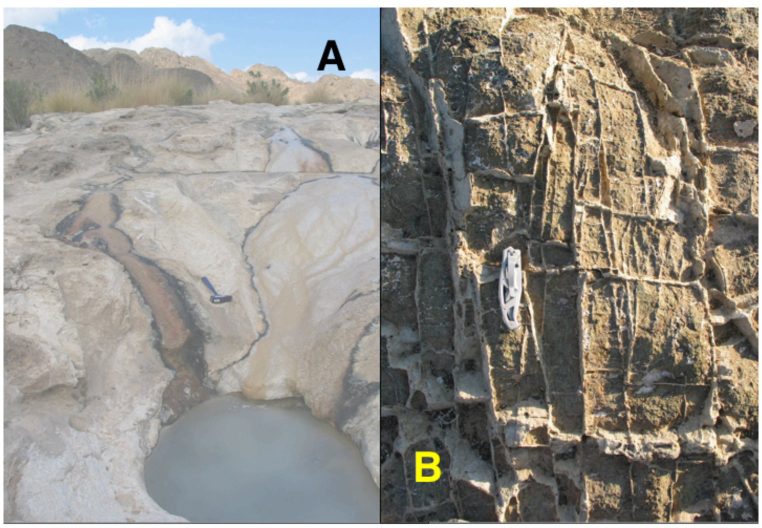

Figure 8: *A. Travertine at an alkaline spring in a peridotite catchment, near the village of Falaij, Oman. B. Carbonate veins in serpentinized peridotite, near the town of Birkat al Mawz, Oman. P. Kelemen photos.*

Drilling in Oman will provide opportunities to test the past habitability of peridotites and gabbros when they were altered, and to examine where and how active serpentinization supports living subsurface microbial communities. Onland studies will complement observations from similar, submarine systems. Thus, proposed, highly-ranked IODP drilling in the vicinity of the Lost City hydrothermal system (IODP Proposal 758), a site of ongoing peridotite alteration near the Mid-Atlantic Ridge, will form a fertile partnership with studies of similar systems in Oman.

2.4 Carbonation of peridotite for geological carbon capture and storage

Previous sections of this proposal describe natural systems in Oman, in which alteration has converted silicates in peridotite into Mg-Ca carbonate minerals, both in a ~ 100°C subduction zone setting and in the present day weathering environment. Understanding natural mineral carbonation systems in Oman, which in some cases have formed carbonate minerals from all of the Mg and Ca present in peridotite protoliths, can provide insight into design of potential, engineered systems for geological capture and storage of carbon springs [*Kelemen and Matter*, 2008; *Kelemen et al.*, 2011], addressing a major societal challenge. These processes may have the potential to make a large contribution, storing gigatons of CO_2 per year in inert, stable, non-toxic carbonate minerals and were the subject of a sister workshop on "Geological Carbon Capture and Storage in Mafic and Ultramafic Rocks", held in Oman in January 2011 (Appendix 3). As noted above, it is somewhat surprising that peridotites can undergo 100% carbonation, but they do in some circumstances. It is important to learn the spontaneous natural mechanisms for efficient mineral carbonation. These can then be emulated and enhanced in order to achieve rapid reaction with minimal additional energy input.

2.5 Specific science objectives of the Oman drilling project

Arranged from deep to shallow, high temperature to low, and ancient to modern, the headline objectives of the Oman Drilling Project are:

Mantle melting, upwelling, and melt transport processes at fast spreading mid-ocean ridges
Objective OB-1: What are the solid-state mantle and lower crust flow trajectories? How do "mantle diapirs", with steep flow trajectories, relate to surrounding mantle with horizontal trajectories due to corner flow beneath the ridge? Is there a shear-sense inversion due to rapid mantle upwelling beneath slowly spreading crust? **Measurement**: Trajectories will be measured via crystal shape and lattice preferred orientation (LPO). Gradual transition from steep to inward dipping to outward dipping indicates rapid upwelling in the diapir "fed" the surrounding mantle and crust. A sharp change indicates that the diapir is a late intrusion into an older oceanic plate. A shear sense inversion indicates that mantle upwelling was more rapid than crustal spreading.
OB-2: What is the spatial relationship between mantle melt transport features and "mantle diapirs", and how is melt focused from a partial melting region ~100 km wide into a zone of crustal accretion at a mid-ocean ridge a few km across, and the crust? Were transport features deformed in the diapir and surrounding mantle**?** **Measurement**: The attitude of planar features, crystal shape and LPO in melt transport features.

Accretion of the lower oceanic crust at fast spreading mid-ocean ridges
OB-4: Do new melts enter the lower oceanic crust by porous flow or by magmatic injection in sills or dikes? **Measurement**: Chemical variation in layered gabbros constrains the amount of porous flow of melt that can have passed through the rocks [*Korenaga and Kelemen*, 1998].
OB-5: What is the extent of solid state versus crystal mush deformation and how does this vary with depth in the lower oceanic crust? **Measurement**: Shape and LPO of plagioclase and olivine will constrain the amount of deformation. Work on drill core will define the presence or lack of high strain "shear zones" as well as the overall vertical trend.
OB-6: What is the vertical distribution of cooling via hydrothermal convection versus thermal diffusion? **Measurement**: Geothermometry, cooling rate estimates (zoning profiles in minerals), isotope data yielding water/rock ratios, and volumetric proportion of hydrothermal alteration.
OB-7: How is the lower oceanic crust modified by hydrothermal alteration? **Measurement**: Comparison of the composition of altered and unaltered rocks along strike in layered gabbros.
OB-8: What is the role of discrete crustal scale faults in channeling deep hydrothermal circulation and the extraction of heat from the lower crust. **Measurement**: Spatial distribution and width of hydrothermally altered zones.

Hydrothermal mass transfer from sediments to peridotite across the basal thrust
OB-9: What is/are the source(s) of carbon-rich fluids responsible for the complete carbonation of specific horizons of shallow Samail mantle? **Measurement**: Isotope studies of metasediments, carbonates, surrounding peridotite,
OB-10: What were the mechanical processes of fluid migration and alteration? **Measurement**: Crack and vein composition, spacing and width, SEM and TEM studies of crystal plastic deformation at crack tips, anisotropy of magnetic susceptibility.
OB-11: What were the pressure-temperature-fluid conditions of mineral carbonation and the mass transfer fluxes? **Measurement**: Geothermometry, fluid inclusion studies, metamorphic petrology of observed mineral assemblages.

The hydrology, geochemistry and microbiology of a modern peridotite catchment
OB-12: What is the extent of sub-surface hydration in the Semail ophiolite peridotites and are there vertical and lateral gradients in serpentinization? **Measurement**: Sampling fluids and core in spatially related boreholes at a variety of depths.
OB-13: What is the vertical extent and distribution of hydrothermal veins and diffuse alteration, fracture densities and permeabilities, and potential pore-scale habitats for microbes? **Measurement**: Crack and vein mineralogy, spacing, ^{14}C, isotope ratios, as well as fluid contents.
OB-14: What are the present day rate and spatial distribution fluid flow? **Measurement**: multi-scale permeability, conductivity, dispersivity, flow rate in boreholes and core.
OB-15: What are the variations of physical conditions and properties, fluid compositions, biogeochemical reactions, and microbial density and diversity with depth and flow path from meteoric recharge to alkaline spring discharge? Is there a vigorous sub-surface biosphere in the peridotite alteration environment or – despite the availability of chemical energy, are there nutrient limitations or toxins that limit microbial abundance? **Measurement**: As above, plus microbial density, DNA and protein sequence, incubation studies, comparison of different sites..

Carbonation of Peridotite for Geological Capture and Storage
OB-16: How do natural systems overcome the negative feedbacks of volume expansion during fluid-rock reactions to produce 100% carbonated rocks? **Measurement**: Crack and vein density and geometry, texture, nature and timing of vein mineral crystallization.
OB-17: What are the sources of carbon and essential cations (Mg, Ca) tracers that precipitate sub-surface carbonates and surficial travertines? **Measurement**: isotope and other tracer studies.
OB-18: What are the water and carbon budgets for mineral carbonation and what by-products (economic, toxic or otherwise) are produced? **Measurement**: Fluid and mineral compositions.

3. Why drill the Samail ophiolite?

The Samail Ophiolite offers the best opportunity for the subaerial study of the mantle, igneous and hydrothermal processes that form new oceanic lithosphere at fast spreading rates. The ophiolite is very well exposed, with ~30-50% bedrock outcrops in the lower crust and upper mantle sections, and respectable exposure of the upper gabbros, sheeted dikes and the lavas in the southern massifs. Given the huge existing literature on Oman and the excellent exposure of the ophiolite, why is drilling necessary? The answer is two fold: (1) many of the pressing science questions require the objective quantification of geological features, and (2) we wish to undertake sampling and experimentation of active hydrological, geochemical and microbial processes associated with ongoing serpentinization of peridotite.

3.1 Objective quantification of geological features

Although there are extensive outcrops in the lower crust and upper mantle of the Samail ophiolite, these are biased to lithologies that are resistant to weathering and erosion – mainly unaltered, crystalline igneous rocks. Fault zones and lithologic boundaries are commonly weathered, yet these may be the most important conduits of fluid flow and hydrothermal chemical exchange. The mountains in Oman are steep, blocky and often covered with scree so that surface sampling and detailed logging generally takes place only along restricted, water worn outcrops along wadis (canyons).

Most outcrops tend to be strongly jointed, with fractures tending to open along pre-existing veins. Sampling with a hammer typically exploits existing joins and fractures, biasing sampling toward more altered edges (vein halos). Many of the observations critical to testing the hypotheses posed above require unbiased quantitative spatial data that are almost impossible to objectively acquire from surface outcrops. These include fracture densities, mineral fabrics, intrusive features, the scale of compositional heterogeneities, fault zones, cross cutting relationships, lithologic boundaries, and the spacing and extent of hydrothermal veins and their alteration zones. Drill core imposes a 1-dimensional discipline that is challenging to emulate in even the freshest outcrops. The quantification of deep crustal hydrothermal fluid fluxes, chemical exchange budgets, and subtle changes in mantle mineral fabrics are imperative to improve our knowledge of ocean ridge mantle and magmatic processes.

Diamond drill core will allow us to take strip samples and make quantitative composite samples to geochemically quantify the bulk composition of the crust, hydrothermal exchange and the abundance of veins and micro-intrusions in gabbros and the mantle. Continuous sensor-track measurements of physical properties (e.g., density, natural gamma, magnetic susceptibility), and whole round and split surface high resolution images will provide non-destructive archives of the core and enable core log integration, core re-orientation into the geographic framework, and geological calibration when combined with the wireline geophysical logs.

The near 100% recovery we can anticipate from on-land diamond coring, coupled with the level of intensity of visual core description and instrumental scanning typical of ODP and IODP cruises, will be powerfully complemented by geophysical logs, regional and local detailed mapping, extensive two- and three-dimensional outcrop surfaces that provide context, and by the opportunity to collect arbitrarily large, equant outcrop samples when needed. Our project will allow direct comparison of drill core and downhole observations with outcrops. These can then be used to evaluate drill core observations obtained over decades by scientific ocean drilling. Such a process will provide a clearer view of the extent to which different aspects of ocean drilling results are representative of the invisible, three dimensional world beneath the seafloor.

3.2 Sampling active systems

Active, subsurface processes in the ophiolite today, mainly fluid flow, chemical weathering, fracturing induced by weathering, and microbial activity, cannot be observed without drilling. Despite more than 40 years of ocean drilling there are very few data on the depth extent, age and rate of low temperature alteration and weathering processes in oceanic crust and upper mantle. One of the most interesting parts of the ongoing weathering process in the Samail peridotites is the relatively rapid uptake of CO_2 – via reaction of rocks with groundwater and then via uptake of atmospheric CO_2 by alkaline fluids on the surface – to form solid carbonate minerals. The subsurface processes –forming ~ 10 times more carbonate than is deposited at the surface and producing alkaline vent fluids– have never been observed (Figures 7 and 8).

These subsurface reaction zones are accessible via drilling in Oman. Assuming that alkaline fluids do not cool significantly during ascent, spring temperatures of 40°C or less (average 27°C, close to the mean annual temperature in Oman) together with the observed geotherm (40°C at 300 m depth in boreholes) suggest that all of the springs have source depths ≤ 300 meters (Neal & Stanger, 1985; Matter, Kelemen and co-workers unpublished data). Alkaline waters with pH 11 to 12 were present throughout the lower three quarters of a 400 meter well sampled in January 2012, so we infer that the reaction zone – forming these waters from pH 8, Mg-HCO_3 waters – is probably within 400 meters of the surface, and "upstream" from this well. Tellingly, dissolved H_2 contents in the well water were 10 to 100 times higher than in alkaline springs sampled on the surface, attesting to degassing during ascent and/or mixing of end-member fluids with shallow ground water to produce surface spring compositions (Matter, Shock, Kelemen and co-workers). Via drilling, we will sample end-member fluid reactants and the subsurface reaction zone where there is ongoing mineral carbonation and hydration. We will determine flow rates and hydrological properties. The results will be highly significant for understanding weathering, the natural carbon cycle, and potential engineering mechanisms to increase subsurface mineral carbonation rates for geological CO_2 capture and storage.

Drilling will also allow sampling and radiometric dating (^{14}C, Uranium decay series) of recent carbonate veins at depth that record previous episodes of reaction and mineral precipitation. Previous work has shown that carbonate veins that formed in the subsurface, subsequently exposed by erosion, commonly contain measurable ^{14}C, yielding ^{14}C "ages" of < 50,000 years. Clearly, the next step in understanding ongoing CO_2 uptake by subsurface mineral carbonation is to drill, sample, and date carbonate veins at depth, including those forming at the present time.

There are no data worldwide on the nature and extent of the subsurface biosphere in weathering mantle peridotite, more than 50 m below the surface. The chemical potential energy, inherent in tectonic emplacement of mantle peridotite near the Earth's surface, should sustain rich and varied subsurface communities of chemosynthetic micro-organisms. However, in contrast to predictions of biogeological studies of alkaline springs, and short boreholes in peridotite in California, have yielded very low cell counts and diversity. Potential explanations for this are that (a) highly alkaline waters have already reacted with and equilibrated with peridotite upstream, so there is little remaining potential energy in the systems where they are sampled, (b) the subsurface reactions that transform Mg-HCO_3 waters to Ca-OH alkaline fluids by precipitating Mg-carbonate minerals, consume almost all the carbon, leaving little available for microbes, or (c) most microbial electron transfer mechanisms are adapted for low to moderate pH environments, not the high pH environment represented by alkaline fluids. For all of these reasons, we believe that prior sampling may have been in the "wrong place"; we should seek the reaction zone where pH 8 groundwater is transformed into pH 12 alkaline water, where dissolved oxygen and carbonate from the surface are abundant but first encounter meet the highly reducing environment imposed by peridotite alteration reactions. This will require several holes in a region of active peridotite alteration, to locate and sample geochemical transition zones.

Presently there are no measurements on the apertures and spacing of fractures in subsurface lithologies in the Samail ophiolite, and the subsurface permeability of the ophiolite lithologies remains largely unknown except for the pioneering work of Dewandel et al. [2005]. Investigations of ongoing alteration and the associated subsurface biosphere are ideally suited to studies of cores and in boreholes. Core will be used to observe the vertical extent and distribution of vein lithologies and diffuse alteration, variation of fracture density and permeability, and the pore-scale habitat of microbial communities. Downhole measurements and fluid sampling will determine the multi-scale variation of fluid composition and flow, crack aperture, porosity, permeability, temperature, stress, microbial density and species diversity. In-hole experiments will determine geochemical transport properties and allow microbial culture and incubation experiments. Hole-to-hole measurements will characterize the nature and frequency of natural fracture events, due to volume changes during ongoing alteration, changing temperature, and precipitation events, monitor microseismicity induced by fluid injection for permeability and geomechanical measurements, and monitor the results of reactive tracer experiments.

4. Drill Site Selection and Proposed Work

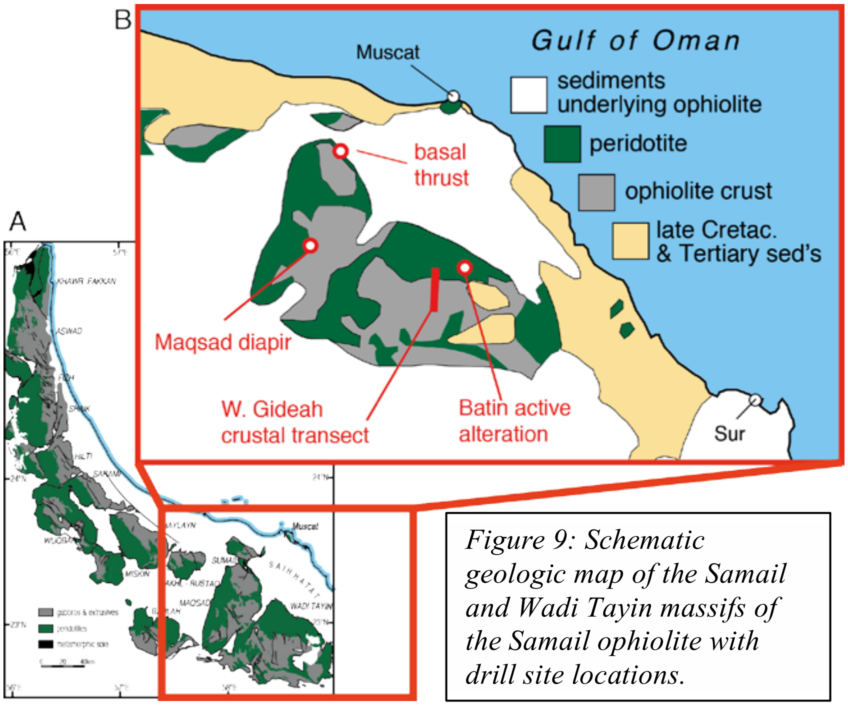

Figure 9: Schematic geologic map of the Samail and Wadi Tayin massifs of the Samail ophiolite with drill site locations.

The proposed drilling program is a direct outcome of working group discussions at the ICDP Oman Workshop (see Appendix 2), and will achieve the science goals of this proposal. In compiling these plans, we used cost information provided by Mawarid Mining LLC and Lalbuksh Irrigation and Drilling Company LLC, both Oman based companies actively exploring for and mining copper and chromite deposits in the ophiolite. These companies have offered to provide their equipment and personnel on contract for this project. A summary of this cost information is provided in Appendix 4. Because drilling costs per meter increase with depth, but startup costs are a larger proportion of the total for short holes, the data yield an approximately constant value of $250 per meter for wireline diamond drilling and coring (Figure A4-1). Because of the robust properties of the target lithologies, drillholes will not be cased, other than near surface collars to protect the hole. Water for lubrication will be supplied from drinking water trucks that routinely supply villages, at a surprisingly low cost.

For water sampling and some geophysical logging, it will be necessary to drill additional holes using rotary drill bits. Less detailed information from Lalbuksh yields an approximate cost of $140 per meter for rotary drilling of 6-inch boreholes without coring. At Site BA1, where microbiological sampling is a top priority, we will attempt to minimize the use of lubricants and drilling mud, subject to on-site cost/benefit analysis.

Comparing wireline logs to observations on drill core is far more effective when the core can be oriented using criteria independent of geophysical logging data. In order to accomplish this routinely, we will orient inclined drill holes so that the core intersects known, planar horizons (layering in gabbros, intrusive contacts, etc) at an appreciable angle.

By merging the recommendations of the three final working groups at the Oman Drilling Workshop, and then eliminating all but the highest priority sites, we have compiled the plan proposed here. The different drill sites described in Appendix 5, with regional locations as shown in Figure 9, are keyed to the overarching science themes outlined in Section 2, based on the theme for which each hole is ideally suited. Other science goals can also be achieved at each site. Table 1 provides information on specific objectives that will be addressed at each hole.

Table 1: proposed drill sites (OB columns refer to objectives in Section 2.5)

igneous and metamorphic processes at oceanic spreading ridges

site	lat	description	1*	2nd	layer	hole	az	incl	mode	depth	cost
	lon		OB	OB	dip (°)		(°)	(°)		(m)	US$
MD1	23.109N	Maqsad diapir,	1,2	4-6,	00	A	360	90	core	400	$100,000
	57.957E	crust-mantle		9-18							
GT1	22.890N	W. Gideah	4-8	12	25 SSW	A	360	90	core	400	$100,000
	58.520E	lower crust			25 SSW	B	360	90	rotary	400	$56,000
GT2	22.852N	W. Gideah	4-8	12	20 SSW	A	360	90	core	400	$100,000
	58.520E	mid-crust									
GT3	22.796N	W. Gideah dike-	4-8		10 SSW	A	360	70	core	400	$100,000
	58.533E	gabbro trans									

mass transfer into the shallow mantle at subduction zones

site	lat	description	1*	2nd	layer	hole	az	incl	mode	depth	cost
	lon		OB	OB	dip (°)		(°)	(°)		(m)	US$
BT1	23.366N	MOD Mtn	9-11	1,	40 S	A	360	70	core	250	$67,000
	58.184E	basal thrust	16-18	12-15							

low temperature alteration hydrology, and microbial communities in peridotite

site	lat	description	1*	2nd	layer	hole	az	incl	mode	depth	cost
	lon		OB	OB	dip (°)		(°)	(°)		(m)	US$
BA1	22.866N	Batin	12-18	1	NA	A	360	90	rotary	400	$56,000
	58.710E	active			NA	B	360	90	rotary	400	$56,000
		alteration			NA	C	360	90	rotary	400	$56,000
					NA	D	360	90	rotary	400	$56,000
					NA	E	360	90	core	600	$153,500
					NA	F	360	90	core	600	$153,500

totals

	days	depth	cost
		(m)	US$
total meters & cost, diamond drilling and coring		5450	$774,000
total meters & cost, rotary drilling		3450	$280,000
total meters & cost		8900	$1,054,000
total days startup	48		
total days drilling	101		
total days	149		

5. Geophysical logging, hydrology, fluid & microbial sampling

5.1 Geophysical wireline logging

Down-hole geophysical wireline logging is an essential part of the project. Wireline logs will be recorded at each drilling site to obtain continuous records of in situ physical and chemical properties of the lithology and formation fluids (Table 2). Wireline logs are needed to complement incomplete core recovery, to pin individual core sections to specific borehole geophysical measurements, and to geographically orient the recovered core sections. The integration of core and wireline data will determine relationships between physical properties, fluid flow, deformation, and the extent of alteration. Focus will be given to the determination of vertical variation of fracture and crack density and width, porosity, permeability, differential stress, fluid composition, and temperature. Comparing wireline logs to observations on drill core is more effective when the core can be oriented using criteria independent of geophysical logging data. To accomplish this routinely, we will orient drill holes so that the core intersects known, planar horizons (layering in gabbros, intrusive contacts, etc) at an appreciable angle.

Table 2. Properties to be analyzed via wireline logging

Properties	Tools / methods	Note
Magnetic	Magnetic susceptibility	Lithology ID, core to wireline correlation
Porosity	Electrical resistivity, sonic, acoustic, dual induction, single induction, dual laterolog	Lithology ID, rock strength & elasticity, seismic velocity, fracture and permeability indication
Permeability, borehole flow	Heat-pulse flowmeter, impeller flowmeter, magnetic susceptibility	Multi-scale permeability and porosity distribution
Formation lithology	Spectral gamma (total gamma plus U, Th, K counts), magnetic susceptibility, optical televiewer, sonic	Extent and orientation of alteration, cracking, veins
Borehole geometry	4-arm caliper	Fracture, fault & borehole breakouts (stress) ID, well-to-well correlation
Borehole fluid	pH, Eh, p, T, C_w	Vertical variation of fluid composition
Borehole images	Acoustic & optical televiewer	Lithology, fracture/crack spacing, orientation and width, local stress, core orientation

The wireline logging will be conducted with slimhole equipment from the Borehole Geophysics Group at the University of Montpellier, France (Dr. Philippe Pezard). All the proposed probes can be operated in small diameter (3”), open boreholes. Two logging engineers from Univ. Montpellier will conduct the logging. The geophysical wireline logging requires funding of US$285,870 (Appendix 6).

5.2. Fluid sampling and borehole tests

Fluid sampling for chemical, isotopic and microbial analysis as well as hydrological borehole tests will be critical for the study of physical, chemical and geomicrobial processes. Fluid sampling will be conducted in selected holes in the crustal and mantle section. There are distinct differences in the hydrologic environment between the crustal (gabbro; Na-Ca fluids) and the mantle sections (peridotite; Mg-HCO_3 and Ca-OH fluids; Figure 7), which result in different chemical composition of the groundwater.

Relatively inexpensive boreholes will be drilled with a rotary bit, without coring, for water sampling. The target diameter for these holes is 6", which will allow us to conduct pumping and tracer tests using packers to study the subsurface permeability and solute transport in fractured peridotite. The following tests will be conducted at water sampling sites:

Pumping tests: Pumping tests will be conducted using a straddle-packer system to evaluate the transmissivity and storativity of specific intervals. Water levels will be measured continuously before, during and after pumping using pressure transducers. Borehole televiewer and vertical flow meter logs (Table 2) will be examined prior to the tests to locate likely permeable zones.

Injection tests: In case of very low permeability, we will perform injection tests in isolated zones using straddle-packers. As for pumping tests, injection tests measure permeability and storativity but they can be employed over a wider range of permeabilities. We will use groundwater that was pumped prior to the injection test and stored in a tank as an injection fluid.

Push-pull tracer injection tests: Single-well push pull tracer tests will be conducted in isolated zones with straddle-packers to quantify solute transport, mass transfer, and effective porosity. In addition, these tests can be used to determine in situ microbial activities [e.g., *Istok et al.*, 1997].The tests consist of a pulse-type injection of tracer solution including biologically reactive components followed by an extraction phase during which the tracer solution is pumped back. Changes in the solute concentration will be measured to obtain breakthrough curves. The quantities of reactant consumed and products formed will be computed.

Fluid samples will be collected, again using straddle packers to ensure that fluids are derived from a specific depth interval, with gas-tight sample chambers to avoid degassing during transport to the surface. A more extensive sampling campaign with repeated collection of fluid and dissolved gas (mainly H_2, CH_4) samples will be conducted at the proposed multi-borehole BA1 Site where peridotite is undergoing alteration. Alkalinity, electrical conductivity, pH, temperature, redox potential as well as spectro analysis for dissolved oxygen, ammonia, nitrate, sulfide, silica and phosphate will be analyzed on site in the field. Fluid and gas samples will be shipped to off-site labs for further chemical and isotopic analysis.

Borehole testing and fluid sampling will be conducted by the project teams and their research groups. Two research associates will conduct the packer tests while the PIs and project manager will oversee the tests at the multi-well test site, and are responsible with their team members for the fluid and dissolved gas sampling. The total cost of the borehole packer and fluid sampling experiments is estimated at US$447,721 (Appendix 7).

5.3 Microbiological Sampling

Petrological and geophysical questions drive selection of several of the proposed drill sites, but much the core from these sites will be valuable for geobiological studies. Evidence of microbial activity may be preserved in core, especially where they intersect zones of serpentinization and other types of alteration. Many forms of fossil evidence of microbiological activity can be sought in cores, and preserving some types of evidence poses minimal constraints on sample handling. Sampling for living microbes requires more stringent methods. These will be applied chiefly during drilling into the active serpentinization system at Site BA1.

5.3.1 Sulfur Isotope Records

Freezing of core samples for sulfide analysis, or packaging in an inert atmosphere, will inhibit sulfide mineral oxidation. This generally has not been done with the samples from IODP holes used for sulfur isotopic investigations of microbial activity [e.g., *Alt and Shanks*, 2011; *Schwartzenbach et al.*, 2012]. We anticipate that samples from all cores taken for petrologic and geophysical studies will be amenable for sulfur isotopic investigations of past microbial activity.

5.3.2 Microbiological and organic geochemistry sampling of core

There are well established techniques for sampling drill cores to minimize microbial contamination following more than a decade's research on the sub-surface biosphere [e.g., *Ménez et al.*, 2012]. Core samples for microbial sampling will be identified at the rig-site on recovery, quickly sub-sampled using organic-free tools wrapped in muffled aluminium, flash frozen in liquid nitrogen, and shipped to Sultan Qaboos University, where an anaerobic chamber in the lab of Prof. Raeid Abed will be used to further prepare selected samples by removing the periphery of the core and preserving cm-sized sub-samples of the center. These sampling efforts will be carefully coordinated with core logging to maintain a balance of efficiency and comprehensive descriptions during the coring process.

In the laboratory at SQU, flash-frozen core centers will be logged and transferred to -80°C freezers for long term preservation (and use for DNA, RNA, and lipid analyses). Samples for cultivation and activity experiments will be processed under anoxic conditions in an anaerobic chamber to evaluate the abundance and characteristics of viable microorganisms and their metabolic activities. This will be primarily accomplished using standard microbiological approaches such as microscopic cell counts and spectrophotometry, as well as more sensitive approaches such as stable isotope tracing of microbial metabolism. Several incubator ovens will be necessary to cover different chemical/thermal conditions.

5.3.3 Minimizing Contamination during Drilling

Drilling into zones of active serpentinization (BA1 and SA1), where a primary goal is to obtain geochemical and microbial samples, will use procedures to minimize contamination. The strategy developed over the years in IODP and other projects is to use anthropogenic organic tracers, such as perfluorocarbons, and microscopic latex beads on the scale of microbial cells to document the extent of contamination of the core during drilling [*Santelli et al.*, 2010]. Where possible at Site BA1, we will store groundwater pumped from rotary drill holes, and/or the existing water monitoring well there, as a drilling fluid. It may also be possible to obtain desalinated, relatively pure water for drilling at this site, from one of the many desalination plants recently completed in Oman.

The total cost of the microbiological sampling is estimated at US$345,572 (Appendix 8).

6. Core description & scanning, publication, sampling & curation

6.1 Core description & scanning

Cores recovered by the Oman Crustal Drilling Campaign will be visually and instrumentally described at modern Integrated Ocean Drilling Program (IODP) standards. There is a wealth of experience to train new scientists in the systematic IODP core logging approaches because many of the proponents of the Oman Drilling Project have served as shipboard scientists, Chief Scientists, and proponents on multiple IODP cruises.

Following drill site labeling, basic curation (depth, interval, way-up), general description of rock types in each section, microbiological (and other ephemeral property) sampling, drill cores will be sealed for transport and stored in Muscat, Oman by the Geological Survey of Oman at no cost to this project. Detailed core description, instrumental scanning, and sampling will be undertaken at a later date by members of the extended science party (proponents + post-docs and graduate students) working in a shipboard expedition mode.

The IODP riserless drill ship, RV JOIDES Resolution (JR), has a recently upgraded, state of the art laboratory for formal curation, and the visual and instrumental description of drill core, including advanced digital database and archiving capabilities. Due to budgetary constraints the JR will not be in continuous, year-round operation at sea for the next five years or more. As a result, it is available for use for at least two months per year in 2015-2017 (see supporting letters from the US National Science Foundation and IODP TAMU, Appendix 17).

Diamond drill cores will be secured for transport, containerized in Oman, and shipped to the JR in port. Scientists will travel to the JR, live and eat onboard, and engage in 24 hour core description operations as if they were at sea on an IODP drilling cruise. Logging of the core will take place for two months per year over three years. The core will be logged in topical groups, so that science teams to log the core can be selected based on research expertise.

We have investigated alternatives including logging core at the IODP Repository in Bremen, the Geological Survey in Berlin, and the IODP Gulf Coast Repository at Texas A&M University, but the JR has the best combination of facilities and is the most cost- and time-effective solution.

The cost to describe ~3000 m of drill core to IODP standards will be US$706,000 (Appendix 9).

6.2 Publication of Oman drilling project reports

We will ensure the systematic and complete publication of basic observations from geophysical logging, water sampling, and core description will be undertaken in a standardized and accessible manner, analogous to the electronic, open-access Initial Reports volumes of the IODP. This is in addition to numerous, anticipated research papers that will report on more specific results of this project in peer-reviewed, international journals. IODP Publications Services at Texas A&M University has offered to help us assemble and publish an Initial Report volume on Phase I of the Oman Crustal Drilling Campaign, with a total cost of US$150,000 (Appendix 10).

6.3 Permanent archiving and storage of drill core

The American Museum of Natural History has offered to permanently curate and store core, and to process sampling requests from research scientists that are submitted more than two years after the core is logged. Other options were considered – including storage in Oman or at the Geological Survey in Berlin. We have selected the AMNH because of their past role in curating and storing the core from the first and largest ICDP undertaking, the Hawaiian Drilling Project. Costs for sorting and storage are estimated at US$17,900 (Appendix 11) as outlined in a letter of support from Dr Edmond Mathez of the AMNH (Appendix 17). We note that if, at some time before completion of this project, the Omani government or Sultan Qaboos University were to offer permanent storage facilities at a similar cost, this might be preferable.

6.4 Off-site analyses of samples and data

A systematic and comprehensive suite of off-site analyses of core, water and biological samples will be undertaken on the samples from this drilling project. Funding for sample analysis will be entirely supported by research grants to the proposal PI's and to other scientists from international and national funding agencies and private foundations. (Appendix 15).

Analyses of core samples will include electron microprobe, laser ICP-MS and ion probe analyses of minerals in thin section, whole rock trace element analyses via XRF, ICP-MS, and volatile element analyzers (e.g., S, C, H_2O); carbon isotope measurements for ^{14}C geochronology, light stable isotope measurements on whole rocks and powders, including clumped C-O isotope measurements for carbonate mineral thermometry, heavy radiogenic isotope measurements and zircon geochronology via multi-collector ICP-MS and/or TIMS, and high precision zircon geochronology via TIMS. We will adopt a "Pool" sampling approach where possible, in which collaborative teams of investigators will share samples (thin sections and powders) to ensure that a representative sample suite is comprehensively analyzed for a standard suite of geochemical parameters (e.g., for whole rock samples: major, trace, and volatile elements; Fe^{3+}/Fe^{tot}; δD, $\delta^{18}O$, $\delta^{34}S$, $^{87}Sr/^{86}Sr$) to provide a reference dataset for more time consuming and specialist analyses (e.g., U-Pb, $\delta^{11}B$, $\delta^{7}Li$).

Core samples will also be subjected to magnetic and physical properties (e.g., ρ, vp, vs, porosity, etc) testing to determine essential properties for correlation with wireline measurements and regional geophysical measurements. Rock and mineral fabrics will be determined by electron back scatter distribution (EBSD), mineral shape analysis, and X-ray goniometry.

Analyses of water samples will include ^{3}H-^{3}He and radiocarbon and noble gas analysis for geochronology.,Samples will be analyzed for dissolved organic and inorganic carbon by carbon analyzer, major and trace elements by ion chromatography, ICP-AES, and ICP-MS using the NIST standards. Dissolved gas concentrations (H_2, N_2, Ar, CH_4, hydrocarbons) will be analyzed by gas chromatograph, as well as stable isotopes ($\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C_{DIC}$, $\delta^{13}C_{DOC}$) by gas source IRMS or by laser spectroscopy. As for the core sample analysis, we will use a "pool" sampling approach, in which the different investigators share samples and the same samples get analyzed for the same parameters in different laboratories for the purpose of quality control and to ensure the comprehensive analysis of the sample set.

Microbial cultures and incubation experiments initiated at the time of sampling will determine the identity and biotechnological potential of the organisms isolated as well as their metabolic capabilities. Frozen samples will be used for extraction and characterization of biomolecules. DNA can be extracted for characterization of the microbial community diversity in subsurface core samples [*Flores et al.*, 2011; *Lin et al.*, 2006; *Sahl et al.*, 2008; *Santelli et al.*, 2008], as well as their metabolic and physiological characteristics using techniques known as quantitative PCR, metagenomics and metatranscriptomics [*Brazelton et al.*, 2011; *Canfield et al.*, 2010; *Flores et al.*, 2011; *Inskeep et al.*, 2010]. If treated appropriately, RNA can be extracted from the core section, to evaluate the active (transcribing) portion of the microbial population and their activities [*Jones and Lennon*, 2010]. Coupled to these data, lipids can be retrieved from the frozen core samples and serve as a bridge between microbiological analyses and organic geochemical analyses. Finally, the abundance of microbial populations and their relationships to mineral phases can be evaluated using scanning and transmission electron microscopy, fluorescence in-situ hybridization and other advanced imaging techniques. Examples of new approaches well-suited to analysis of microbial communities associated with serpentinized rocks include micro-FTIR [*Igisu et al.*, 2012], micro-Raman [*Ménez et al.*, 2012] and cathodoluminescence spectroscopy [*Rommevaux-Jestin and Menez*, 2010], as well as synchrotron-based x-ray microscopy [*Menez et al.*, 2007] and x-ray fluorescence microspectroscopy [*Mayhew et al.*, 2011; *Templeton et al.*, 2009]. Bulk and spatially-resolved C, S and Fe isotopic analyses can also be conducted on the same suite of samples [*Alt and Shanks*, 2011; *Rouxel et al.*, 2008]. All of these techniques can be applied to samples frozen, fixed or preserved in ethanol or RNA later upon sampling and serve to relate bulk analyses to local environments of the microbial populations.

7. Expected benefits of the proposed work

The Oman drilling project will address an array of fundamental science topics on which scientific consensus has not yet been achieved or in emerging fields requiring initial exploration. Data from core, geophysical logs and water samples will resolve long-standing uncertainties, provide strong constraints on developing hypotheses, and provide initial data in emerging fields.

A web site reporting on the progress and results of this project will be coordinated by a project manager and administrative assistant, using the web site facilities of ICDP. This site will provide open access to the Oman Drilling Project Initial Reports when published, as well as a comprehensive list of proponents and a bibliography of abstracts and published articles. All data resulting from the project will be available on the site, following the IODP database format.

Societal benefits from this project will include the incalculable benefit of the basic research described above. More tangible benefits will include increased understanding of natural mineral carbonation processes, at high temperature near magmatic ocean ridges, at moderate temperature above subduction zones, and at low temperature in the present day alteration environment. Understanding of these processes can be used to design engineered methods for geological CO_2 capture and storage. CO_2 capture from shallow seawater, mineral carbonation at depth, return of carbon-depleted water to the sea surface, and uptake of CO_2 from the atmosphere, may constitute a relatively cost-effective method for distributed air capture of CO_2 coupled with geological storage. Unfortunately, distributed air capture of CO_2 may become necessary in the second half of this century, if unchecked greenhouse gas emissions lead to an unsustainable global climate. *This method of in situ mineral carbonation involves direct emulation of natural mineral carbonation systems, with no reaction rate enhancement, via drilling and reservoir stimulation to induce hydrothermal circulation of seawater through sub-seafloor peridotite*.

Understanding the process of “reaction-driven cracking” is likely to have major societal benefits. In this process, solid uptake of H_2O, CO_2, O_2, and other components from fluids, increases the solid volume, causing high stress and fracture. Fractures, in turn, enhance fluid flow and expose reactive mineral surfaces in a positive feedback mechanism. Although this is observed in hydration and carbonation of tectonically exposed mantle peridotite, the conditions favorable for this mechanism – as opposed to constant volume replacement, and to self-limiting filling of pore space and armoring of reactive surfaces – are poorly understood. Improved understanding could permit engineered applications that create a dense fracture network for fluid transport at the grain scale, not only for CO_2 capture and storage, but also for generation of geothermal power, in situ mining and extraction of hydrocarbon resources from “tight” reservoirs.

The most substantial educational benefit from the proposed Oman drilling project will be involvement of Omani undergraduate and graduate students from Sultan Qaboos University (and perhaps other Omani Universities) in all aspects of the project. Omani students will participate in water sampling (Section 5.2), and travel to the JOIDES Resolution for extensive experience with core observations (Section 6.1) in the world’s best laboratory for this purpose, working shoulder-to-shoulder with high experienced international scientists. Numerous international graduate students and early career researchers will also take part in this project.

The proponents of the Oman drilling project have a strong record of public and media engagement [e.g,, huge media impact of *Teagle and Ildefonse*, 2011]. We anticipate that this will continue anticipate major interest from an international audience. In addition we would like to generate enthusiasm and interest in the local Omani and regional population beyond geologist at Sultan Qaboos University. We will do this through public lectures to schools, learned societies, and displays in local libraries and museum. We plan to publish a richly illustrated children's book describing the Samail ophiolite and the unique geology of Oman that will be available in Arabic as well as other international languages [e.g,, *Laverne*, 2008] http://www.christine-laverne.com/en/livres-de-geologie/.

8. Project Management

A Project Steering Committee (PSC) will oversee all aspects of this project through completion of the Initial Reports volume and archiving of the core at the American Museum of Natural History. The PSC will meet at least twice a year, once in Oman and once elsewhere. The Chair of the PSC will be Prof. Peter Kelemen. Other members of the PSC will have responsibilities to oversee specific aspects of the project (Appendix 13).

The PSC or their designated representatives will coordinate off-site analyses of rock, water and biological samples. Access to Oman Drilling Project samples and data will be overseen by the Sample Oversight and Allocation Committee, a sub-group of the PSC (Teagle, Kelemen, Goddard, Shock, Schrenk) following the sample allocation procedure in Appendix 14).

The PSC will coordinate proposals for additional funding from international and national funding agencies and private foundations (see Appendix 15), and discuss and approve any necessary changes to the drilling plan and the budget. They will act as, or will appoint, two Chief Scientists to oversee each drilling season, and two Chief Scientists for the two, two month core logging efforts onboard the R/V JOIDES Resolution. They will be the editors of the Initial Reports volume and oversee publication requirements.

The 38 Principal Investigators on this proposal will participate in many aspects of detailed site selection, drilling, geophysical logging, water sampling, core logging, and biogeological sampling, and will ensure that there are sufficient, highly qualified volunteers for the basic characterization of core and boreholes outlined in this proposal.

A Project Manager, on contract to ICDP and reporting to the PSC, and will have operational responsibility for day-to-day coordination of proposed travel, drilling and sample shipment. A co-located Administrative Assistant will assist the Project Manager. The Project Manager will be employed for 75 days in the field in years 1 and 2, and in addition for 5-day weeks in in the office the remainder of year 1, three months in year 2, and month in year 3. The Administrative Assistant will be employed 6 months in years 1 and 2, and 3 months in year 3. The estimated costs for the management and administrative positions totals US$429,602 (Appendix 12A).

The PSC will meet annually in years 1-4 at a cost of $40,000 per year. Sixty members of the Science Party (all scientists involved in the drilling and logging process), will meet in Oman in years 2 and 4 at a cost of $190,000 per year. Thus, the total cost of project coordination meetings will be $460,000 (Appendix 12B).

9. Budget summary

Activity		Cost USD$
Diamond coring and rotary drilling costs (Table 1)		$1,054,000
Geophysical wireline operations (Appendix 6)		$285,870
Borehole tests and fluid sampling (Appendix 7)		$447,721
Microbial sampling and geobiological experiments (Appendix 8)		$345,572
Description of drill core (Appendix 9)		$706,000
Initial Reports Volume (Appendix 10)		$150,000
Permanent archiving and storage of the OCDC Drill Core at the AMNH (Appendix 11)		$17,900
Project management (Appendix 12)		$429,602
Project coordination meetings (Appendix 12)		$460,000
Permitting Fees for Drilling (Appendix 16)		$10,000
	Total Costs	**$3,896,665**
Request from ICDP		**$1,948,332**

10. Time Table

year(s) 0	obtain matching funds, especially for drilling costs, geophysical logging, water sampling and hydrology, microbiological sampling; obtain permits for drilling in Oman, refine site selection
year 1	rotary drilling of two 400-m holes at Site BA1 and one 200-m hole at Site GT1 (1000 m total)
	wireline diamond drilling and coring at Sites MD1, GT1, BT1 (1650 m total)
	water sampling at Sites BA1, GT1
	geophysical logging at all drilled sites in year 1
	core sample shipment to Joides Resolution
year 2	rotary drilling: two 400-m holes at Site BA1 plus deepening to 400-m at Site GT1 (1000 m total)
	wireline diamond drilling at Sites GT2, GT3 and BA1 (1400 m total)
	core description Sites MD1, GT1, BT1 (1650 m total)
	water sampling at Sites GT1, BA1
	geophysical logging at all drilled sites in year 2
	core sample shipment to Joides Resolution logging lab
year 3	core description Sites GT2, GT3 and BA1 (1400 m total)
	core sample shipment from Joides Resolution to American Museum of Natural History
	begin preparation initial reports volume
year 4	curation and permanent storage of core
	completion of initial reports volume

Drilling will take place during November though March, avoiding the hottest months of the year. Geophysical logging will be undertaken as soon as possible after drilling to minimize hole stability problems. It will also be desirable to sample water in holes several times in order to assess and minimize the effects of contamination during drilling. Rotary drilling and sampling at Site BA-1 in year 1 will enable us to determine the site of the active reaction zone, in preparation for choosing the locations of the two cored, diamond drill holes to be drilled at this Site.

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Appendix 1: Relationship of the Oman Drilling Project to other international geoscience programs

The Cyprus Crustal Study Project

The Oman Drilling Project will build on the pioneering research drilling by the International Crustal Research Drilling Group. The ICRDG was formed in the late 1970's to organize on-land deep drilling investigations to allow direct comparison with results from the Deep Sea Drilling Project and the subsequent Ocean Drilling Program. The particular focus of the ICRDG was to better understand the structure and composition of the ocean crust. This led to a campaign focused on the Troodos ophiolite, Cyprus – at the time the best studied ophiolite. The Cyprus Crustal Study Project (CCSP) drilled a series of 5 holes (CY-1, 1A, 2, 2A, 4) intermittently from April 1982 until March 1985 (See Robinson et al., 1987; Gibson et al., 1989; Gibson et al., 1991), yielding ~4563m of hard rock drill core with an average recovery of over 95%. The domal structural of the Troodos ophiolite enabled an offset drilling approach with overlapping holes to obtain a near continuous section of the relatively thin Troodos crust in CY-1, 1A, and 4. Unfortunately drilling was halted in the deep plutonic hole CY-4 a few hundred meters above the mantle peridotites. Consequently, the crust-mantle transition was never penetrated. Holes CY-2 and 2A investigated the alteration halo and stockwork mineralization associated with the Agrokipia cupriferous volcanic-hosted massive sulfide deposit.

Together with related field mapping, geochemistry and petrology, the CCSP determined the small size of magma chambers (e.g., Browning et al., 1989), made significant advances in the understanding of the volcanic stratigraphy and primary magma compositions of the Troodos ophiolite (Schmincke et al., 1983; Rautenschlein et al., 1985), identified the importance of detachment faulting and graben formation at slow spreading ridges (Varga and Moores, 1985), and illuminated the geometry and extent of hydrothermal alteration and mineralization in the ocean crust (e.g., Gillis and Robinson, 1988, 1990; Bednarz and Schmincke, 1989, 1990; Richards et al., 1989; Richardson et al., 1987; Schiffman et al. 1987; Schiffman and Smith, 1988; Bickle and Teagle, 1992).

Although compact and easily accessible, the Troodos ophiolite does not provide a good analog for fast spreading ocean crust; graben formation in the sheeted dikes indicates relatively slow rates of spreading and significant amagmatic extension (Varga and Moores, 1985). Troodos magmas have distinctively supra-subduction zone chemistries. (Rautenschlein et al., 1985; Muenow et al., 1990). The lower half of the lower crust in CY-4 was comprised of ultramafic lithologies (mostly pyroxenite), which cannot be representative of oceanic lower crust.

However, the CCSP made important contributions to the understanding of ocean crust formation through hard rock drilling. In particular, the project illustrated the imperative of combining drillhole studies with intensive field mapping campaigns. Unfortunately due to contemporary practice and funding constraints the petrographic logging, curation, and archiving of the cores and data were not completed to modern scientific ocean drilling standards. The post-drilling laboratory investigations led to an only partial characterization of the core. The Oman Drilling Project will build on the science and lessons of the CCSP and apply scientific drilling to the Samail ophiolite that is a better analog of fast spreading Pacific-type ocean crust.

Scientific Ocean Drilling: DSDP, ODP, IODP

Many of the scientific goals of the Oman Drilling Project are closely aligned to scientific challenges outlined in the most recent affirmation of scientific ocean drilling objectives (Illuminating Earth's Past, Present, and Future, 2013-2023). Indeed, many of the proponents of the Oman Drilling Project played leadership roles in the formulation of the new drilling plan (e.g., Teagle et al., 2009; IODP Science Plan 2013-2023), as lead and co-proponents of ODP and IODP proposals and as co-chief and shipboard scientists on scientific drilling and other explorations of the oceanic crust and tectonically exposed, shallow mantle (e.g., lithospheric drilling at the Superfast site: Hole 1256D; ODP Leg 206 and IODP Expeditions 309/312, 335; ODP Proposal 522Full-MDP, P.I. Teagle; at Hess Deep: ODP Leg 147 and IODP 345; ODP Proposal 551Full, P.I. Gillis; at Atlantis Bank: ODP Legs 118, 176 and 178 and IODP Prop 800-MDP – Indian Ocean Mohole, P.I. Dick; and at 14-16°N on the Mid-Atlantic Ridge, ODP Leg 209, P.I. Kelemen).

Our understanding of the accretion and evolution of the oceanic lithosphere has been greatly advanced by marine geophysical experiments, submarine geological mapping, hydrothermal fluid sampling, and numerical modeling. However. remote observations and hypotheses developed require geological testing through observations at depth. In the oceans this is only possible through scientific ocean drilling and in rare locations where faulting has exposed deep crustal rocks on the seafloor. Rocks from tectonic windows tend to be strongly affected by the faulting processes that led to their exposure, obscuring the ocean ridge processes of most interest. Scientific ocean drilling is expensive, intermittent, and technically challenging (e.g., Hole 1256D – very hard formations, elevated temperatures). The use of rotary coring bits leads to low and biased rates of core recovery, potentially precluding the accurate quantification of seafloor properties (e.g., fracture densities, hydrothermal exchange budgets). Ocean cores are often challenging to re-locate into the geographic reference frame, inhibiting structural and paleomagnetic interpretations.

The combination of excellent field exposures and high recovery diamond drilling will enable the Oman Drilling Project will make important contributions to the following primary challenges in the 2013-2023 IODP Science Plan ("author" IODP in reference list below):

Challenge 8: | What are the composition, structure, and dynamics of Earth's upper mantle?

Challenge 9 | How are seafloor spreading and mantle melting linked to ocean crustal architecture?

Challenge 10 | What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?

Challenge 14 | How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

The Oman Drilling Project will not address upper crustal volcanic stratigraphy and hydrologic objectives that can be better addressed by shallow drilling operations in the ocean basins (e.g., Juan de Fuca ridge – ODP Leg 168, IODP Exp 301 and 327; IODP Prop 769APL2 Costa Rica Crustal Architecture, P.I. Tominaga; or IODP Prop 772APL2 North Atlantic Crustal Architecture, P.I. Tominaga) or by drilling (e.g. CCSP CY-1 & 1A) and mapping in the Troodos and other ophiolites.

Synergy with the Mohole to the Mantle Project (M2M)

IODP Challenge 8 refers to plans to drill completely through Pacific ocean crust formed at a fast spreading rate to penetrate the Mohorovicic Discontinuity and sample fresh peridotites from the upper mantle. Most of the proposed drilling, and associated scientific objectives of the Oman Drilling Project, should be seen in the context of the proposed Mohole to the Mantle Project (M2M; IODP Proposal 805-MDP (2012), information at http://www.mohole.org). The two projects are very different in their overall scale and budgets. At most, including off-site studies not fully described in this proposal, Oman ophiolite drilling and related science investigations will reach ~ 1 to 2% of the ~ $1 billion cost of M2M. Oman drilling will yield progress in understanding a variety of important global processes. By contrast, M2M will provide unique samples from an environment that has never been visited, and which is more inaccessible and much less well known than the surface of the Moon.

In this context, Oman drilling provides an opportunity to evaluate M2M strategies at a relatively low risk. Reviewers of past and present Mohole proposals often ask, what can be learned from a one-dimensional sample through a three-dimensional object such as an oceanic plate? One clear and valid answer, of course, is that if you don't go, you won't ever know. But scientific drilling in the Samail ophiolite provides opportunities for a more subtle and quantitative response. In Oman, we can make observations in drill core, and then – in many cases – map the surrounding three-dimensional geology at any desired scale. Thus, we can statistically determine – just as a simple example – the statistics of serpentine vein density in olivine in 100 m of drill core, and compare them to the values for samples from surrounding outcrops with significant structural relief at a density of 1 sample/km^3, or 10, or 100, or 1000. Such comparisons can provide a statistically valid answer to the question, how representative is a single drill core?

Many Oman drilling proponents are also M2M proponents. We hope to see synergy arising from the Oman project to make M2M a success, and – in doing so – to awaken the public to the potential of basic earth science investigations to explore the unknown, bringing back results with global scientific impact and clear value to society.

Serpentinization and the extremes of life

The IODP Science Plan 2013-2023 highlighted the growing recognition of the role that reactions between mantle peridotite and surface waters play in global tectonics, geochemical cycles, and potentially the origin of life. The discovery at "Lost City" on the Mid-Atlantic Ridge, where off-axis, peridotite-hosted springs emanating tepid hyperalkaline fluids that precipitate huge carbonate mounds and towers, provides evidence for previously unknown biogeochemical cycles associated with the serpentinization of mantle peridotites, and inspiration for approaches to permanent carbon capture and storage through mineral carbonation. Drilling and active experiments in the modern peridotite watersheds in the Oman mountains will contribute important observations to complement proposed seafloor drilling, sampling and experimentation at the Lost City site in the next phase of scientific ocean drilling (IODP Prop 758Full2 – Atlantis Masif Seafloor Processes, P.I. Früh-Green).

Oman drilling will also complement the on-going Coast Range Ophiolite Microbiological Observatory (CROMO) project (Brazelton et al. 2012; Cardace et al., 2011, 2012; Schrenk et al. 2012; Twing et al. 2012; see http://nai-cromo.blogspot.fr/). This project, supported by the NASA Astrobiology Institute with on-going sampling and observations funded by the deep Carbon Observatory, recovered ~ 50 m of drill core using microbiologically clean approaches from an actively serpentinizing terrane near Lower Lake, CA. Several different petrological horizons were encountered during the drilling, and subsampled from coordinated geo-biological analyses. Subsequently, new wells created through the drilling have been sampled quarterly using submersible pumps to monitor microbiology and geochemistry. The CROMO project serves as an important testbed to refine rock, fluid, gas, and biological sampling, and to develop in situ experiments for the active system boreholes in Oman.

Geological Carbon Capture and Storage through Mineral Carbonation

Carbon dioxide emissions into the atmosphere continue to increase rapidly despite efforts aimed at reducing them. Geologic carbon capture and storage through mineral carbonation (CCSM) provides a long-term solution for offsetting these emissions. As described in the main text of the proposal, reactions between mantle peridotites, surface water and CO_2 result in permanent storage of carbon in form of carbonate minerals. Mantle peridotites have the potential to store gigatons of CO_2 per year (Kelemen and Matter, 2008; Kelemen et al. 2011).

The Oman Drilling Project will not only further our understanding of natural mineral carbonation processes in mantle peridotite but it will also provide insight into design of engineered systems. It will complement the ongoing CarbFix project in Iceland (Gislason et al. 2010; see: www.carbfix.com). This project, which is supported by the U.S. Department of Energy, the Icelandic Science Foundation, the European Commission, the Center National de la Recherche Scientifique France, and Reykjavik Energy, involves a ~2,000 tons pilot CO_2 injection into a basalt formation for studying the feasibility of permanent CO_2 storage via mineral carbonation. Basalt, similar to mantle peridotite reacts with CO_2 to form calcium carbonate. An injection of pure CO_2 (~170 tons) was accomplished in May 2012, followed by a continuous CO_2+H_2S injection (waste gas from the Hellisheidi geothermal power plant), which is still ongoing. At the test site, several monitoring wells were drilled into the storage reservoir, and have been sampled weekly to monitor changes in the fluid geochemistry and microbiology. Sample analysis shows fast reaction of the injected CO_2 with the basaltic host rocks.

A similar project, which involves the injection of 1,000 tons of CO_2 into a deep basalts of the Columbia River Basalt Group (CRBG), is being conducted in Wallula, WA, USA (see: Big Sky Carbon Sequestration Partnership; http://www.bigskyco2.org/research/geologic/basaltproject). The project is supported by the U.S. Department of Energy. The objective of this project is to assess the viability and capacity of deep basalt formations as an option for permanent geological carbon storage. To date, an injection well has been drilled to a depth of 1,250 m and a permit to inject CO_2 has been submitted to the responsible authorities. Core, fluid and microbiological samples collected at depth have been analyzed, and results from the seismic survey represent the first known success of surface-based imaging of basalt geology

The CarbFix pilot CO_2 injection test in Iceland and the Big Sky Columbia River project both serve as a testbed for engineered mineral carbonation in mantle peridotites in Oman. Experience gained in these project will help to further develop monitoring techniques for *in situ* mineral carbonation, including the improvement of fluid, microbiology, and gas sampling.

In 2007-2008, Kelemen and Matter were funded by Petroleum Development Oman (PDO) to begin feasibility studies for geologic capture and storage of CO_2 via mineral carbonation in peridotite in Oman. This ended as overall industry participation in CCS declined in 2009. There is potential for this partnership to be restored, if industry interest in CCS recovers.

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Appendix 2: Workshop on Scientific Drilling in the Samail Ophiolite, Sultanate of Oman (Oman Drilling Workshop)

Reports are also online at http://www.icdp-online.org, and at http://www.ldeo.columbia.edu/gpg/projects/icdp-workshop-oman-drilling-project.

Summary

For more than a decade, plans have been afoot for scientific drilling in the Samail ophiolite in Oman. Plans to study formation and evolution of the Samail crust and upper mantle at an oceanic spreading have been augmented by recent interest in ongoing alteration and weathering, and the associated sub-surface biosphere supported by the chemical potential energy inherent in exposure of mantle peridotite at the Earth's surface. This interest is motivated, in part, by the possibility of geological carbon capture and storage via engineered, accelerated mineral carbonation in Oman.

An International Continental Drilling Program (ICDP) pre-proposal led to the Workshop on Scientific Drilling in the Samail Ophiolite, Sultanate of Oman, in Palisades, New York, from September 13 to 17, supported by the ICDP ($50,000), the Sloan Foundation's Deep Carbon Observatory (DCO, $30,000), and the US National Science Foundation (NSF, $10,000). There were 77 attendees (listed below) from 11 countries (9 members of ICDP). 21 were women and 20 were early career scientists.

After keynote presentations on overarching science themes, participants in working groups and plenary sessions outlined a US$2 million drilling plan that practically addresses testable hypotheses and areas of frontier discovery in understanding the subsurface biosphere, characterizing the rates and mechanisms of ongoing mineral hydration and carbonation, characterizing chemical and physical processes of mass transfer across a subduction zone, evaluating well-posed hypotheses on hydrothermal circulation, cooling, and emplacement mechanisms of igneous rocks in the lower crust, and investigating key problems in the dynamics of mantle flow and melt transport beneath oceanic spreading ridges.

Workshop Proceedings and Results

Keynote speakers outlined hypotheses and areas of frontier scientific exploration to be addressed via drilling. These included:

- the nature of mantle upwelling,
- the chemical and physical mechanisms of mantle melt transport,
- the processes of lower crustal accretion and cooling,
- the frequency and magnitude of microseismicity during weathering,
- the rate and location of ongoing alteration, and
- the composition, density and spatial distribution of subsurface microbial communities.

Additional keynote talks covered state-of-the-art geological logging of drill core, geophysical logging in boreholes, and data management.

Breakout groups considered overarching science themes, then designed idealized projects to address these themes, and finally considered practical constraints. There were three breakout sessions, with three different groups in each session, first chosen alphabetically, then by age, then randomly. We agreed to focus on studies relevant to global processes. There is a consensus that to achieve the desired goals for this project, core must be logged to the IODP standard by dedicated science teams, and there must be extensive geophysical logging and experiments in boreholes. We planned for individual holes extending to a maximum of 600 meters, using local drilling technology and expertise, reasoning that current understanding of variation with depth does not warrant the extra expense required to import specialized equipment and engineers required for deeper holes. Most holes will be inclined relative to known, planar structural features, to facilitate reorientation of core in a three dimensional geographical reference frame.

After wire line diamond drilling with continuous coring, it will be necessary to widen some holes, or to drill parallel holes without coring, by rotary-drilling in order to obtain the ~ 15 cm diameter required for many geophysical logging tools and likely downhole experiments.

We derived an approximate value of US$250/meter for continuous coring, based on approximate, informal estimates from two contractors operating in Oman (Appendix 4). Though drilling costs per meter increase with depth, startup costs comprise a larger proportion of the total cost for shallower holes, so that this linear approximation of cost versus depth is reasonable, within uncertainty. While awaiting more detailed information, we assumed that costs would be about half as much for rotary drilling without coring. In retrospect, based on an estimate of $140 per meter from an Omani drilling contractor, our assumption was a bit low.

Using these estimates, the three breakout groups in the final discussion session were charged with designing a "Phase I" drilling program costing about US$2 Million. In a striking demonstration of consensus, all three recommended similar plans.

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Table A2-1: Drilling plans proposed by the final three working groups.

working group hole depths, meters	group 1	group 1	group 2	group 2	group 3	group 3
	diamond drilling & coring	rotary drilling	diamond drilling & coring	rotary drilling	diamond drilling & coring	rotary drilling
dike-gabbro trans 1	600		600	600	600	600
dike-gabbro trans 2			600		250	
plutonic crust 1	600	600	600	600	600	600
plutonic crust 2	600					
crust-mantle transition 1	600		600	600	600	600
crust-mantle trans 2			600		250	
crust-mantle trans 3					250	
mantle 1	600	600	600	600	600	600
mantle 2			600			
basal thrust 1			100		250	
basal thrust 2			100		250	
basal thrust 3			100			
basal thrust 4			100			
basal thrust 5			100			
basal thrust 6			100			
active alteration 1	250		600	600	600	600
active alteration 2	250	250	600	600	600	600
active alteration 3	250	250			300	
active alteration 4	600	600			300	
active alteration 5	600	600			300	
active alteration 6					300	
shallow seafloor 1	600					
shallow seafloor 2	600	600				

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Appendix 3: IODP/ICDP Workshop on Geological Carbon Capture & Storage in Mafic and Ultramafic rocks

More information is available online at http://www.ldeo.columbia.edu/gpg/projects/

Reduction of greenhouse gas emissions and mitigation of the effects of increasing atmospheric concentrations of these gases are among the most pressing technological challenges to society in this century. Given international needs for continued economic growth and development, fossil fuels will supply energy essential for growth, so that CO_2 capture and geological carbon storage will be key components of mitigation strategies. In situ mineral carbonation may be the safest and most effective means to achieve this. In addition to storage, geological carbon capture – via fluid/rock reactions that remove carbon from air or surface waters – may provide an alternative to industrial CO_2 capture and transport, a method for mitigating distributed emissions from vehicles and agriculture, and a route to achieve "negative emissions" should atmospheric CO_2 concentrations become unacceptably high in the future.

A workshop hosted by the Sultan Qaboos University in Muscat (Sultanate of Oman) in January 2011, brought together scientists from communities associated with the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP), joined by colleagues from the geothermal, chemical, and mining industries. The aim of this workshop was to advance research on carbon capture and storage in ultramafic and mafic rocks. The interest in these rocks stems from their high potential for mineral carbonation – reaction with CO_2-bearing fluids to form inert, non-toxic, stable carbonate minerals.

Workshop participants formulated integrative scientific questions and the identification of potential implementation approaches. Five key conclusions were reached.

A key outcome of this workshop was the formulation of integrative scientific questions and the identification of potential implementation approaches.

Five key conclusions were reached.

1. The potential for several different, engineered mineral carbonation methods should be explored in parallel, by integrated, international research networks, including (a) carbonation of ultramafic mine tailings and sediments, (b) in situ carbonation of ultramafic rocks (peridotite), and (c) in situ carbonation of mafic rocks (basalt). No one can foresee the size or urgency of the societal demand for CO_2 storage in the coming century, nor is it possible to predict the outcome of ongoing research on alternative or complementary methods.

2. It is necessary to understand the physical properties of potential mineral carbonation sites. Specifically, it is essential to quantify permeability, porosity, mineralogy (igneous minerals, plus extent and nature of existing alteration), fracture toughness and other material properties as a function of lithology and depth.

3. It is necessary to understand coupled chemical reaction and fluid transport in natural mineral carbonation systems better, especially in two key areas.

4. Scientific drilling has two key roles to play, (a) study of natural processes throughout the world, and (b) characterization of potential sites for CO_2 storage experiments.

5. The scientific community will probably need to take the lead in mineral carbonation research in the near future, developing and quantifying practical methods for use by government and industry when a consensus arises on the need for these techniques.

Discussions outlined specific, new science plans for international ocean and continental drilling programs. Immediately after the Workshop, a group of participants submitted a proposal for an ICDP sponsored workshop on scientific drilling in the Samail ophiolite in Oman. In addition to more traditional questions about the formation and evolution of oceanic crust, scientific drilling in Oman will investigate present-day alteration processes, their relationship to the deep biosphere, and their potential for acceleration to achieve carbon capture and storage via in situ mineral carbonation. This proposal was approved by the ICDP, and the workshop was held in September 2012 (Appendix 2).

Support

Major financial support for the meeting was raised from Integrated Ocean Drilling Program Management International, Inc. (IODP-MI), Sultan Qaboos University (SQU), the US National Science Foundation (NSF), the European Science Foundation (ESF), UK-IODP, InterRidge and the (US) Consortium for Ocean Leadership. The meeting was also officially sponsored by the International Continental Scientific Drilling Program (ICDP).

Participation

The workshop was attended by 87 registered participants from 15 countries (ICDP members in **bold font**) including : **Australia**, **Canada**, **China (PRC)**, **France**, **Germany**, **The Netherlands**, Hungary, **Iceland**, **Italy**, **Japan**, **Norway**, Oman, Switzerland, the **UK** and the **US** (listed below). The opening ceremony was attended by Her Royal Highness, Mona Al Saaid and His Excellency Dr. Ali Bin Saud Al Bimani, Vice Chancellor of Sultan Qaboos University. Addresses were given by Dr. Saif Al-Bahri, Dean of the College of Science, and Prof. Peter Kelemen, Chairman of the Workshop.

Goals

By bringing together specialists researching the biogeochemical, mineralogical, mechanical and hydrodynamic processes associated with reaction and storage of CO_2-rich fluids in ultramafic and mafic rocks, with representatives from industry, the workshop had 5 principal aims:

1. To integrate knowledge of natural hydrothermal systems, laboratory experiments and numerical modeling to define the required characteristics for geological carbon storage in ultramafic and mafic rocks, and potentially for geological carbon capture as well.

2. To review the first injection tests in mafic reservoirs, and identify potential sites for developmental deployment of this nascent technology in on-shore and submarine environments in both mafic and ultramafic rocks

3. To develop partnerships between scientists and engineers from industry and the oceanic and continental scientific drilling communities working in related but not overlapping fields, to harness knowledge from existing experience, and to evaluate the potential for CO_2 storage in igneous rocks, and its environmental, economical and societal benefits.

4. To outline plans for continental and marine drilling experiments to acquire key data from natural systems for mineral carbonation in mafic and ultramafic rocks and make pilot experiments testing proposed techniques for enhancing natural rates.

5. To evaluate the environmental, economical and societal costs and benefits of CO_2 storage in mafic and ultramafic rocks

The workshop was organized as a series of presentations alternating with breakout sessions for discussion. After a plenary lecture summarizing the general state of knowledge on CO_2 capture and storage from the point of view of chemical engineering, keynote lectures were on natural and enhanced geological storage of CO_2 in mafic and ultramafic rocks, experimentally determined rates of CO_2 reaction with rocks, processes in which volume expansion due to formation of hydrous minerals and/or carbonates leads to fracture, experience with monitoring permeability and CO_2 storage at sea and on land, use of ultramafic mine tailings for mineral carbonation, ongoing projects involving CO_2 injection into mafic rocks, and methods for engineered hydraulic fracture in the geothermal power and mining industries. Small working groups met to discuss mineral carbonation on land and at sea, monitoring of CO_2 storage sites, geophysical rock properties necessary for CO_2 storage, ideal storage site characteristics on land and beneath the seafloor, and the role that could be played by ICDP and IODP in this new field of research.

An important goal or the workshop was to create synergies between scientists working in CCS research and on natural analogues. Therefore, after the workshop, two optional, one day field trips were organized to build a common basis of knowledge and to favor discussion between these different scientific communities, part of which have little to no knowledge of the geology of the ultramafic and mafic reservoirs targeted for CCS studies. On Day 1, we explored the unique outcrops, exposed in the Oman Mountains, illustrating the processes of forming solid minerals containing CO_2, including spectacular white travertine deposits and associated "blue pools". Day 2 aimed at offering a broad overview of the geology of the Oman ophiolite, from ultramafic outcrops to the mafic igneous crust.

Site selection criteria for drilling related to in situ storage of CO_2

Elevated temperature, up to ~ 120 to 250°C of olivine, enhances mineral carbonation kinetics, as does elevated partial pressure of CO_2. Thus, potential advantages of in situ mineral carbonation methods include (a) insulation of the reacting volume from low temperature surface conditions by overlying rocks with low thermal conductivity, (b) preservation of high fluid pressures due to lithostatic or hydrostatic load from overlying rocks and fluid networks, and (c) presence of elevated temperature at depth, especially in areas with an elevated geothermal gradient. The geothermal gradient below ~ 100 m depth but in the upper few km of the Earth, away from plate boundaries, generally ranges from about 15 to 30°C per km depth. Thus, for an area with an average surface temperature of 20°C, 120°C might be reached at ~ 3 to 10 km depth. Near plate boundaries with active volcanism, especially along oceanic spreading ridges, the gradient can be much higher. On the other hand, drilling costs per meter of depth rise almost exponentially with increasing depth. Such conditions dictate selection of a site with a high geothermal gradient, when possible.

For CO_2 capture from stationary industrial sources, it is obviously desirable to choose carbon storage reservoirs as near as possible to the source. However, this criterion can be overemphasized. Though the initial capital cost is high, transportation of fluids through pipelines is surprisingly inexpensive, on the order of $1 to $8 per ton of CO_2 per 250 km at rates of 40 to 5 megatons per year, respectively, for the mature CO_2 transportation network in the US (IPCC Special Report on Carbon Dioxide Capture and Storage, 2005). However, note that these low costs at high flow rates require a downstream storage site sufficient to consume the delivered flux. Tanker shipment of supercritical CO_2 is substantially more costly, though use of otherwise empty LPG tankers on their return from producer to consumer is sometimes discussed.

Drilling and injection costs are substantially higher for seafloor compared to onland sites, by approximately a factor of ten for comparable depths and applications. On the other hand, environmental and societal impacts of leakage and ground deformation may be substantially reduced at submarine sites. It may be optimal to access shallow, submarine storage reservoirs via drilling from the shoreline, as schematically illustrated in Figure 5. Pipelines may also be used for CO_2 transport to near-shore, submarine sites.

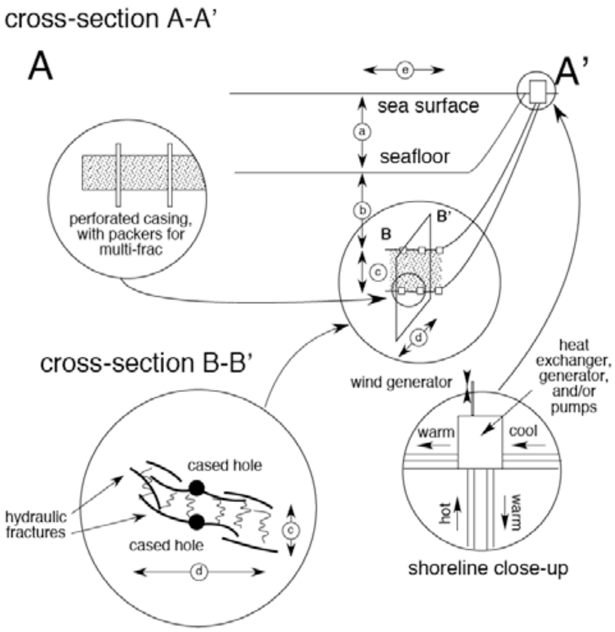

Figure A3-1: *Notional design of shoreline installation for capture and storage of CO_2 from thermal convection of seawater through sub-seafloor peridotite via thermal convection, with low-grade geothermal power as a by-product.*

The presence of an impermeable caprock is commonly invoked as an essential ingredient for carbon storage sites. This is indeed desirable. However, note that this criterion is far more important for sites where long term storage will be in the form of buoyant, CO_2-rich (or methane-rich!) fluids. Where storage sites are deep and cold, as in ancient, near-seafloor lavas, CO_2-rich fluids will be denser than aqueous fluids, so that the presence of an impermeable cap is less important. Similarly, where rapid mineral carbonation takes place, and long term storage will be in the form of inert, stable carbonate minerals, the presence of a low permeability caprock remains advantageous, but an impermeable cap may not be required.

Consensus was reached on the need to support the development of experimental CO_2 storage projects in mafic and ultramafic rock formations. Only field-scale tests will allow evaluation of the different methods envisaged for delivering and storing CO_2. While injection of CO_2-rich fluids into mafic lava formations is underway, there are no pilot sites for carbon storage in ultramafic rock formations yet. Studies at such a site would be an invaluable complement to the two on-going pilot projects in mafic lavas.

As a first step toward future off-shore and on-land pilot studies, the participants defined ideal characteristics for experimental sites, where an engineered pilot study can be carried out, and for study areas, where information can be gathered to address scientific and technical requirements for the pilot site:

(i) Study areas and experimental sites should be well-surveyed areas (geophysics, hydrogeology, availability of baseline monitoring over years, e.g. to control seasonal variability) where subsurface biosphere can be (is) characterized; multiple holes are necessary to allow cross-hole studies (to allow tracer tests for example);

(ii) Study areas should allow observations relevant to other scientific objectives, e.g. paleo-oceanographic and tectonic objectives for oceanic drilling, sub-surface biosphere, present-day weathering, melt extraction and crustal formation studies for onland drilling.

(iii) Experimental sites should be close to CO_2 production sites, have a sufficient permeability to allow large of CO_2 fluxes, have a seal (e.g., sedimentary cap-rock) and also, be scalable to larger studies. If the North Sea injection project by Statoil at Sleipner is taken as a benchmark, an “pilot site” should involve injection of ~ 1 kT CO_2 per year, whereas a “full-scale site” would involve injection of ~ 1MT per year.

(iv) The sub-surface at experimental sites should preferably be dominantly composed of fresh igneous minerals (olivine, pyroxenes, plagioclase) to favor reactivity (heavily-altered hydrothermal systems should be avoided);

(v) Concerns over permitting and societal acceptance may be addressed via creation of offshore CO_2 storage reservoirs. To limit costs, sites should preferentially be close to land with drilling from the shoreline if possible;

(vi) Where storage of CO_2-rich fluids in pore space will be as important as storage in solid carbonate minerals, and where achieving rapid mineral carbonation at high temperature is not a priority, sub-seafloor storage sites should be in deep water (at water depths>2700m, CO_2 is denser than seawater at < 10°C, reducing the need for caprock).

Possible target areas were proposed for experimental and pilot sites. Potential sites abound on-land in basalts and flood basalts. The most favorable basaltic sites would allow a combination of CO_2 storage and hydrocarbon research (e.g., China, Norway, Kudu Gas fields, Deccan …). Ultramafic lavas (komatiites), although they represent only small volumes, could be attractive local storage reservoirs (e.g., southern India, South Africa, Australia). Proposed off-shore study areas in basalts are Juan de Fuca and the 504B/896 area (drilled and open thus allowing cross hole studies), and for experimental sites, the deep pyroclastic zones adjacent to ocean islands (e.g., Iceland) and flood basalts (close to shore such as the north Atlantic), where sparse submarine observations can be supplemented by more extensive studies of more easily accessed subaerial exposures.

Possible on-land and near-shore, submarine ultramafic massifs – both study sites and experimental sites – are in the Samail ophiolite of Oman and the United Arab Emirates, the US Pacific Northwest (particularly in northern California, where the Trinity peridotite extends in the subsurface beneath the Cascades volcanic chain, and where some peridotite massifs of the Franciscan subduction mélange are in the Geysers region, both with well-known, elevated geothermal gradients), Baja California, Nicoya Peninsula in Costa Rica, New Caledonia, southeastern Spain (Ronda) and northern Morocco (Beni Boussera), Adriatic, Cyprus, Tuscany (geothermal), and North Queensland, Australia (Marlborough which is near many coal-fired electric power plants). Papua New Guinea hosts large peridotite massifs, some of which extend beneath volcanic chains, but was generally considered to be too remote.

Potential, offshore, deeper-water study areas in ultramafic basement were suggested: Natural hydrothermal systems: peridotite-hosted mineral carbonation processes are ongoing at the Lost City, Rainbow, Galicia Margin, and the ultraslow spreading Lena Trough hydrothermal systems. Proposed experimental sites in the oceans were mostly near shore ultramafic formations associated with the afore-mentioned, large orogenic peridotite massifs.

Figure A3-2: Dark colored peridotite in the mantle section of the Cretaceous Samail ophiolite, unconformably overlain by Eocene limestone, dipping offshore along the northern coast of Oman near the capital city of Muscat. Photo from http://www.beauxsonges.fr/IMG/jpg/H0H7YH1W1111111.jpg.

General site selection criteria for geological capture and storage of CO_2

Geologic capture of CO_2 by reaction of surface waters with ultramafic rocks may be an effective alternative to industrial capture of CO_2 followed by geologic storage. Site selection for this approach differs significantly from selection of a site for injection of fluids with high CO_2 concentrations. For example, a low permeability caprock may be unnecessary. Furthermore, because of the low concentration of CO_2 in surface waters, it will be necessary to circulate a huge volume of water through the rock reactant to capture a significant mass of carbon. Thus, though CO_2 uptake will be supply limited even at low temperature and correspondingly slow reaction rates, a high geothermal gradient will be desirable to drive thermal convection and escape the cost of pumping.

Obviously, the ocean represents a huge reservoir of surface water equilibrated with atmospheric CO_2, whereas in most places fresh water is relatively scarce and in high demand. However, extraction of CO_2 from, e.g., oceanic bottom water will have no impact on atmospheric greenhouse gas concentrations, so it is necessary to return CO_2-depleted fluid to the sea-surface, where it will draw down CO_2 from the air. Furthermore, because fluid will be heated during reaction with sub-surface rocks, it is desirable to extract heat from the produced, CO_2-depleted fluid – with generation of geothermal power as a possible by-product – before returning the fluid to the surface ocean.

All of these considerations suggest that near-shore sites are desirable.

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87 participants *(including 10 PhD students and 11 post-docs and young scientists).* 32 participants were European (Iceland not included) and 13 from the Sultanate of Oman..

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Appendix 4: Information on drilling costs in Oman

Table A4-1: Cost estimates for wireline diamond drilling & coring, Mawarid Mining LLC, Oman.

min depth	max depth	drill $/m	cumulative cost to max depth	supplies	drilling days	other days at $8000 per day	total cost	total $/m
0	100	$130	$13,000	$1,000	2	2.5	$40,000	$400
100	200	$150	$28,000	$2,000	4	3	$60,000	$300
200	300	$180	$46,000	$3,000	6	3.5	$83,000	$277
300	400	$220	$68,000	$4,000	8	4	$110,000	$275
400	500	$270	$95,000	$5,000	10	4.5	$142,000	$284
500	600	$340	$129,000	$6,000	12	5	$181,000	$302
0	100	$115	$11,500	$1,000	2	2.5	$38,500	$385
100	200	$130	$24,500	$2,000	4	3	$56,500	$283
200	300	$150	$39,500	$3,000	6	3.5	$76,500	$255
300	400	$175	$57,000	$4,000	8	4	$99,000	$248
400	500	$200	$77,000	$5,000	10	4.5	$124,000	$248
500	600	$245	$101,500	$6,000	12	5	$153,500	$256

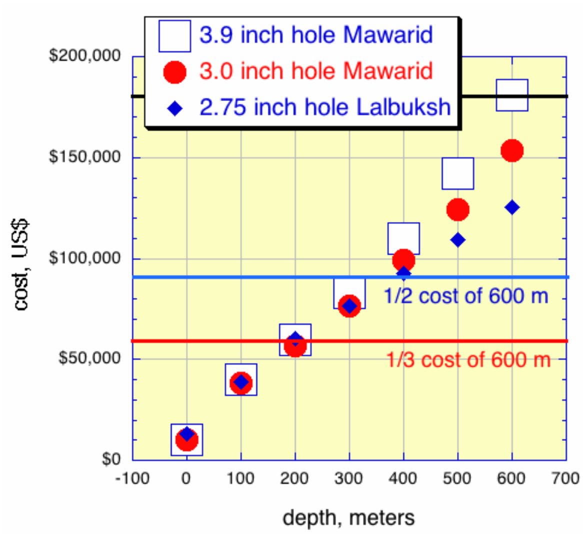


Figure A4-1: Drilling cost estimates from Mawarid Mining and Lalbuksh Irrigation and Drilling Company LLC, both Oman based wireline diamond drilling contractors.

Rotary drilling cost estimate from Lalbuksh Irrigation and Drilling Company LLC in Oman: Cost for rotary drilling of 6-1/8''diameter bore hole to 600 m, without cost of access road.

Item	Description	Unit	Qty	Rate, Omani Rials	Amount
A	**Preliminaries**				
1	Mobilization & demobilization	Item	1	**6,300.000**	6,300.000
	Sub-total (A)	-	-	**-**	**6,300.000**
B	**Bore Hole - 600m**				
1	Move & set up Rig at each location	BH	1	**1,200.000**	1,200.000
2	Drill for, install & cement 7'' x 10m steel casing	BH	1	**980.000**	980.000
3	Drill 6-1/8'' borehole **TD - 600m**	M	590	**41.000**	24,190.000
	Sub-total (B)	BH	1	**-**	**26,360.000**
4	Rig Standby (10hrs/day)	Hr		**65.000**	Rate only
	Total (A+B)				**32,670.000**

Appendix 5: Description of drill sites & strategy

General remarks

Accessibility:

All proposed drill sites except GT1 are adjacent to existing gravel roads and tracks, and/or reachable by driving off road on alluvial plains. Site GT1 will require about 1 km extension of an existing gravel track up a wadi. In general, mobilization and demobilization costs, including use of a bulldozer for site preparation, is incorporated in the drilling cost estimates; this will be more costly at Site GT1, and less costly at some other sites.

Contingencies:

We expect nearly 80 to 100% recovery of core down to the target depths from wireline diamond drilling in 80 to 100% of holes. This is based on our personal experience with wireline diamond drilling of gabbro for mineral exploration in East Greenland (PI Kelemen), personal communication from geologists involved in chromite exploration via wireline diamond drilling of partially serpentinized peridotite in Oman, and our experience in rotary drilling of sub-seafloor gabbro in IODP.

Typically, in mineral exploration drilling similar to that proposed here, hole problems are encountered near the surface, and at depth when holes intersect major, dry faults with high permeability that drain away lubrication water. The former problem can often be countered via minor changes in drill site location early in the operation. The latter problem may cause us to fall short of depth targets in some holes. We do not expect to generate cost over-runs. If we manage to raise more than the minimum amount of matching funds, we could allocate 15% of the funds to retry drilling of some sites, by stepping away from previously undetected, high permeability faults. However, if we cannot find sufficient funding, then such problems will simply result in shorter than planned holes.

Water table:

We have visited and sampled 10 water monitoring wells in the Samail and Wadi Tayin massifs of the Samail ophiolite, the massifs in which our drilling is planned. In these wells, we have found water levels ranging from 4.5 to 22 meters below the surface. This is encouraging from a practical perspective, as this renders it unlikely that lubrication water will drain into dry formations, and from a scientific perspective as we are assured of obtaining the water samples we seek.

No available core from prior drilling:

Mineral exploration drilling has obtained core from sections of the Oman ophiolite. Well preserved core is available for some volcanic-hosted massive sulfide deposits. However, these deposits are not a focus of our proposed research. Exploration drilling for chromite deposits in peridotite from the Samail ophiolite has been conducted in an informal, haphazard fashion, with core lost or scattered, without records of depth or continuity. There has been no prior scientific drilling in the Samail ophiolite. Thus, there are no existing cores available for our proposed research.

1. Igneous and metamorphic processes at oceanic spreading centers

A5.1.MD1 Crust-mantle transition zone, mantle flow, and melt transport features

Site MD1 (23.109°N, 57.977°E) is along a gravel road on the periphery of the steep lineation zone of the "Maqsad diapir", the best mapped and studied part of the ophiolite, close to the west end of cross-section E in Jousselin et al. [1998], (their Figure 7, reproduced here as Figure A5-1-1). Drilling at this Site will collect core through the crust mantle transition zone, and into the underlying residual mantle peridotites.

Site MD-1 will sample the hypothesized, but never observed, zone of rotation in which mantle flow trajectories – which are steep within the diapir, and horizontal to gently outward dipping around the periphery – dip gently inward [e.g., *Jousselin et al.*, 1998]. If the rotation zone can be found, this will support hypotheses in which rapid, ductile vertical flow of the partially molten mantle within the diapir spread radially to fill the surrounding mantle. If the rotation zone is not present, this will indicate that the diapir may be a late, "ductile horst", intruding older residual mantle and oceanic crust.

Coring here will also sample the proposed shear sense inversion [e.g., *Ildefonse et al.*, 1995] that is hypothesized to be present where mantle flow away from the spreading ridge is faster than the plate spreading rate. Outcrop data from elsewhere in the ophiolite have been interpreted to support this hypothesis, but the data are noisy, with many exceptions. Continuous measurements on core will resolve the remaining uncertainty about this crucial structural observation.

Melt transport features at this site will be analyzed to determine their structural orientation (parallel or oblique to the crust-mantle boundary), width, spacing, mineral compositions (in equilibrium with the melts that formed the overlying crust, or not), and extent of deformation (deformed by corner flow beneath the spreading ridge, or not). These data will help to evaluate hypotheses for the presence and origin of melt transport networks that coalesce toward spreading ridges [e.g., *M.G. Braun and Kelemen*, 2002b; *Katz et al.*, 2006; *Rabinowicz and Ceuleneer*, 2006; *Spiegelman and Kelemen*, 2003].

Chemical layering and crystal lattice preferred orientation in gabbros above the crust-mantle transition and in gabbro lenses within the transition zone will be studied to complement similar observations from holes in lower crustal gabbros in Wadi Gideah (Sites GT1 through GT3). Alteration of both peridotites and gabbros will be studied at this site, to complement more extensive observations of peridotite alteration in the Batin area at Site BA1.

Data on hand specimens sampled near this site indicate substantial, systematic, multi-scale mineral compositional variation, ranging from centimeter to 100 meter scales [*Abily and Ceuleneer*, 2013; *Koga et al.*, 2001; *Korenaga and Kelemen*, 1997]. Using data from elsewhere in the ophiolite, Browning [1984] showed that the vertical scale of mineral variation can be used to estimate the height of melt lenses from which cumulates crystallized, and Korenaga and Kelemen [1998] showed that the same kind of data can provide strong constraints on the proportion of reactive, porous flow of melt through layered gabbros and gabbroic lenses. However, because samples are rarely taken or analyzed on the centimeter scale, such data sets are aliased, and yield over estimates of the length scale of chemical variation, the height of magma chambers, and the allowable amount of reactive porous flow of melt through the section. Detailed studies of continuous drill core will resolve these problems.

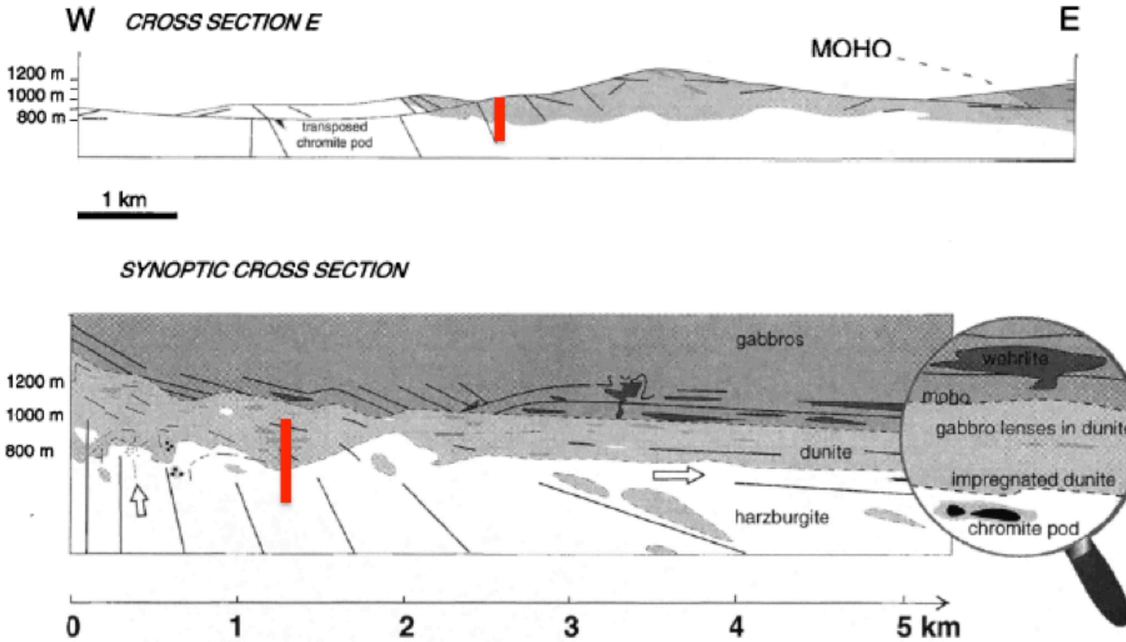


Figure A5-1.1: *Top: Cross section E from Jousselin et al. [1998} at the periphery of the "Maqsad diapir", a region with steep solid-state flow trajectories in the shallow mantle, extending into the crust-mantle transition zone, with proposed drill site marked. Bottom: Synoptic cross section from Jousselin et al.[1998], showing the geological context of the proposed drill iste in the context of the Maqsad diapir, with mantle flow trajectories parallel to the base of the igneous crust (for example, at right) surrounding a roughly circular region with a diameter of about 10 kilometers, in which mantle flow trajectories are nearly perpendicular to the base of the crust (at the left side of the cross section).*

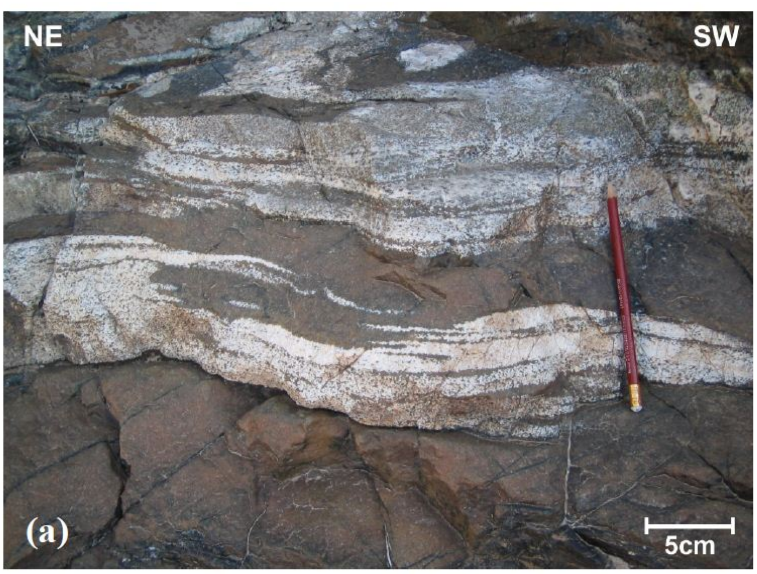


Figure A5-1.2: *Gabbroic lenses in the crust-mantle transition zone of the Maqsad diapir, near Site MD1. Geochemical studies of such lenses offer the opportunity to study melt transport in the uppermost mantle, and deformation structures that reveal the relative velocities of the upwelling mantle and the spreading, oceanic crust [e.g., Jousselin et al., 2012; Kelemen et al., 1997; Korenaga and Kelemen, 1997; Korenaga and Kelemen, 1998].*

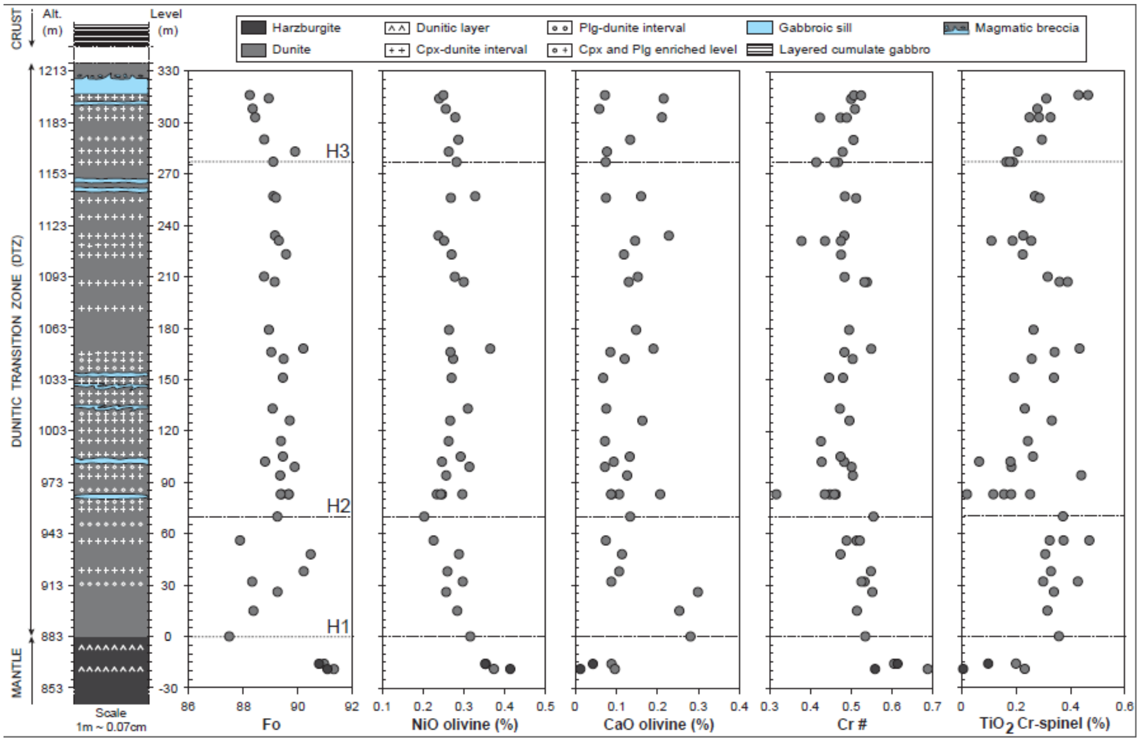


Figure A5-1.2: *Variation in mineral composition on the 10 meter scale, in the immediate vicinity of Site MD1. Figure from Abily & Ceuleneer [2013].*

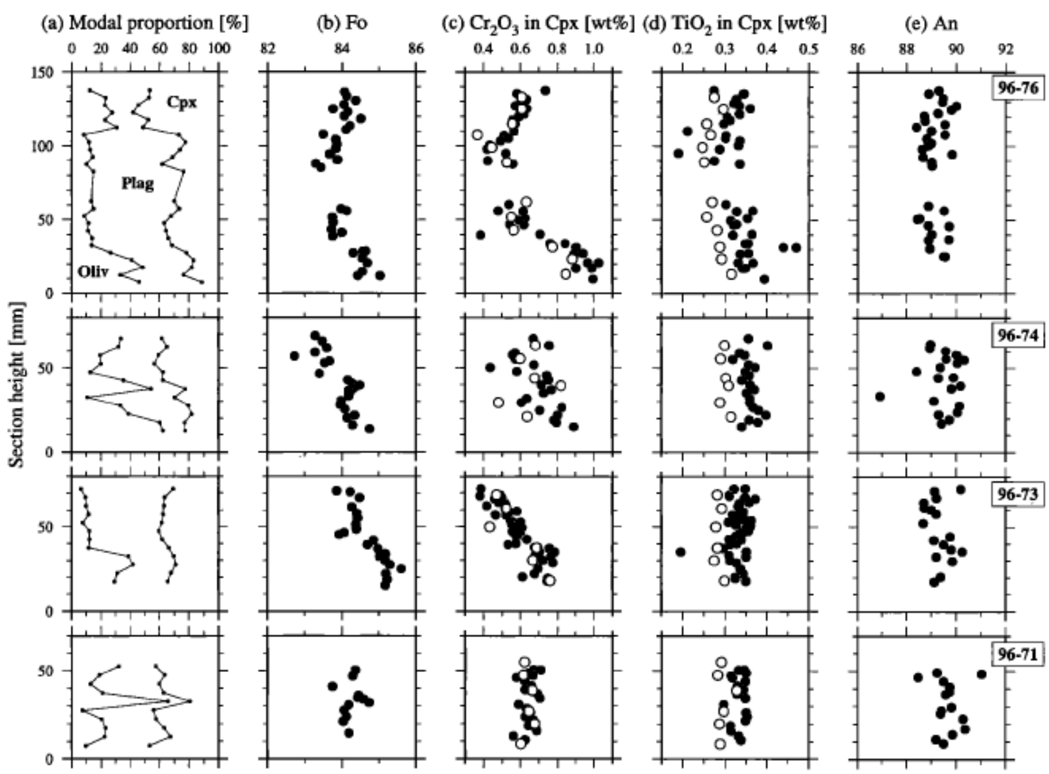


Figure A5-1.2: *Variation in mineral composition on the centimeter scale, in the immediate vicinity of Site MD1. Figure from Korenaga & Kelemen [1997].*

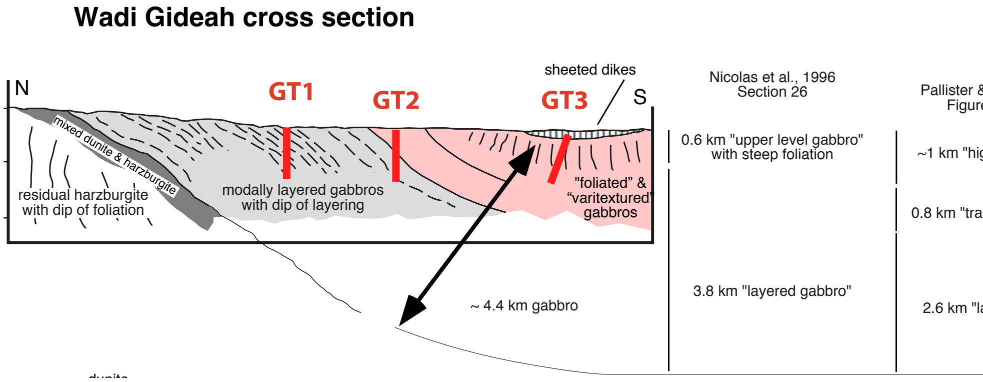


***Figure A5-2**: Cross section along Wadi Gideah, drawn based on published maps and cross-sections [Nicolas et al., 1996; Pallister and Hopson, 1981] and on data from Koepke et al. (pers. comm.) is about 12 km wide, with no vertical exaggeration; tick marks on left side are 1 km apart.*

A5.1.GT1 Lower crustal section in Wadi Gideah

Site GT1 (22.890°N, 58.520°E), two holes: one 400 m, cored hole and an adjacent 400 m rotary hole for logging and fluid sampling. Reaching Site GT1 will require minor extension of a gravel road.

Wadi Gideah, in the Wadi Tayin massif, is the best site for study of an intact crustal section in the Samail ophiolite. The section is well mapped, by the US Geological Survey, the Oman Geological Survey, the Nicolas group at the Université de Montpellier II, and Prof. Tjerk Peters of the University of Bern, Switzerland, and has recently been extensively sampled by Jürgen Koepke and colleagues (e.g., Figure A5-3). Wadi Gideah drains southward from a divide near the crust-mantle transition. Around the wadi, the crustal section dips gently to the south, exposing deeper levels upstream, to the north, and shallower levels to the south, culminating with submarine lava flows in the “Ibra syncline”. This proposal includes four sites at key points within the Wadi Gideah section (Figures A5-2 and 3). It is hoped that a later phase of drilling – not proposed here – will obtain a complete sample through the entire section, in a series of offset holes sampling overlapping parts of the crustal “stratigraphy”.

Site GT1 (22.890°N, 58.520°E) is in lower crustal, layered gabbros, and is ideal for investigation of vertical variation of igneous mineral chemistry, cooling rates over a variety of temperature intervals, mineralogical and geochemical indices of alteration, and crystal lattice preferred orientation. The resulting data will address the ongoing uncertainty regarding the processes that form and cool oceanic lower crust, as outlined in previous sections of this proposal. A 600 meter cored hole, and an adjacent 600 meter rotary hole, will be sited to include a ~ 100 m wide zone of hydrothermally altered gabbros in greenschist facies – a good example of the little studied “focused fluid flow zones” (FFFZ) in the Samail lower crust, which could have been the locus of hydrothermal alteration and advective, lower crustal cooling [*L A Coogan et al.*, 2006].

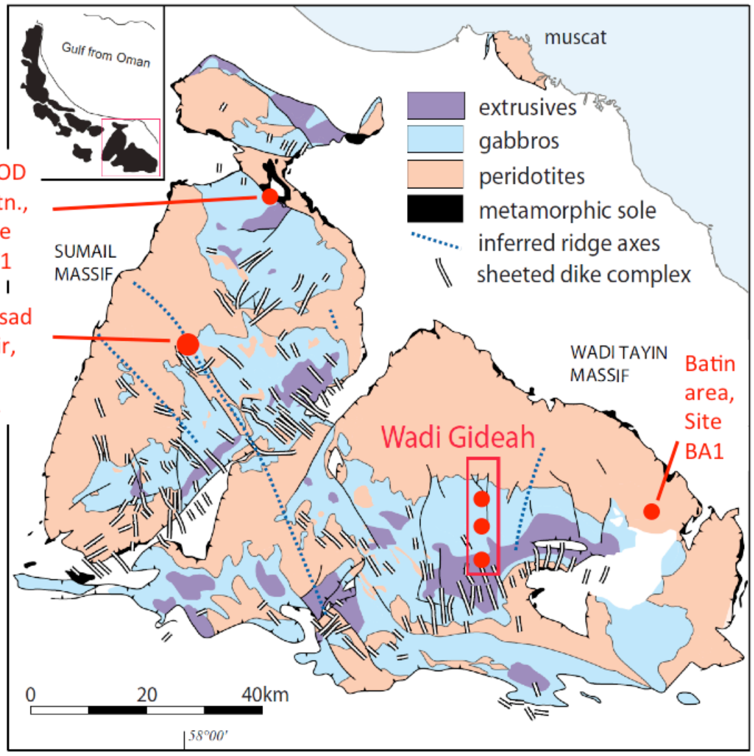
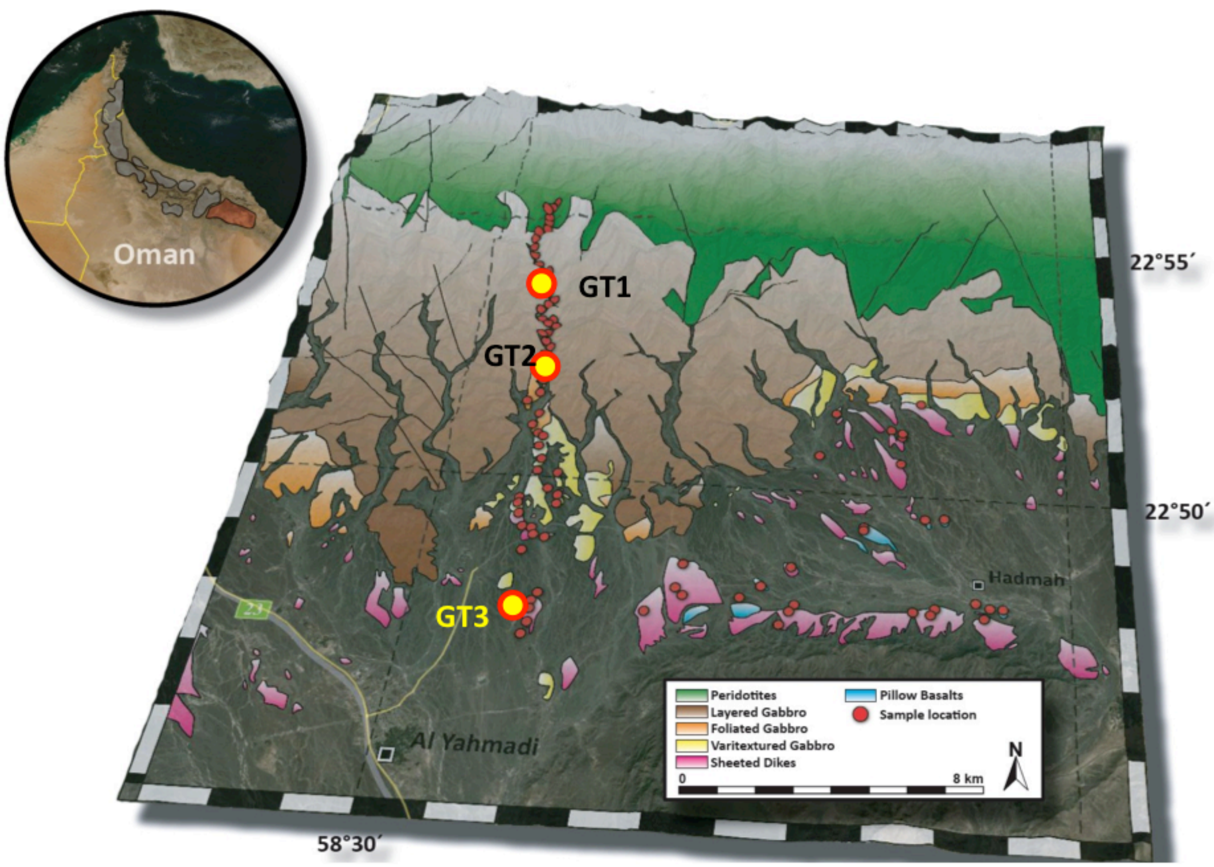


__Figure A5-3__: Two geologic maps showing locations of proposed drill sites in the Samail and Wadi Tayin massifs. Top, map from Nicolas et al. [2000]. Bottom, map based on recent work by Koepke and co-workers (personal communications) showing their sample locations and the proposed drill sites of the Wadi Gideah transect.



Geophysical logging will be valuable as a supplement to mineralogical and geochemical analyses. The rotary hole at this site will be used for water sampling, fluid flow and permeability measurements of hydrology and fluid compositions within the Samail crustal section, for comparison with data from Site GT1 in the mantle part of the Gideah transect, and with more extensive studies of fluid flow and composition in zones of active peridotite alteration at Site BA1.

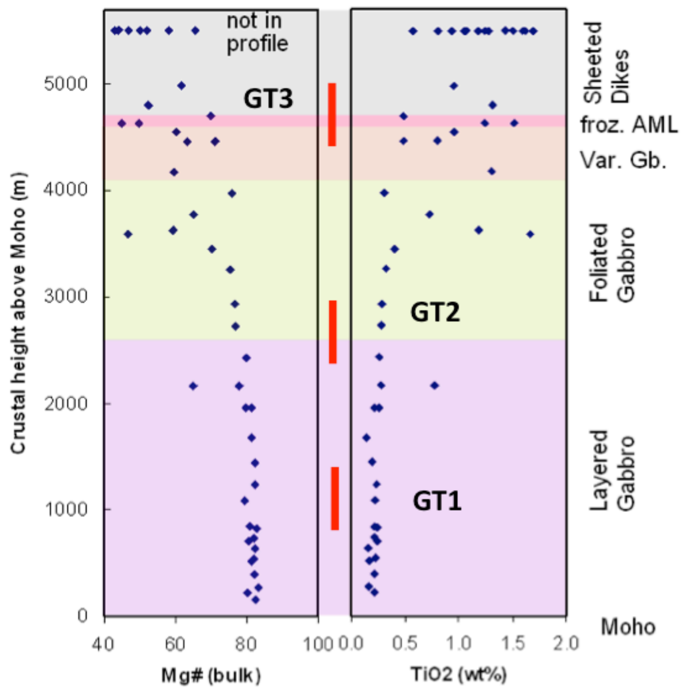


Figure A5-4: *Bulk composition of gabbro and sheeted dike samples from the Wadi Gideah transection of the Wadi Tayin massif, based on recent work by Koepke et al. (personal communication).*

A5.1.GT2 Mid-crustal section in Wadi Gideah

Site GT2 (22.852°N, 58.520°E) is sited along a gravel road, to sample the transition from upper, "foliated" gabbros to lower, "layered" gabbros, associated with a gradient in igneous mineral composition recently documented by Koepke et al. (personal communication), which is essential for determining the relative importance of gabbro glacier versus sheeted sill mechanisms for constructing oceanic lower crust. This hole will also transect at least one, greenschist-facies zone of focused hydrothermal alteration, allowing evaluation of the role of these zones in overall crustal cooling and mass transfer. One 400 meter cored hole will be drilled at this site.

A5.1.5 Dike-gabbro transition in Wadi Gideah

Site GT3 (22.796°N, 58.533°E) is sited along a gravel road, to sample the transition from sheeted dikes into upper "varitextured" and "foliated" gabbros. One cored hole will be drilled at this site, with a depth up to 400 m. The outcrop of the drill site is surrounded by alluvial gravels of the Ibra plain, so that the nature of the bedrock to be drilled is less certain than at our other proposed sites. Thus, cost/benefit analyses during drilling will determine the usefulness of continuing based on the nature of the rock types recovered on a core-by-core basis. The hole will begin in sheeted dike outcrops, and inclined at 70° to sample as much of the paleo-vertical section as possible.

Small, sill-like melt bodies, imaged by multi-channel seismic studies at mid-crustal (1-2 km) levels, are quasi-permanent feature beneath the axes of intermediate- to fast-spreading mid-ocean ridges (MOR) and marginal basin spreading centers. The crystallized melt lens in oceanic crust and in ophiolites lie at the transition between plutonic rocks of the lower crust below and a sheeted dike complex above, at the approximate location of the seismic seismic layer 2–3 boundary in Pacific oceanic crust. As well as representing the roof of the sub-axial magma chamber the dike-gabbro transition this transition is also the locus of the boundary between convective systems: of magma at 1150–1200°C in the melt lens; and of hydrothermal fluids circulating at ~ 400°C through the sheeted dikes and lavas above, extracting magmatic heat and feeding black smoker vents at the seafloor. The two convective systems are thought to be separated by a thin conductive boundary layer <100 m-thick that has a thermal gradient across it of ~ 8°C per meter: by the far the most extreme quasi-steady-state thermal boundary on Earth. Deconvolving the geological processes operating at this horizon will allow us to constrain the controls on heat and mass transfer within the uppermost plutonic oceanic crust.

2. Mass transfer into the shallow mantle above subduction zones

A5.2.BT1 Basal thrust between Samail mantle with listwanite bands and metamorphic sole

Site BT1 (23.366°N, 58.184°E) is in an outcrop area we call MOD Mountain in reference to a nearby Ministry of Defense compound, on the north side of the wide gravel plain of Wadi Mansah, reached by a gravel track. The site is just above the basal thrust of the ophiolite, juxtaposing mantle peridotite in the hanging wall with underlying metasediments and metabasalts of the metamorphic sole and the Hawasina Group. This area hosts extensive bands of "listvenite" (please see Figure 5 in the main proposal text), fully carbonated peridotites, in which all of the Mg and Ca have been incorporated in carbonate minerals, with the SiO_2 remaining as quartz. Relict chromian spinel, and/or the Cr-rich mica, fuchsite, attest to the mantle origin of these thoroughly metasomatized rocks. The site chosen here is the most extensive outcrop of "listvenites" in Oman (similarly large outcrops are present in the Dibba zone of the Samail ophiolite in the United Arab Emirates), and is relatively unusual in that listwanite bands are found 100 to 500 m structurally above the basal thrust of the ophiolite, as thrust-parallel bands up to ~ 200 m thick within less altered, partially serpentinized residual mantle peridotite. In contrast, most listvenites in the Samail ophiolite crop out along contacts juxtaposing metaperidotite with metasediments of the metamorphic sole and the Hawasina group, rendering it difficult to be certain of the pre-metasomatic protolith (peridotite or metasediment) in many cases.

Sr isotope ratios in listvenites are elevated relative to present day and Cretaceous seawater, and similar to those in the nearby metasediments below the basal thrust. An Rb/Sr isochron of mineral separates from a single, fuchsite-bearing sample yields 97 ± 17 Ma (2 σ), indicating that the listvenites formed by metasomatic introduction of CO_2-bearing fluids from underlying metasediments during emplacement of the ophiolite onto the Arabian continental platform. Peak temperatures were ~ 100 to 200°C. Two continuous listvenite bands extending for about 5 km along strike contain ~ 1 billion tons of CO_2 in carbonate minerals formed by interaction between subduction zone fluids at the "leading edge of the mantle wedge" [*Falk*, 2013; *Falk and Kelemen*, 2013; *Kelemen et al.*, 2011; *Streit et al.*, 2012]. Detailed studies here promise to shed light on an important, unexpected, little-studied process that could be of fundamental importance in the global carbon cycle [*Kelemen et al.*, 2013a; b].

A 250 meter cored hole at this site will begin in listvenite, penetrate underlying harzburgite, pass through a band of metabasalt with pillow structures, and end in phyllitic metasediments of the metamorphic sole and the Hawasina Group. This will permit detailed sampling around crucial contacts between listvenite and harzburgite, harzburgite and the metamorphic sole, and metamorphic sole and underlying Hawasina sediments, for detailed studies of mass transfer from subducting sediments into mantle peridotite.

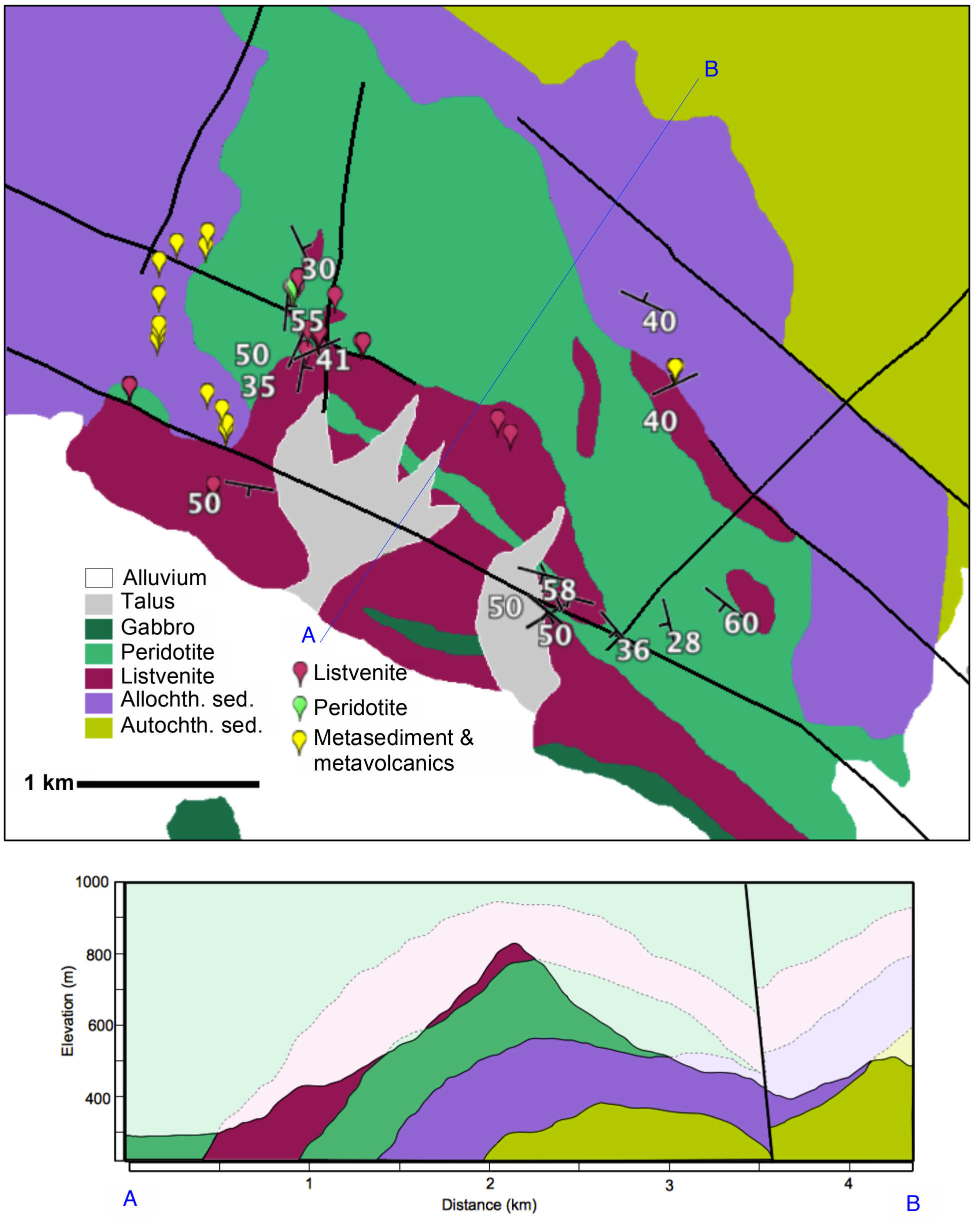


Figure A5-5: *Geologic map and representative cross-section of the MOD Mountain listvenite locality, including individual sample locations (placemarkers). Adapted from Villey et al. (1986), Google Earth data, and field observations (including hand-held GPS measurements and attitudes of composition banding, contacts, and fault surfaces). From [Falk, 2013; Falk and Kelemen, 2013].*

3. Low temperature weathering, present-day hydrology and biogeosience

A5.3.BA1 Active alteration and microbial communities in peridotite

Site BA1 (22.866°N, 58.710°E), about 10 km NNE of the village of Batin, has been chosen for detailed study of ongoing, low temperature alteration of mantle peridotite via interaction with groundwater in Oman. There are many gravel tracks in this area, and it is easy to drive off these tracks on alluvial terrances. The Site is centered on a 400 meter water monitoring well

(NSHQ14) drilled about ten years ago by the Omani Ministry of Water Resources, that was logged and sampled by Jürg Matter, Everett Shock and co-workers in January, 2012. Logging data and water sampling demonstrated an approximately linear increase of temperature with depth, from 35°C at 11 meters, to 41°C at 295 meters depth, the presence of alkaline water (pH 11.0) over a depth range extending from less than 70 m to more than 260 m, and dissolved H_2 concentrations of 1.3 mM, more than four times higher than in alkaline springs at the surface (0 to 0.33 mM).

Site BA-1 is near active travertine formation and springs issuing pH ~11 Ca-OH fluids. The Batin area is chosen specifically because it is in the midst of the mantle section of the Wadi Tayin massif, in a catchment underlain entirely by peridotite. Gravity data indicates that the mantle peridotite in this region is ~ 5 km thick [*Ravaut et al.*, 1997]. Hence we can be confident that our drill holes will be entirely in peridotite, and that the mineral carbonation process in this region involves only groundwater and peridotite. This assuages concerns that carbon, Ca, or other components involved in mineral carbonation might come from the underlying metasediments that contain marine carbonates. Such external sources can also be ruled out using isotope data for all samples analyzed so far, but these data are not available for many of the alkaline springs that, for hydrological reasons, issue close to the edge of the ophiolite near fault contacts with the underlying Hawasina metasediments.

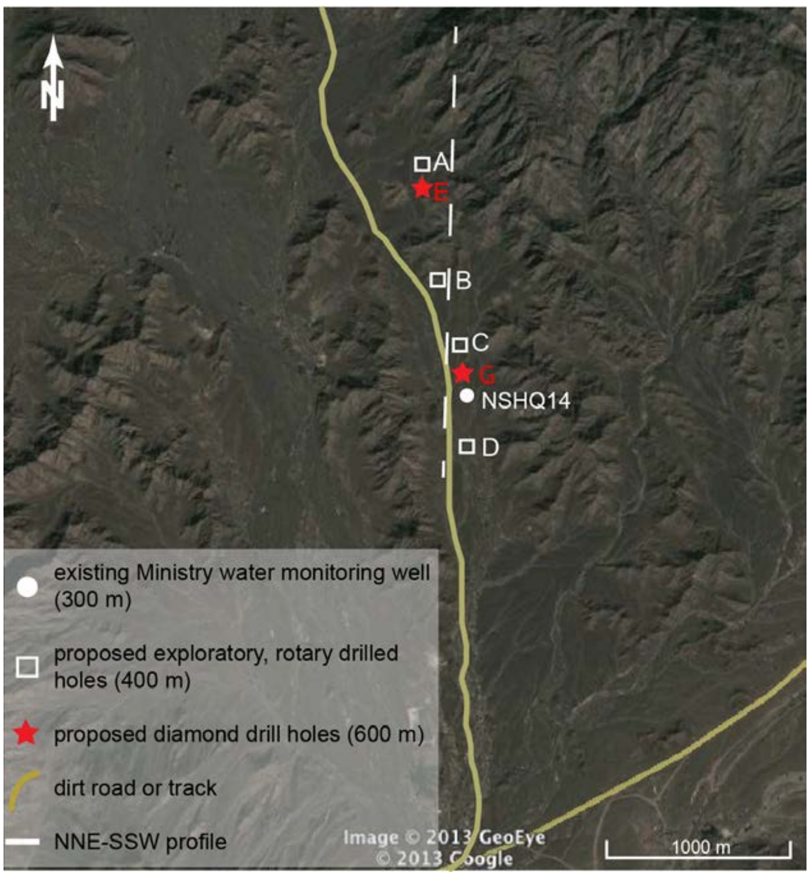


Figure A5-6. Map of proposed drilling site BA1 near the village of Batin. The site is located in partially altered mantle peridotite and includes an existing water monitoring well (NSHQ14) from the Omani Ministry of Regional Municipalities and Water Resources. Four proposed 400-m deep rotary drilled exploratory holes are aligned along the likely ground water flow path from the local recharge area (top of the mountains to the east) to the adjacent alluvial fan, to locate the "reaction zone". Two proposed cored holes will be sited based on results from observations in, and water samples from, the rotary holes.

The drilling strategy for this site will be different from all other sites. Pre-filtered, ozonated, drinking water will be used as a lubricant to drill at least one cored hole, to minimize contamination of formation waters with drilling fluid. As noted in Section 2.3, we believe that the reaction zone, where pH 8 to 9, Mg-HCO_3 ground water is transformed into pH 11 to 12, Ca-OH alkaline water by reaction with peridotite, is present within 300 meters of the surface. However, the geographical position, depth range, and lateral extent of the reaction zone are unknown. Four, 400 meter rotary holes will be drilled and sampled as described in the section on water sampling strategy below, in order to locate reaction zone(s) or reaction front(s). The target diameter for these holes is 6", which will allow us to conduct pumping and tracer tests using packers to study the subsurface permeability and solute transport in fractured peridotite. Once compositional gradients are located, we will drill two 600 m cored holes to sample these zones. Boreholes will be drilled from the recharge area to the "reaction zone" and the discharge zone of Ca-OH-rich hyperalkaline end-member fluids, as shown schematically in Figure A5-6.

A schematic illustration of this strategy is shown in Figure A5-6. However, the exact sites of the cored holes will depend on information gathered during drilling. Figure A5-7 shows a hydrogeological section along the general groundwater flow path from NNE to SSW. The alluvium along the transect has a maximum thickness of 10 meters, and measured groundwater level in the existing well (NSHQ-14) is15 meters below ground surface. According to drill chip analysis and geophysical logs from NSHQ14, the boundary between (a) highly fissured and partially serpentinized peridotite with dominantly calcite vein fillings (Figure A5-8) and (b) less fissured, partially serpentinized peridotite with magnesite veins is 150 m below ground surface.

The multi-well borehole test site in the mantle peridotite section will provide us with "legacy holes". Such a test site will serve as a hydrological observatory, that can be used to facilitate future hole-to hole tests to further study fluid circulation, alteration and geomicrobial processes as well as engineered carbon capture and storage beyond the end date of this project.

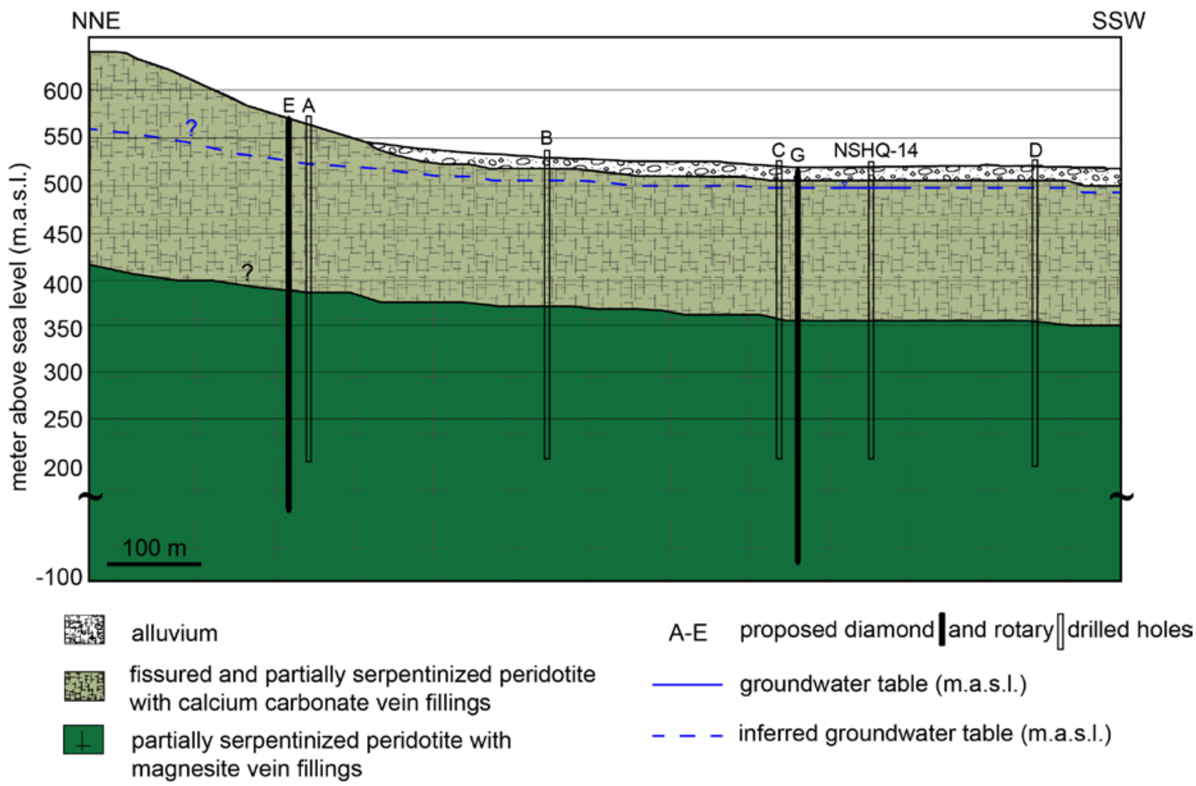


Figure A5-7. *Hydrogeological cross section of proposed drilling site BA1 near the village of Batin.*

Figure A5-8: *Carbonate veins in serpentinized peridotite just below the unconformity with overlying Tertiay limestones in Wadi Fins.*

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Appendix 6: Geophysical wireline logging budget (US$)

	Year 1	Year 2	Total
Mobilization/Demobilization	$6,427	$6,748	$13,174
Logging & insurance	$13,621	$12,336	$25,957
Tools stand-by cost	$23,135	$23,135	$46,271
Tool shipping and shipping insurance	$25,706	$26,991	$52,697
Travel for two loggers	$3,856	$4,049	$7,905
Lodging in Oman for 2 loggers	$3,856	$4,049	$7,905
Vehicle rent in Oman	$10,282	$10,797	$21,079
Salary and wages for 2 loggers	$30,847	$32,390	$63,237
Subtotal	$117,730	$120,495	$238,225
Overhead (20%)	$23,546	$24,099	$47,645
Total	**$141,276**	**$144,594**	**$285,870**

Appendix 7: Borehole test & fluid sampling budget (US$)

	Year 1	Year 2	Total
Mobilization/Demobilization	$10,000	$10,000	$20,000
Robertson borehole winch with 600 m cable	$10,530		$10,530
Robertson Surface electronics	$10,330		$10,330
Logging cable (4 core cable)	$5,040		$5,040
Slimhole water quality sonde with conductivity, pH, dissolved oxygen, pressure	$26,730		$26,730
Straddle packer system	$15,619		$15,619
Grundfos submersible pump, 600 m 4 conductor cable, 600 m Parker high pressure hose	$15,999		$15,999
Generator	$4,000		$4,000
Gas tight water sampler	$9,360		$9,360
Field supply	$10,000	$10,000	$20,000
Equipment insurance	$30,000	$30,000	$60,000
Tool shipping and shipping insurance	$25,000	$25,000	$50,000
Vehicle rent in Oman for 30 days each year	$5,500	$5,500	$11,000
Travel for two research staff (tech)	$3,570	$3,570	$7,140
Lodging for two research staff (tech) for 30 days each year	$6,000	$6,000	$12,000
Salary and wages for two research staff (tech)	$23,653	$23,653	$47,306
Subtotal	$211,332	$113,723	$325,055
Overhead (53%) not on equipment (>US$5,000)	$62,393	$60,273	$122,666
Total	$273,725	$173,996	$447,721

Appendix 8: Microbiology sampling budget (in US$)

	Year 1	Year 2	Total
Two -80°C freezers	20,000		20,000
One anaerobic chamber	12,000		12,000
Three incubators	9,000		9,000
One laminar hood	10,000		10,000
Field supply (e.g. vials, filters, liquid N_2 etc.)	20,000	20,000	40,000
Shipping equipment, supply from US-Oman	5,000	5,000	10,000
Shipping samples from Oman-US	10,000	10,000	20,000
Vehicle rent in Oman for 30 days per year	5,500	5,500	11,000
Travel for 3 research staff	5,355	5,355	10,710
Lodging for 3 research staff for 30 days per year	9,000	9,000	18,000
Salary and wages for three research staff	45,000	45,000	90,000
Subtotal	150,855	99,855	250,710
Overhead (47.5%), excluding permanent equipment (>$5000)	47,431	47,431	94,862
Total	198,286	147,286	345,572

Appendix 9: Core description expenses

Estimate from Dr. Jay Miller, IODP Manager of Technical & Analytical Services at Texas A&M University, based on ~ 1 month per 700 TO 1000 m of core onboard RV Joides Resolution (JR) followed by shipment to the American Museum of Natural History (AMNH) for permanent curation & storage. Technical staff line includes travel, room&board on JR and salary cost. Scientist line includes travel and room&board on JR cost.

	Year 1	Year 2	Year 3	Total
Technical staff (8 people per 2 months)	$0	$122,000	$122,000	$244,000
Scientists (20 people per 2 months)	$0	$142,000	$142,000	$284,000
Laboratory supplies onboard JR	$0	$9,000	$9,000	$18,000
Shipping from Oman to JR and then JR to AMNH	$40,000	$80,000	$40,000	$160,000
Total	$40,000	$353,000	$313,000	$706,000

Appendix 10: Expenses for publication of "Initial Reports Volume"

Estimated by Angie Miller, Manager of IODP Publication Services, Texas A&M University, based on publication and travel costs of IODP Initial Reports volumes.

travel and lodging for 20 scientists for one week editorial meeting	$50,000
technical support and web publication at TAMU	$100,000
total cost	$150,000

Appendix 11: Costs to this project to initiate core curation and storage at the American Museum of Natural History

Estimated by Dr. Edmond Mathez, Curator, AMNH Dept. of Earth & Planetary Sciences

AMNH year 1 costs estimated by Dr. Edmond Mathez, curator	
Racks and shelving for 6000 m of core (based on cost of racks for ICDP Hawaiian Drilling Project core+ 10%)	$15,700
Collection manager support for unloading, sorting,storing core in racks (8 person days @ $270/day; salary + benefits = $60,000/yr-1/222d yr-1 = $2200)	$2,200
total cost	$17,900

Appendix 12: Project management and coordination costs

Estimate for Project Manager cost from Dr. Bruce Keinlen, Mineral Exploration Drilling Consultant. Estimate for Administrative Assistant based on comparable positions at Columbia University. Travel costs estimated at $2500 per person. We expect the Project Manager and Assistant will be under contract from ICDP.

Appendix 12A: Project management

	year 1	year 2	year 3	year 4	total
project manager, salary $550 per day in the field, $475 per day in the office	$173,805	$71,511	$11,786		$257,102
2.5 months travel, per diem and vehicle rental in Oman in years 1 and 2	$30,000	$30,000			$60,000
administrative assistant, annual salary & benefits $100,000	$50,000	$50,000	$12,500		$237,667
total pay and travel for project managers	$253,805	$151,511	$24,286		$429,602

Appendix 12B: Project coordination meetings

meetings in Oman for 60 members of the project team, with overhead, $2500 pc		$150,000		$150,000	$300,000
additional annual meeting for 14 Project Steering Committee members plus 2 others	$40,000	$40,000	$40,000	$40,000	$40,000
total cost	$40,000	$190,000	$40,000	$190,000	$460,000

Appendix 13: Responsibilities of the Oman Drilling Project Steering Committee (PSC)

Name and Affiliation	Responsibility
Prof. Peter Kelemen: Arthur D. Storke Professor and Vice Chair of the Dept. of Earth & Environmental Sciences, Columbia University, USA	Chair PSC;Lead Principal Investigator on OCDC
Dr. Ali Al Rajhi: Assistant Director General of Minerals, Ministry of Commerce and Industry, Oman	Permitting and government liaison in Oman
Dr. Marguerite Godard: Chargée de Recherche, Université de Montpellier II, France	Geochemical and isotopic analyses of rock samples
Dr. Benoit Ildefonse: Directeur de Recherche, Université de Montpellier II, France	Outreach, and liaison with the IODP
Prof. Jürgen Koepke: Leibniz Universitaet, Germany	Petrology of igneous and hi-T metamorphic rocks from the lower crust and mantle
Prof. Chris MacLeod; School of Earth and Ocean Sciences, Cardiff University, UK	Structural and petrological work on igneous and hi-T metamorphic rocks in the middle crust and sheeted dikes.
Prof. Craig Manning: former Chair, Dept. Earth & Space Sciences, University of California Los Angeles, USA	Analyses of low temperature metamorphic rocks
Prof. Jürg Matter: National Oceanography Centre Southampton, University of Southampton, UK	Geophysical logging, physical properties measurements, and hydrology
Prof. Katsu Michibayashi: Shizuoka University, Japan	Structural analyses of igneous and high T metamorphic rocks from the lower crust and upper mantle
Dr. Jay Miller: IODP Manager of Technical & Analytical Services, Texas A&M University, USA	Core logging, publication of the Initial Report, and other liaison with IODP personnel.
Prof. Sobhi Nasir: Head, Dept. of Geology, Sultan Qaboos University, Oman	Participation of undergraduates and graduate students from the University
Prof. Matt Schrenk: East Carolina State University	Biogeological sampling and borehole incubation experiments
Prof. Everett Shock: University of Arizona	Water and gas sampling and analysis
Prof. Eiichi Takazawa: Niigata University, Japan	Detailed site selection and associated surface mapping and sampling
Prof. Damon Teagle: Director of Research, National Oceanography Centre Southampton, University of Southampton, UK	Vice Chair of the PSC; Oversight of the Sampling Oversight and Allocation Committee (SOAC)

Appendix 14: Sampling policy

We will encourage a "pooled" sampling approach, commonly used on IODP Expeditions, to ensure that a comprehensive geochemical and physical properties measurements are made on a representative suite of shared samples/powders. We will encourage "boutique" isotopic measurements to be initially undertaken on the well characterized "pool" samples. We will create a number of Samail ophiolite geochemical standard reference materials (e.g., Oman diabase, gabbro, dunite, harzburgite, listvanite) that will be shared with all analysts for quality control in addition to international reference standards.

The Project Steering Committee (PSC) or their designated representatives will coordinate off-site analyses of rock, water and biological samples. Access to Oman Drilling Project samples and data will be overseen by the Sample Oversight and Allocation Committee, a sub-group of the PSC (Teagle, Kelemen, Goddard, Nasir, Shock, Schrenk), to be chaired by Teagle.

Access to Oman Drilling Project samples and data will be overseen by the Sample Oversight and Allocation Committee (SOAC), a sub-group of the Project Steering Committee. The SOAC will operate by consensus and will:

- Determine membership of named investigators;
- Decide priorities and precedence with regard to sample and data use;
- Oversee the fair allocation of samples/data to maximize science outputs and impacts;
- Arbitrate sampling/data conflicts between investigators;
- Grant formal agreement to publish;

The initial membership of the SOAC has been determined by input into the proposal development and to ensure a range of expertise. Future membership may change to reflect financial inputs to the Oman Drilling Project and will be decided upon by the PSC, recognizing the need to maintain international and scientific balance.

Named ODP Investigator Pool

All scientists who wish to engage in the Oman Drilling Project and use samples or data must apply for membership of an Investigator Pool by submitting a brief proposal, outlining their research expertise and goals with respect to the Drilling Project. Acceptance into the Investigator Pool requires researchers to abide by Drilling Project protocols. A deadline for submissions for inclusion into the Investigator Pool will be set 3 months before each season of ODP operations begins. Scientists will submit specific sample/data requirements for each ODP Site. Investigators will be kept informed of sample application deadlines via a secure website to be developed.

Samples will remain under moratorium, available only to members of the Investigator Pool, for 24 months following completion of drilling and logging at each site. Any scientist, in addition to the proponents of this proposal, can apply to be a member of the Investigator Pool. It is anticipated that scientists from outside the proponent group will provide additional resources, core logging commitments, or novel analytical or scientific methods. All scientists receiving data or samples in the moratorium period will be expected to publish peer-reviewed publications in the international literature. There will be scope for electronic data reports to be published in association with the Oman Drilling Project Initial Reports. All publications must acknowledge ICDP, the Oman Drilling Project, and the principal funders of the Oman Drilling Project.

Immediate data availability

All data (field observations, geophysical data, chemical data, physical properties) should be made available to the ODP Investigator Pool via a password-protected internet portal, as soon as practicable (probably after the core logging and curation). All data will eventually become open-access following the moratorium period and the publication of ODP results.

Sample availability by application

To obtain samples, investigators must submit requests outlining what samples are required, what techniques will be used to analyze them, and the likely significance of the results. In the case of multiple requests for the same core/feature/data, the SOAC will encourage researchers to collaborate to maximize the science output, but the decision of SOAC will be final. Researchers must return remaining material in a timely fashion. Thin sections, cut for core logging purposes, mineral separates, etc., must also be returned once they are no longer needed for the research. Costs incurred in sample and data allocation (likely to comprise some contribution to the time taken for those administering the process to obtain the samples; costs of materials to prepare samples to specification; postage and handling charges) may be recovered from the researchers requesting them.

Inclusive work practices and publication

The Oman Drilling Project expects true and open collaboration amongst its investigators, and expects researchers to invite contributions from others where significant value-addition is possible, or where they have already been integrally involved in some way in the collection/generation of data or samples. A high level of inclusion is particularly important in the case of publication of initial results of key samples or datasets. It is mandatory to obtain formal agreement to publish from the SOAC.

Formal acknowledgment of the Oman Drilling Project

We expect all publications and abstracts to explicitly use the words “Oman Drilling Project” in the title and abstract. Keywords should include “Oman Drilling Project” and “Samail Ophiolite”. All publications must acknowledge the principal funders of the Oman Drilling Project (list to be developed) and the International Continental Drilling Program.

Appendix 15: Planned and active proposals for matching funds for this project and for related research

Matching funds (planned proposals)

Proponents	Title	Agency	Requested funding in US$	Submission Deadline	Note
Kelemen, P., G.Hirth. C. Manning, J. Matter, A. Park, H. Savage, E. Shock, M. Spiegelman	Reaction of surface waters with mantle peridotite: Geochemical fluxes and dynamics of far from equilibrium transport	U.S. NSF, Integrated Earth Systems	~2.7M	November 14, 2013	Will include matching funds for geophysical logging and core logging
Spiegelman, M., H. Savage, P. Kelemen	A combined experimental and theoretical investigation of reactive flow in brittle media with applications to solid Earth geodynamics	U.S. NSF, Geophysics	364K	December 3, 2013	Will include matching funds for analysis of fractured samples
Kelemen, P.	Integrative Field Studies for the Deep Carbon Observatory	Sloan Foundation (invited proposal)	650K	January 15, 2014	Includes $350K matching funds for drilling, logging, core description at Site BA1
Shock, E. Poret-Peterson, A. Cox, A. Boyd, E.	The geochemistry of habitability: case study of serpentinization	NASA, Exobiology	600K	2014	Scientific research funds
Goldstein, S. et al	Geochemical and isotopic studies of ocean crust formation processes using the Oman ICDP drill cores	US NSF, Marine Geology and Geophysics	375K	August 2014	Scientific research funds including matching funds for core logging
Schrenk, M. Shock, E. Templeton, A.	Using biogeochemistry and molecular biology to look at carbon exchange between the geosphere and the biosphere in serpentinizing systems	US NSF, BIOL DEB cluster	800K	Spring 2014	Scientific research funds

Templeton, A. Shock, E. McCollom, T. Schrenk, M. Santelli, R. Cardace, D.	Active serpentinization in Oman: investigating H_2-dependent microbial communities that may populate the deep subsurface of Earth and Mars	NASA Exobiology and Evolutionary Biology Program	850K	July 2014	Scientific research funds and matching funds for drilling
Schrenk, M.	Microbial biogeography of actively serpentinizing terranes: linking geochemical and microbiological records of evolution	US NSF, Career, BIOL	750K	Summer 2013	Scientific research funds
Godard, M. Bach, W., Fumagalli, P. Garrido, C. Gouze, P. Jamtveit, B. Koepke, J. Menez, B. Rampone, E. Teagle, D.	ABYSS: Training network on reactive geological systems from the mantle to the abyssal sub-seafloor	European Union, FP7-People-2013-ITN	4.3M	Funded	Scientific research funds (mainly salary for PhD students and postdocs)
Godard, M. Gouze, P. Ildefonse, B. Ceuleneer, C.	Drilling the ocean onshore in Oman (DOOO)	Agence Nationale pour la Recherche (ANR, France)	670K	January 2014	Scientific research funds
Teagle, D. MacLeod, C. Morris, A. McCaig, A. Maclennan, J	Accretion and hydrothermal cooling of the lower oceanic crust: Evidence from the Samail Ophiolite, Oman	UK Natural Environment Research Council	2M	July 2014	Scientific research funds including matching funds for drilling
Matter, J. Teagle, D. Powrie, W.	Shallow mantle peridotite hydration and carbonation: Feedback between fluid flow, alteration and fraturing	UK Natural Environment Research Council	1.6M	June 2013, declined, will resubmit July 2014	Scientific research funds including matching funds for drilling, geophysical logging, borehole testing

Bernasconi-Green, G. et al.	Tracing fluid-rock-microbe interactions: fluid and volatile compositions in the Oman ophiolite	Swiss National Science Foundation	220K	April 2013	Scientific research funds
Koepke, J. Bach, W. Strauss, H. Garbe-Schoenberg, D	The Wadi Gideah reference section for plutonic ocean crust	DFG, German Research Foundation	200K	August 2014	Matching funds for drilling
Bach, W. Strauss, H. Koepke, J	Metasomatic rocks as witness of fluid flow	DFG, German Research Foundation	130K	August 2014	Scientific research funds
Strauss, H. Bach, W. et al.	Stable isotope tracers of past and recent redox cycling in water-microbe-rock reactions	DFG, German Research Foundation	130K	August 2014	Scientific research funds
Matter, J., D. Teagle, P. Kelemen	Support for core description and training of Arab scientsts in the Oman Drilling Project	Qatar Foundation	$3M	2014	Matching funds for core description, focused on travel and training for Arab university students, plus purchase of XRF core scanner for Sultan Qaboos University, Oman

Appendix 16: Permitting of drill holes in the Samail ophiolite, Oman

Dr. Ali Al Rajhi, Assistant Director General of Minerals in the Omani Ministry of Commerce and Industry provided the following information on obtaining a permit for mineral exploration drilling in the ophiolite. Dr. Al Rajhi plans to handle the permits for our drill sites in approximately the same way, since from a permitting point of view our drill sites are very similar to exploration drilling for chromium and copper deposits in the ophoilite.

The applicant for a permit must provide:

- Coordinates of the location
- Type of mineral that is sought
- The purpose of the project
- The exploration plan

This information is submitted to the Ministry with a cover letter from the applicant. A fee of 350 Omani Rials plus 50 Rials per square kilometer (total of ~ US$ 1000 per site) is paid with the application. The Ministry studies the application to determine if there is overlap with other applications, whether the minerals being sought are available in the selected area, and whether the exploration program is well designed. If all this is acceptable then the Ministry contacts other relevant Ministries and Institutes to get their input. These are: the Ministry of Environment and Climate Affairs, the Ministry of the Interior, the Ministry of Housing, the Ministry of Regional Municipalities and Water Resources, the Ministry of Tourism, the Ministry of Culture and Heritage, the Ministry of Defense, and the Royal Oman Police. If these Ministries reply without any objection then an exploration permit is issued to the applicant.

While all this sounds somewhat daunting, there are many mineral exploration drilling projects underway in Oman.For scientific research (drilling in the ophiolite) the processes will be not much different than those described here for mineral exploration, but probably much easier.

Appendix 17: Supporting letters from:

- **American Museum of Natural History,**
- **US National Science Foundation,**
- **Integrated Ocean Drilling Program at Texas A&M University,**
- **Deep Carbon Observatory**

AMERICAN MUSEUM OF NATURAL HISTORY
Department of Earth and Planetary Sciences

7 January, 2013

Dear Peter,

I would like to confirm that AMNH will be pleased to accept and curate an Oman drill core as part of our petrology collection. This means proper protection, storage, organization, oversight, and provisions for easy access and use for valid research purposes. AMNH will also bear all curation costs once the core has been delivered to the museum. For the sake of your proposal, I have estimated those costs for the first year (below), after which they will be borne as part of our normal curation activities.

In developing your plan for curating the core, please let me suggest some of the reasons you should consider AMNH.

<u>1. Long-term (in perpetuity) institutional commitment.</u> AMNH can make such a commitment because the collection of natural objects for the benefit of humanity, especially in research and education, is one its core missions. Currently there are 33M objects in the museum's collections. These objects are not just protected physically, they are also protected administratively. Specifically, collection management is carefully described in a 44-page policy document that, among other things, defines governance and management, ethical considerations, acquisition and loan procedures, standards of care, and risk management/disaster preparedness. The document illustrates the focus and care we bring to collection management, which, in addition to the sheer size of our collections, are motivated in part by the fact that AMNH faces many complex collections' issues that in general do not touch the academic community, such as how to deal with human remains and cultural items. I shall be happy to provide a copy of this document to the steering committee should it wish to examine it.

<u>2. Support structure.</u> As one of the largest natural history museums in the world, AMNH has the resources to maintain the staff necessary to accomplish this mission. For example, each of the four collections under the auspices of Earth and Planetary Sciences (gems/minerals, rocks, ore deposits, meteorites) has devoted to it both a collection manager and curator. Again, because collections are part of its mission, AMNH has traditionally dedicated considerable resources to curation.

<u>3. Infrastructure.</u> At present the Department of Earth and Planetary Sciences has sufficient space under its control to store 6000 m of core. Should it be necessary, I am confident that the museum administration would provide whatever additional space would be needed for the reasons stated above. Indeed, the administration has supported us in the past, , for example, by providing the $9.8k worth of racks necessary for the storage of the ICDP Hawaiian drill core. Most of our rock collections, including the Hawaiian drill core, are stored at the Brooklyn Army Terminal. I shall be happy to take interested members of your committee there to inspect this facility.

<u>4. Relation to existing collections.</u> The core would fit well within the existing petrology collection, the current strengths of which are mafic and ultramafic systems. For example, other

important collections in addition to the ICDP Hawaiian drill core include those of numerous volcanic/xenolith localities (e.g., Jagoutz, Irving, Prinz) and mafic intrusions such as the Skaergaard (McBirney), Nain (Morse), Noril'sk (Federenko/Czamanske), and Bushveld (Mathez).

5. Access. It is my impression that the community has been happy with the way that we have managed the Hawaiian drill core and other petrology collections, specifically in our efforts to be as accommodating and helpful as possible to researchers wanting to use the core in a timely manner. I shall be happy to provide you with names of several individuals who have accessed the core so that you can see what they have to say.

In the case an Oman core, I would recommend that after bringing the core to AMNH we establish a review committee composed mainly of the PIs of the scientific program to accept and adjudicate on proposals for research on the core for some initial period (e.g., 3 to 5 years), after which that entire responsibility could be taken over by the Museum.

I trust this will be helpful for your deliberations.

Sincerely yours,

Edmond A. Mathez
Curator

AMNH Year 1 costs

Racks and shelving for 6000 m of core (based on cost of racks for Hawaiian drill core + 10%)	\$15700
Collection manager support for unloading, sorting, storing core in racks (8 person days @ \$270/day [salary + benefits = \$60kyr^{-1}/222d yr^{-1} = \$2200)	2200
Total	\$17900

January13, 2014

Peter Kelemen
Lamont-Doherty Earth Observatory of
Columbia University
Palisades, New York, 10964

Dear Peter,

This letter acknowledges that National Science Foundation supports, in principle, the use of the laboratories aboard the drillship JOIDES Resolution to process and log core material obtained during the Oman Drilling Program. We understand that this work will involve use of the JOIDES Resolution while in port and when not otherwise in use for International Ocean Discovery Program or commercial activities. It is also our understanding that this work will be done over a two-°©-month period in each of three years and is to be scheduled at the convenience of the US Implementing Organization (Texas A&M University). It is expected that this work, including travel, shipping, staffing, and use of all laboratory and other facilities aboard the JOIDES Resolution, will result in no additional cost to the National Science Foundation or the US Implementing Organization.

Please feel free to contact me with any questions.

Sincerely,

Thomas Janecek

Thomas Janecek
Program Director, Ocean Drilling Program
National Science Foundation
Arlington, VA 22203

Cc:
James Allan, Brad Clement

Integrated Ocean Drilling Program
United States Implementing Organization

December 28, 2013

Dear Peter,

The IODP-TAMU current funding model includes eight months of active operation per year, as well as four months each year when the shipboard laboratories are not in service in support of an expedition. Historically, we have used these hiatuses in operation to perform routine maintenance and major equipment and infrastructure overhauls, to support education and outreach activities, and more rarely to place the core logging systems in service to perform measurements on cores. We envision our future funding model to continue to have periods of laboratory quiescence each year where alternative use of the equipment might be accommodated with appropriate additional funding. We recognize that having the equipment in service full time is a prudent use of NSF resources, as equipment failures are common following extended periods of in operation, we enhance professional development of our staff when using the equipment, and we can potentially avoid some expenses related to demobilization and remobilization. One of the potential innovative uses of the laboratory equipment on the *JOIDES Resolution* would be providing facilities for logging cores recovered during the Scientific Drilling in the Semail Ophiolite Project.

Our Publication Department at IODP-TAMU currently supports production of Proceedings volumes for the entire International Ocean Discovery Program. These volumes summarize and report the scientific and technical accomplishments of each IODP expedition. After consideration, with appropriate planning, foresight, and funding it is possible that our Publications group could support production of a Proceedings-like volume to compile, edit, and create an electronic report of the results of Scientific Drilling in the Semail Ophiolite without negatively impacting our IODP production schedule. In addition, our Science Operations group, which includes our Expedition Project Managers, can consider providing personnel to fulfill the project management requirements of this drilling effort if planned well enough in advance and appropriately funded.

Sincerely,

Jay

Jay Miller
Manager of Technical and Analytical Services
United States Implementing Organization-Texas A&M University
Integrated Ocean Drilling Program

Texas A&M University • 1000 Discovery Drive • College Station TX 77845-9547 USA

TEL 979-845-2673 • FAX 979-845-1026 • www.iodp-usio.o

DEEP CARBON OBSERVATORY
SECRETARIAT

9 January 2014

Dear ICDP Colleagues,

On behalf of the Deep Carbon Observatory (DCO) Executive Committee (EC) and Secretariat, we are delighted to offer our strongest support for the proposal, "Scientific Drilling in the Samail Ophiolite, Sultanate of Oman," to the International Continental Scientific Drilling Program (ICDP). We encouraged and supported lead ICDP proponent Peter Kelemen, Columbia University, in submitting an invited DCO proposal to the Alfred P. Sloan Foundation that included a request for $350,000 to conduct exploratory drilling, geochemical and geophysical surveys, analyses, and research in the Samail Ophiolite. We expect to hear a response from the Sloan Foundation by the end of March 2014. If successful, this award would constitute co-mingled funding for the proposed ICDP Oman Drilling Project. The Sloan Foundation previously awarded a grant, "Planning Workshop: Oman Drilling Proposal," that enabled DCO to co-sponsor the ICDP planning workshop in Palisades, New York on 3-17 September 2012, which led to the current ICDP proposal.

The ophiolites of Oman contain perhaps the best-exposed zones of active serpentinization on Earth, with their attendant dynamic physical, chemical, and biological activity, as well as the largest and best-exposed section of oceanic crust and upper mantle. Drilling the Oman ophiolites in conjunction with geochemical and geophysical surveys, fluid and microbial sampling, and related research would advance the broad interests of DCO's four science communities and would address many of DCO's decadal goals. The proposed Oman Drilling Project has tremendous scientific merit and assembles an extraordinary international team of scientists.

Broadly stated, DCO's mission is to understand Earth through carbon. More than 90% of Earth's carbon may reside in the planet's deep interior, and DCO's overarching goal is to understand the complete carbon cycle. The DCO is a visionary scientific endeavor that was initiated 1 July 2009 with support from the Sloan Foundation. See deepcarbon.net for more information. DCO aims to facilitate and leverage major scientific advances in understanding Earth's deep carbon cycle by 2019, followed by 1-2 years of intense dissemination. DCO has four scientific communities (Deep Life; Reservoirs and Fluxes; Deep Energy; Extreme Physics and Chemistry) with three cross-community units (Secretariat; Communication and Engagement; Data Science) amplifying DCO's impact and making the whole greater than the sum of its parts.

At this time and with this background in mind, we urge ICDP reviewers and committees to give this excellent proposal its strongest consideration.

With best regards,

Craig M. Schiffries, Ph.D.
Director, Deep Carbon Observatory

Rbert M. Hazen, Ph.D
Executive Director, Deep Carbon Observatory

Appendix 18: References cited throughout this proposal

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Wilson, D. S., D. A. H. Teagle, J. C. Alt, N. R. Banerjee, and e. al. (2006), Drilling to gabbro in intact ocean crust, Science, 312, 1016-1020.

Appendix 19: CV's of Principal Investigators

Peter B. Kelemen, Arthur D. Storke Memorial Professor
Dept. of Earth & Environmental Sciences, Columbia University **Telephone:** 845 365 8728
Lamont Doherty Earth Observatory, Palisades NY 10964 **E-mail:** peterk@ldeo.columbia.edu

PROFESSIONAL PREPARATION:

1980 A.B, Dartmouth College, Cum Laude, Honors in Earth Science.
1985 M.Sc., University of Washington, Department of Geological Sciences
1987 Ph.D., University of Washington, Department of Geological Sciences

APPOINTMENTS & AWARDS, 2004-2012

2013-16 Diamond Jubilee International Fellow & Visiting Prof., University of Southampton
2013–present Fellow, Geochemical Society and European Association of Geochemistry
2012–present Vice Chair, Dept. of Earth & Environmental Sciences, Columbia University
2012 Chapman Lecturer, University of Alaska
2010 CIRES Distinguished Lecturer, University of Colorado
2009 Visiting Professor, Université de Lausanne
2008 MARGINS Distinguished Lecturer
2007 Hallimond Lecturer, Mineralogical Society
2006–present Fellow, Mineralogical Society of America
2004–present Arthur D. Storke Memorial Professor, Columbia University
2004–present Assoc. Research Scientist, Dept. of Earth and Planetary Sci., Amer. Museum Natural History
2004–present Adjunct Scientist, Woods Hole Oceanographic Institution (WHOI)
2004–present Fellow, American Geophysical Union
2001-04 Tenured Senior Scientist & Charlies Francis Adams Chair, WHOI

PUBLICATIONS IN PAST FIVE YEARS MOST RELATED TO PROPOSED DRILLING IN OMAN*:*
(a fairly complete list of all publications is available at Google Scholar (h-index 55)
http://scholar.google.com/citations?hl=en&user=zUc0U58AAAAJ&view_op=list_works&pagesize=100)

Achenbach, K.L., M.J. Cheadle, U. Faul, **P. Kelemen** and S. Swapp, Lattice-preferred orientation and microstructure of peridotites from ODP Hole 1274A (15°39'N), Mid-Atlantic Ridge: Testing models of mantle upwelling and tectonic exhumation, Earth Planet. Sci. Lett. 301, 199–212, 2011.

Collier MI & **PB Kelemen**, Case for reactive crystallization at mid-ocean ridges, J Pet 51, 1913-1940, 2010

Falk, E. S. and **P. B. Kelemen** (2013), Fully carbonated peridotite (listvenite) from the Samail ophiolite, Oman, *Fall Meeting AGU, San Francisco CA 9-13 Dec*, MR22A-03

Gadikota, G., J. Matter, **P.B. Kelemen** and A.-H. A. Park, Chemical and morphological changes during olivine carbonation for CO_2 storage in the presence of NaCl and $NaHCO_3$, Physical Chemistry Chemical Physics, in press, 2014

Godard, M., **P. Kelemen**, S. Nasir and D. Teagle, 2011, WORKSHOP REPORT: Geological carbon capture & storage in mafic and ultramafic rocks; IODP/ICDP Workshop, http://ccs-oman2011.org/, 2011.

Hanghøj, K., **P.B. Kelemen**, D. Hassler and M. Godard, Composition and genesis of depleted mantle peridotites from the Wadi Tayin massif, Oman ophiolite… J. Petrol. 51, 206-227, 2010.

Homburg, J., G. Hirth, and **P.B. Kelemen**, Investigation of the strength contrast at the Moho: A case study from the Oman Ophiolite, Geology 38, 679-682, 2010.

Kelemen, P.B., Planning the drilling of the Samail Ophiolite in Oman, EOS 94, 32, 2013.

Kelemen, P.B., The origin of the land under the sea, Scientific American 300, no. 2, 52-57, February 2009

Kelemen, P.B. and G. Hirth, Reaction-driven cracking during retrograde metamorphism: Olivine hydration and carbonation, Earth Planet. Sci. Lett. 345–348, 81–89, 2012.

Kelemen, P.B. and **J. Matter**, *In situ* mineral carbonation in peridotite for CO_2 storage, Proc. National Acad. Sci. 105, 17,295-17,300, 2008.

Kelemen, P.B., Jürg M. Matter, and Columbia University US Patent Application 13/383,082: Systems and methods for enhancing rates of carbonation of peridotite, 2008

Kelemen, **P.B.** and 10 others, White Paper for IODP Decadal Science Planning Meeting, INVEST, *In situ* mineral carbonation in peridotite and basalt for CO_2 capture and storage, available online, 2009.

Kelemen, P.B., J. Matter, E.E. Streit, J.F. Rudge, W.B. Curry, J. Blusztajn, Rates and mechanisms of mineral carbonation in peridotite: Natural processes and recipes for enhanced, *in situ* CO_2 capture and storage, Ann. Rev. Earth Planet. Sci. 39, 545–76, 2011.

Kelemen, P.B., Heather Savage, Theodore A. Koczynski and Columbia University, US Patent Application 61/673,825: Reaction driven cracking for unconventional hydrocarbon extraction, geothermal power generation, and geological capture and storage of carbon dioxide, 2012.

Kelemen, P., A. Al Rajhi, M. Godard, B. Ildefonse, J. Koepke, C. MacLeod, C. Manning, K. Michibayashi, S. Nasir, E. Shock, E. Takazawa and D. Teagle, Scientific drilling and related research in the Samail Ophiolite, Sultanate of Oman, Scientific Drilling J. 15, 64-71, 2013.

Kelemen, P.B., H. Savage and G. Hirth, Reaction-driven cracking during mineral hydration, carbonation and oxidation, in C. Hellmich, B. Pichler and D. Adam, editors, Poromechanics V: Proc. 5^{th} Biot Conf. Poromechanics, Amer. Soc. Civil Engineers, Reston VA, 823-826, 2013

Kelemen, P. B., C. E. Manning, E. S. Falk, and B. R. Hacker (2013a), Carbon fluxes: Seafloor alteration and mantle wedge alteration of peridotite, *Presentation, ExTerra Workshop presentation, Florence IT, August 2013*.

Kelemen, P. B., C. E. Manning, E. S. Falk, and B. R. Hacker (2013b), Keynote: Carbon cycling in subduction zones: Perspectives from field observations in Oman, Santa Catalina, and Sambagawa, *Deep Carbon Observatory Workshop on Tectonic Fluxes of Carbon, San Francisco, December 2013*.

Matter, J. and **P.B. Kelemen**, Geochemical controls on permanent CO_2 storage in geologic reservoirs, Nature Geoscience 2, 837-841, 2009.

Matter, J.M and **P.B. Kelemen**, Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation, Nature Geoscience 12, 837-841, 2009.

Mervine, E.M., Humphris, S.E., Sims, K.W.W, **Kelemen, P.B.,** Jenkins, W.J. (2013) Carbonation rates of peridotite in the Samail Ophiolite, Sultanate of Oman constrained through ^{14}C dating and stable isotopes, submitted to Geochim. Cosmochim. Acta, 126, 371-397.

Morgan, Z., Y. Liang and **P.B. Kelemen**, Significance of the concentration gradients associated with dunite bodies in the Josephine and Trinity ophiolites, G-cubed 9, doi:10.1029/2008GC001954, 2008.

Paukert, A.P., J.M. Matter, **P.B. Kelemen,** E.L. Shock and J.R. Havig, 2012, Reaction path modeling of enhanced in situ CO2 mineralization for carbon sequestration in the peridotite of the Samail Ophiolite, Sultanate of Oman: Chem. Geol. 330-331, 86-100, 2012

Peucker-Ehrenbrink, B., K, Hanghøj, T. Atwood and **P.B. Kelemen**, Rhenium-osmium isotope systematics and platinum group element concentrations in oceanic crust, Geology 40, 199-202, 2012

Power, IM, AL Harrison, GM Dipple, S Wilson, P Kelemen, M Hitch, G Southam, Carbon Mineralization: From natural analogues to geoengineered systems, Rev Mineral Geochem 77, 305-360, 2013

Rioux, M., S. Bowring , **P. Kelemen** , S. Gordon , R. B. Miller , and F. Dudas, Tectonic development of the Samail ophiolite: High precision U-Pb zircon geochronology and Sm-Nd isotopic constraints on crustal growth and emplacement, J. Geophys. Res., 118, 2085-2101, 2013.

Rioux, M., S. Bowring, **P. Kelemen**, S. Gordon, F. Dudás, R. Miller, Rapid crustal accretion and magma assimilation in the Oman-U.A.E. ophiolite: High precision U-Pb zircon geochronology of the gabbroic crust, J. Geophys. Res. 117, B07201, doi:10.1029/2012JB009273, 2012.

Rudge, J.F., **P.B. Kelemen** and M. Spiegelman, A simple model of reaction induced cracking applied to serpentinization and carbonation of peridotite. Earth Planet. Sci. Lett. 291, 215-227, 2010.

Skemer, P., J. Warren, **P. Kelemen** and G. Hirth, Microstructural and rheological evolution of a mantle shear zone, J. Petrol. 51, 43-53, 2010.

Streit, E., **P.B. Kelemen**, and J. Eiler, Coexisting serpentine and quartz from carbonate-bearing serpentinized peridotite in the Samail Ophiolite, Oman, Contrib. Mineral. Petrol., 164, 821-837 2012.

Suhr, G., **P.B. Kelemen** and H. Paulick, Microstructures in Hole 1274A peridotites, ODP Leg 209, Mid-Atlantic Ridge…, G-cubed 9, Q03012, doi:10.1029/2007GC001726, 2008.

Sundberg, M, G. Hirth and **P.B. Kelemen**, Trapped melt in the Josephine peridotite: Implications for permeability and melt extraction in the upper mantle, J. Petrol. 51, 185-200, 2010.

VanTongeren, J.A., **P.B. Kelemen** and K. Hanghøj,, Cooling rates in the lower crust of the Oman ophiolite: Ca in olivine, revisited, Earth Planet. Sci. Lett. 267, 69-82, 2008.

Warren, J.M., G. Hirth and **P.B. Kelemen**, Evolution of olivine lattice preferred orientation during simple shear in the mantle, Earth Planet. Sci. Lett. 272, 501-512, 2008.

Curriculum Vitae – Jürg M. Matter

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PROFESSIONAL PREPARATION

Swiss Federal Institute of Technology Zürich, Earth Sciences	M.S. 1997
Swiss Federal Institute of Technology Zürich, Natural Sciences	Ph.D. 2001
Lamont-Doherty Earth Observatory, New York, Postdoctoral Training	2002-2004

APPOINTMENTS

2013-	Reader in Geoengineering, University of Southampton, UK
2010-2012	Lamont Associate Research Professor, Columbia University, USA
2005-2009	Doherty Associate Research Scientist, LDEO, Columbia University, USA
2001-2004	Postdoctoral Research Scientist, LDEO, Columbia University, USA
1997-2001	Research Assistant, Swiss Federal Institute of Technology Zurich, Switzerland
1997	Teaching Assistant Swiss Federal Institute of Technology Zurich, Switzerland

5 PUBLICATIONS MOST CLOSELY RELATED TO THIS PROPOSAL

Kelemen, P. B., Matter, J., Streit L., Rudge, J., Curry, Blusztajn, J. Rates and mechanisms of mineralcarbonation in peridotite: natural processes and recipes for enhanced, in situ CO2 capture and storage. Annu. Rev. Earth Planet. Sci. 2011. 39:545-76
Matter, J. M., Kelemen, P. B. Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. Nature Geoscience (2009) 2, 837-841, doi: 10.1038/NGEO683.
Kelemen, P.B., Matter, J. In situ mineral carbonation in peridotite for CO2 storage, Proc. National Acad. Sci. 105, 17,295-17,300, 2008.
Matter, J. M., Goldberg, D. S., Morin, R. H., Stute, M. Contact zone permeability at intrusion boundaries: new results from hydraulic testing and geophysical logging in the Newark Rift basin, Hydrogeology Journal (2006) 14:689-699, 2005.
Matter, J.M., Waber, N. H., Loew, S., Matter, A. Recharge areas and geochemical evolution of groundwater in a shallow alluvial aquifer system in the Sultanate of Oman. Hydrogeology Journal 14(1-2): 203-224, 2005.

5 OTHER RELEVANT PUBLICATIONS

Paukert, A. N., Matter, J. M., Kelemen, P. B., Shock, E. L., Havig, J. R. Reaction path modeling ofenhanced in situ CO_2 mineralization for carbon sequestration in the peridotite of the Samail Ophiolite, Sultanate of Oman. Chemical Geology 2012. 330-331: 86-100.
Gislason, S. R., Wolff-Boenisch, D., Stefansson, A., Oelkers, E., Gunnlaugsson, E., Sigurdardottir, H., Sigfusson, B., Broecker, W., Matter, J., Stute, M., Axelsson, G., T. Fridriksson (2010). Mineral sequestration of carbon dioxide in basalt: The CarbFix project. International Journal of Greenhouse Gas Control 4 (2010), 537-545.
Oelkers, E.H., Gislason, S. R., Matter, J. Mineral carbonation of CO2. Elements, Vol. 4, 331-335, 2008.
Assayag, N., Matter, J. M., Ader. M., Goldberg, D., Agrinier, P. Water-rock interaction during a CO_2 field injection test: Implications on host rock dissolution and alteration effects. Chemical Geology 265, 227-235, 2008.
Matter, J.M., Takahashi, T., Goldberg, D. Experimental evaluation of in situ CO_2-water-rock reactions during CO_2 injection in basaltic rocks: implications for permanent CO_2 sequestration. Geochemistry, Geophysics, Geosystems, v. 8(2), doi:10.1029/2006GC001427, 2006.

SYNERGISTIC ACTIVITIES

(1) TEACHING AT UNIVERSITY OF SOUTHAMPTON & COLUMBIA UNIVERSITY: Contemporary Topics; Earth Resources & Hazards, Environmental Geology; Curriculum Development for CAMEL (Climate, Adaptation, and Mitigation e-learning) NCSE Program; Environmental Chemistry, MPA for Environmental Science and Policy, School of International and Public Affairs (2010-present); Responding to Climate Change, Department of Earth & Environmental Sciences (2011-present); Carbon Capture and Storage, Department of Earth & Environmental Engineering (2008-present).

(2) OUTREACH PRESENTATIONS INCLUDING K-12 EDUCATION AND PRESS COVERAGE: Ridgewood High School, NJ (2012); European Embassy Science Series Event, Washington DC (2010); Montclair State University, Weston Science Scholar Program (2006/2007); Public Lecturer at the Lamont-Doherty Earth Observatory Public Lecture Series (2006); Public Lecturer at the Ministry of Water Resources, Sultanate of Oman (1999, 2002, 2009). **Press coverage** of Kelemen & Matter, *In situ* mineral carbonation in peridotite for CO_2 storage, Proc National Acad Sci 2008 and Matter & Kelemen, Nature Geoscience 2009 papers involved interviews for print, radio and web-based video: Reuters, Economist, Physics Today, The Christian Science Monitor, El Pais (Spain), El Mundo (Spain), Spiegel (Germany), Frankfurter Allgemeine (Germany), CleanSkies TV (CBS), Forbes, NPR Living on Earth, Gizmag (Australia), MSNBC, ORF Radio (Austria), DRS 1 (Swiss Radio), Naked Scientist BBC, Discovery Magazine, Livescience.com, OnEarth, Good Magazine, Australian National Radio, Deutsche Welle Radio (Germany), Gulf Times, The Times of Oman, Toronto Star, Times of India. Consultant to Discovery Channel for Climate Mitigation Technologies

(3) SCIENCE PLANNING: Big Sky Carbon Sequestration Partnership, U.S. Department of Energy (2006-present); Invited speaker ICDP workshop on scientific drilling in the Samail Ophiolite, Sultanate of Oman (2012). Invited speaker USGS workshop on CO2 sequestration in unconventional reservoirs (2012); Invited speaker IODP/ICDP workshop on the role of oceanic and continental scientific drilling, Sultanate of Oman (2011); Invited speaker U.S. Department of Energy, Office of Fossil Energy workshop on “Strategic initiatives for carbon capture and storage (CCS) deployment” (2009)

(4) MEETING CONVENOR/Co-CONVENOR: 2010 AGU Fall Meeting, San Francisco; 10th Intern.Conference on Greenhouse Gas Control Technologies, Amsterdam, The Netherlands (2010); Goldschmidt Conference, Knoxville, TN (2010); 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway (2008).

MATTER’S ADVISORS

M.Sc.: D. Bernoulli, ETH Zurich Switzerland; Ph.D.: S. Loew, W. Kinzelbach, ETH Zurich Switzerland;

Postdoctoral Scholarship: D. Goldberg, T. Takahashi, Columbia University

ADVISOR

PhD: Columbia University: Jennifer Hall (2016); Jonathan Levine (2011); Amelia Paukert (2014), Lisa Streit (co-advising with P. Kelemen, 2013); University of Southampont: Nicolas Bompard; Columbia **postdocs:** Qiang Yiang (10-13), Cantwell Carson (11-13);

Ph.D. or M.Sc. committee: Diana Fernandez de la Reguera (2010), Jonathan Levine (Columbia 2010), Tim Rappold (Columbia 2010), Samuel Krevor (Columbia 2008); Anna Wall (Columbia 2007), Oliver Lopez (Institute de Physique du Globe de Paris, France 06); Nelly Assayag (Institute de Physique du Globe de Paris, France 07).

DAMON A.H. TEAGLE

CURRENT POSITIONS:

Royal Society Wolfson Merit Award Holder, 2014 to 2018
Professor of Geochemistry (since Sept., 2007), Ocean and Earth Science, University of Southampton
Director of Research, Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, European Way, Southampton, SO14 3ZH, UK; Sept, 2012–
Deputy Director (Research) – Southampton Marine and Maritime Institute (SMMI); Apl 2012–
Chair – Programme Advisory Group, UK-IODP, 2013–

POSTS HELD:

2013 Lead author, Southampton-led NERC Doctoral Training Partnership "SPITFIRE", May, 2013
2013 Co-author of Ocean and Earth Science, Research Excellence Framework (REF) assessment, 2013
2010-2012: Head PhD Recruitment, Graduate School National Oceanography Centre Southampton
2010-2012: Acting Head – Graduate School of the National Oceanography Centre Southampton
2006-2009 Co-Chair NOCS Geochemistry Research Group
2003-2009 Co-Chair Geology and Geophysics Curricular Committee.
1999-2007 University Lecturer then Reader (2004-), University of Southampton
1997-1999 Assistant Research Scientist, Dept. Geological Sciences, Univ. Michigan
1993-1997 Post-Doctoral Research Fellow, Dept. Geological Sciences, Univ. Michigan

DEGREES:

1993: Ph.D., Earth Sciences, University of Cambridge, UK.
1987: M.Sc. (with Distinction), Geology, University of Otago, New Zealand
1985: B.Sc. (Hons.), Geology, University of Otago, New Zealand

SHIPBOARD/OCEAN DRILLING EXPERIENCE, EXPEDITIONS AND COMMUNITY SERVICE

2012: Lead proponent (1 of 7) Mohole to Mantle (M2M): IODP Prop 805-MDP (USD$1-2Billion)
2011: Co-Chief Scientist, IODP Expedition 335: Superfast 4 (Apr–June, 2011)
2001: Co-convener "Geological carbon capture and storage in mafic and ultramafic rocks" Oman
2010-2012: IODP Science Advisory Structure Executive Committee; SASEC and SIPCom
2010-2011: IODP Renewal (2013-2023) Science Plan Writing Group (>USD$2 billion over 10 years)
2008: Co-I RRS *James Cook* JC021 – Hess Deep Site Survey, Jan-Feb, 2008
2007: Co-I RRS *James Cook* JC018 – Montserrat – Ash-Seawater Interactions, Dec, 2007
2005: Co-chief Scientist on IODP Expeditions 309/312, Superfast 2-3 (Petrologist on Superfast 3)
2004-2009: Editor: G-Cubed Special Theme – "Formation & Evolution of the Ocean Crust"
2003 Leader – Australian Antarctic Division Project #2327 "Hydrothermal alteration of Macquarie Island", 55th Australian National Antarctic Research Expedition
2002: Co-chief Scientist on ODP Leg 206 Superfast Spreading Rate Crust
2000 – 2006: UK representative on ODP/IODP Science Steering Evaluation Panel
2000 – 2006: UK-ODP/IODP Steering and Peer-Review Committee
1993 to 1998: Petrologist: ODP Leg 183, 169, 163, 148; Shore-based ODP 158.

RESEARCH INTERESTS:

Health effects of atmospheric particles; Mineral carbonation and carbon capture and storage; Environmental effects of and on HV power take-off cables; Autonomous systems and sensors; Analysis of environmental "Big Data"; Hydrothermal alteration in mid-ocean ridges and ophiolites; Modeling of fluid-rock tracer exchange; Global chemical cycles; Radiogenic isotope and trace element analysis; Active analogs of ore mineralization; Metamorphogenic gold deposits; Hydrothermal fluids and deformation;

AWARDS, PRIZES AND SCHOLARSHIPS:

2009 Excellence in Reviewing Citation – AGU – G-cubed, Tarduno, Ed., EOS 90(28) 14 July
2008 Roy. Soc. NZ: International Science & Technology (ISAT) Linkages Exchange.
1995 Sokol Postdoctoral Fellowship, University of Michigan.
1991 Cambridge Philosophical Society Research Studentship.
1988 William Georgetti Scholarship for Social, Cultural & Economic Development of NZ
1988 Commonwealth Scholarship (Cambridge).
1987 Kendall Postgraduate Bursary of Science, Churchill College, Cambridge.
1987 Cambridge Commonwealth Trust Overseas Student Bursary.
1986 James Park Scholarship in Economic Geology (University of Otago).

PROFESSIONAL SOCIETIES:

American Geophysical Union, Geochemistry Society, Geoscience Soc. NZ, Member Royal Soc. NZ.

RECENT MEDIA ENGAGEMENT: (principally relating to Teagle & Ildefonse Nature 2011 – on MoHole): ThomsonReuters Vodcast (009/01/2013); Huffington Post – "Talk Nerdy to Me" (29/10/2012); CNN (01/10/2012); New Scientist (30/03/2012); National Geographic Magazine (01/01/2012); BBC Radio 4 (23/03/11); BBC Five Live Drive (23/03/11); NZ National Programme – Morning Report (24/03/11); ABC-Melbourne (24/03/2011); USA National Public Radio Science Friday (25/03/2011); Radio Ireland (29/03/11); ABC-Sydney (30/03/11); Costa Rica Television (13/04/2011); Reuters (13/04/2011);

SELECTED RECENT PUBLICATIONS

Wright, M.J., **Teagle**, D.A.H., and Feetham, P.M., (2014) A quantitative evaluation of the public response to climate engineering, Nature Climate Change 10.1038/nclimate2087

Marieni, C., Henstock, T.J., **Teagle**, D.A.H., (2013) Geological storage of CO2 within the oceanic crust by gravitational trapping, Geophysics Research Letters, 40, 6219–6224, doi:10.1002/2013GL058220

Loxham, M, Cooper, M.J., Gerlofs-Nijland, M.E., Flemming, C.R., Davies, D.E., Palmer, M.R., **Teagle**, D.A.H., (2013) Physicochemical Characterization of Airborne Particulate Matter at a Mainline Underground Railway Station, Environmental Science and Technology**,** 47(8): 3614-3622, doi: 10.1021/es304481m

Ferrini, V.L., Shillington, D.J., Gillis, K., MacLeod, C.J., Teagle, D.A.H., Morris, A., Cazenave, P.W., Hurst, S., Tominaga, M., and the JC21 Scientific Party, (2013) Evidence of mass failure in the Hess Deep Rift from multi-resolutional bathymetry data. Mar. Geol. 339:13-21, doi.org/10.1016/j.margeo.2013.03.006

Gao, Y.; Vils, F.; Cooper, K. M.; Banerjee, N.; Harris, M.; Hoefs, J.; **Teagle**, D. A. H.; Casey, J. F.; Elliott, T.; Laverne, C.; Alt, J. C.; Muehlenbachs, K. (2012) Downhole variation of lithium and oxygen isotopic compositions of oceanic crust at East Pacific Rise, ODP Site 1256 Geochem. Geophys. Geosyst., Vol. 13 Q10001, 24 PP., 2012 doi:10.1029/2012GC004207.

Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists, 2012. *Proc. IODP,* 335: Tokyo (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.335.2012

Teagle, D.A.H., Ildefonse, B., Blum, P., and Expedition 335 Shipboard Scientists (2012) IODP Expedition 335: Deep Sampling in ODP Hole 1256D. Scientific Drilling 13:28-34, doi:10.2204/iodp.sd.13.04.2011

Hunt, J.E., Wynn, R.B., Masson, D.G., Talling, P.J., **Teagle**, D.A.H., (2011) Sedimentological and geochemical evidence for multistage failure of volcanic island landslides: a case study from Icod landslide on north Tenerife, Canary Islands. Geochem. Geophys. Geosys. 12, Q12007, doi:10.1029/2011GC003740

Coggon, R. M., **Teagle**, D. A. H., and Dunkley Jones, T., (2011), Comment on "What do we know about the evolution of Mg to Ca ratios in seawater?" by Wally Broecker and Jimin Yu, Paleoceanography, 26, PA3224, doi:10.1029/2011PA002186.

Coggon, R.M., and **Teagle, D.A.H.,** (2011) Hydrothermal calcium carbonate veins reveal past ocean chemistry, Trends. Anal. Chem. 30(8):1252-1267. doi:10.1016/j.trac.2011.02.011

Teagle, D.A.H., and Ildefonse, B. (2011) Journey to the mantle of the Earth, Nature 471:437-439

Bickle, M.J., Pälike, H., and **Teagle**, D.A.H., (2010) Secrets of the sea floor, Nature Geoscience, 4:3-4

Coggon, R.M., **Teagle**, D.A.H., Smith-Duque, C.E., Alt, J.C., Cooper, M.J., (2010) Reconstructing past seawater Mg/Ca and Sr/Ca from mid-ocean ridge flank hydrothermal $CaCO_3$ veins. Science 327:1114-1117

Alt, J.C. Laverne, C., Coggon, R.M., **Teagle**, D.A.H., Banerjee, N.R., Morgan, S., Smith-Duque, C.E., Harris, M., Galli, L., (2010) The Subsurface Structure of a Submarine Hydrothermal System in Ocean Crust Formed at the East Pacific Rise, ODP/IODP Site 1256, Geochem. Geophys. Geosys.11(10) Q10010, doi:10.1029/2010GC003144

Tominaga, M., **Teagle**, D. A. H. Alt, J. C. and Umino, S., (2009), Determination of the volcano-stratigraphy of oceanic crust formed at superfast spreading ridge: Electrofacies analyses of ODP/IODP Hole 1256D, Geochem. Geophys. Geosyst., 10, Q01003,doi:10.1029/2008GC002143

Vance, D., **Teagle**, D.A.H., Foster, G.L., (2009) Variable Quaternary chemical weathering fluxes and imbalances in marine geochemical budgets. Nature, 458:493-496, doi:10.1038/nature07828

Teagle D. A. H., Alt J. C., Umino S., Miyashita S., Banerjee N. R., Wilson D. S., and Expedition 309/312 Scientists. (2006). Proceedings of the Integrated Ocean Drilling Program Volume 309/312 Expedition Reports "Superfast 2 and 3 – An intact section of ocean crust formed at a superfast spreading rate" Integrated Ocean Drilling Program Management International, Inc. (DVD)

Wilson D. S., **Teagle** D. A. H., Alt J. C., Banerjee N. R., et al., (2006) Drilling to gabbro in intact ocean crust. Science 312, 1016-1020.

CURRICULUM VITAE

BIOGRAPHICAL SKETCH- ***Raeid M. M. Abed***

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PROFESSIONAL PREPARATION:

1993	B.Sc. (*first class*) in Microbiology, Zoology & Chemistry, Bangalore University, India
1995	M.Sc.(*first class*) in Biotechnology, Mysore University, India
2001	Ph.D. in Marine Microbiology, Max-Planck Institute for Marine Microbiology, Germany
2001- 2003	Postdoctoral Fellow at Max-Planck Institute for Marine Microbiology, Bremen, Germany

APPOINTMENTS:

08/2007- present	Assistant Professor at the Biology Department, College of Science, Sultan Qaboos University, Al-Khoud, Oman
01/2004- 08/2007	Research Scientist and Project Leader at Max-Planck Institute for Marine Microbiology, Bremen, Germany

FIVE PUBLICATIONS MOST RELEVANT TO THE PROPOSED RESEARCH:

1. Weber M., Lott C., Kohls K., Polerecky L., **Abed R. M. M.**, Ferdelman T., Fabricius K. E., de Beer D. (2012) The mechanism of coral damage by runoff sediments. *Proceedings of The National Academy of Sciences of the United States of America* (PNAS). Published online. doi: 10.1073/pnas.1100715109.
2. Kohls K., **Abed R. M. M.**, Polerecky L., Weber M., de Beer D. (2010) Halotaxis of cyanobacteria in an intertidal hypersaline microbial mat. *Environmental Microbiology* 12: 567-575.
3. Neretin L. N., **Abed R. M. M**., Schippers A., Schubert C., Kohl K., Kuypers M. M. M. (2007) Inorganic carbon fixation by sulfate-reducing bacteria in the Black Sea water column. *Environmental Microbiology*. 9: 3019-3024.
4. **Abed R. M. M.**, Kohls K., de Beer D. (2007) Effect of salinity changes on the bacterial diversity, photosynthesis and oxygen consumption of cyanobacterial mats from an intertidal flats of the Arabian Gulf. *Environmental Microbiology*. 9: 1384-1392.
5. **Abed R. M. M.**, Polerecky L., Al Najjar, M., de Beer, D. (2006) Effect of temperature on photosynthesis, light respiration and sulfide production in an extremely hypersaline cyanobacterial mat. *Aquatic Microbial Ecology*. 44:21-30.

FIVE OTHER SIGNIFICANT PUBLICATIONS:

1. **Abed R. M. M.**, Ramette A., Huebner V., De Dekker P., de Beer D. (2012) Microbial diversity of aeolian dust sources from saline lake sediments and biological soil crusts in arid southern Australia. *FEMS Microbiology Ecology* 80: 294-304.

2. **Abed R. M. M.**, Al-Kindi S., Schramm A., Barry M.J. (2011) Short-term effects of flooding on bacterial community structure and nitrogenase activity in microbial mats from a desert stream. *Aquatic Microbial Ecology*. 63:245-254
3. **Abed R. M. M.**, Al-Kharusi S., Schramm A., Robinson M. (2010) Bacterial diversity, pigments and nitrogen fixation of biological desert crusts from the Sultanate of Oman. *FEMS Microbiology Ecology* 72: 418-428.
4. **Abed R. M. M.**, Safi N., Köster J., de Beer D., El-Nahhal Y., Rullkötter J., Garcia-Pichel F. (2002) Microbial diversity of a heavily polluted microbial mat and its community changes following degradation of petroleum compounds. *Applied and Environmental Microbiology* 68: 1674-1683.
5. **Abed R. M. M.**, Schönhuber W., Amann R., Garcia-Pichel F. (2002) Picobenthic cyanobacterial populations revealed by 16S rRNA-targeted *in situ* hybridization. *Environmental Microbiology* 4: 375-382.
.

SYNERGISTIC ACTIVITIES:

- *Ad hoc* reviewer of manuscripts (Environmental Microbiology, Environmental Microbiology Reports, FEMS Microbiology Ecology, Journal of Applied Microbiology, Applied and Environmental Microbiology, Microbial Ecology, Water Research, Marine Pllution Bulletin and Journal of Phycology) and research proposals - NSF (USA), NOW (Netherlands), ANR (France) and GA CR (Czech Republic)-
- Conference Chair (ISBCSAR 2013). International Symposium on Biotechnology and Conservation of Species from Arid Regions
- Invited Speaker (Germany, USA, Belgium, UAE and Saudi Arabia)
- Research Committee. SQU from 2008-now.
- Organizer of several workshops on molecular and microsensor techniques (Barcelona, Dubai and Oman)
- Consultant by oil companies in Oman on bioremediation projects
- Distinguished Lecturer- SQU 2012
- Distinguished Researcher- SQU 2010
- Obtained Research Grant from funding agencies in Germany (DFG, EU) and Oman (TRC, HM)

GARDUATE AND POSTDOCTORAL STUDENTS SUPERVISED: Postdoctoral- (1, Elke Allers); Graduate- (4 Ph.D., 1 at the MPI (Katharina Kohls) and 3 at SQU), (20 M.Sc., 10 at the MPI and 10 at SQU)

COLLABORATORS WITHIN THE PAST 48 MONTHS:
Dirk de Beer, Peter Stief and Phyllis Lahm (MPI-Germany), Natuschka Lee (TUM, Munich), T. McGenity (UE, UK), S. Golubic (BU, USA), K. Palinska (ICBM, Germany), S. Dobretsov (SQU, Oman), T. Vogel (UL, France), S. Kumar (USM, Malaysia)

GRADUATE ADVISORS AND POSTDOCTORAL SPONSORS:

Dr. Katharina Kohls	Ph.D. Advisor	DFG, Germany
Samiha Al-Kharusi	Ph.D. Advisor	TRC, Oman
Sumiya Al-Kindi	Ph.D. Advisor	TRC, Oman
Thirumahal Muthukrishnan	Co-Advisor	HM, Oman

CVURRICULM VITAE

Personal Information

Name:	Title:	Date of Birth:	Place of Birth:	Nationality:
Ali Salim Ali Al- Rajhi	Geologist	19/12/1969	Oman	Omani

Marital status:
Married
Address:
P.O. Box: 550 Muscat , PC:113,
Sultanate of Oman

Tel. No.:
Res.: (+968) 26714000
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Academic Packground

Degree	Major	School	Degree Date
PhD Degree	3D Modeling of Sur Tertiay Basin, eastern Oman	JVRCCS Sultan Qaboos University, Oman	2008
MSc Degree	Sedimentology	Bern University (Switzerland)	1998
Bachelors Degree	Earth Science	Sultan Qaboos University (OMAN)	1991

Professinal Experience

Start. Date	End. Date	Company, Location	Title	Responsibilities
10/2009	Crt.	Ministry of Commerce and Industry (MOCI)	Asistant Director General of Minerals	Replacement of the director general in his absence. Supervising various work activities of the departments. Contribution to future plans and stratigies of the Directorate. Conduction of reseach. Supervising mineral agreement with local and international companies, organisation and universities. Giving advice concerning mineral permits.
4/2007	10/2009	Ministry of Commerce and Industry (MOCI)	Director of Research and Geological Survey	Supervising activities of the geological survey and georesearch in the Sultanate. Supervising the production of geological maps and updating old ones at different scales. Making available data base for geosciences through the GIS department for investor in mieral sector. Preparing technical specifications for geological projects to be implimented by forigen and local companies. Coordinating with other government departments concerning siesmic activities, natural hazards, dams and other construction projects.
9/2006	4/2007	Ministry of	Head of non-	Studying available geological data such as

		Commerce and Industry (MOCI)	metalic minerals exploration department	geological maps and reports. Evaluating rocks and industrial minerals. Studying non-metalic mineral concession areas and issuing prospecting permits and exploration licenses for minerals investors.
9/2002	9/2006	Joint Virtual Reality Center for Carbonate Studies (JVRCCS) Sultan Qaboos University, Oman & Bordeaux University, France	PhD candidate	"3D modeling of Sur Tertiary basin, eastern Oman".
1/2000	9/2002	Ministry of Commerce and Industry (MOCI)	Head of non metalic minerals exploration department	Evaluating industrial rocks and minerals. Responsible for issuing prospecting and exploration permits.
6/1998	12/1999	Ministry of Commerce and Industry (MOCI)	Geologist	Carried out geological work, prospected for metalic and non-metalic minerals areas. Worked as a counter-part with JICA group for Exploration methodology and the discovery of massive sulphide deposites in the Batinah Coastal area.
4/1996	5/1998	(Bern University) Switzerland	MSc candidate	Studied the Lithostratigraphy of the Tertiary Formations in the Batain Plain,Sur region. Mapping of Sur sheet at the scale of 1:100,000.
12/1991	3/1996	Ministry of Petrol. & Mineral (MPM) Oman	Geologist	Carried out geological work (mapping, sampling ... etc) and studies for the following: - Al Kamil Coal fields Development project. - Ghabah Gypsum Project. –Hatat Lead and Zinc Project.

Additional Responsibilities

- Member of the Energy and Indusries Sector in the Reaseach Council.
- Member of the Oman Geological Society.

Publications:

2001 PETERS, TJ., AL BATTASHY, M., BLÄSI, R., HAUSER, M., IMMENHAUSER, A., MOSER, L. AND **AL RAJHI**, A. Geological map of Sur and Al Ashkharah – Explanatory Notes to Sheet **NF 40-8F** and Sheet **40-12C**. Directorate General of Minerals, Oman Ministry of Commerce and Industry.

Shoji Arai

PERSONAL INFORMATION

Date of Birth: OCTOBER 27, 1948
Position: PROFESSOR OF EARTH SCIENCES, KANAZAWA UNIVERSITY

EDUCATION

B.S. in Geology, University of Tokyo, Tokyo, Japan: March 1971.
M.S. in Geology, University of Tokyo, Tokyo, Japan: March 1973.
DSc. in Geology, University of Tokyo, Tokyo, Japan: March 1976.

EMPLOYMENT HISTORY

April 1976-March 1977: Research Associate, University of Tokyo, Japan
April 1977-April 1979: Research Associate, Shizuoka University, Japan
May 1979-March 1981: Assistant Professor, Shizuoka University, Japan
April 1981-November 1985: Assistant Professor, University of Tsukuba, Japan
December 1985-March 1989: Associate Professor, University of Tsukuba, Japan
April 1989-present: Professor, Kanazawa University

SOCIAL ACITIVITY

Member of IODP Planning Committee of Japan (2002-2005)
Member of IODP Science Planning Committee of Japan (2003-2006)
Chairman of Committee of Earth's Interior of Japanese Drilling Earth Science Consortium (2003-2006)
Co-chair of Science Steering and Evaluation Panel of IODP (2003-2005)
Member of ICDP SAG (Science Advisory Group) (2007-2009)
Member of IODP SASEC (Science Advisory Structure Executive Committee) (2010-2012)
President of Japanese Association for Petrologists, Mineralogists and Economic Geologists (2002-2004)

RESEARCH INTEREST (SEE BELOW)

I have been working on petrology of deep-seated rocks (mainly peridotite and related rocks) from the ocean floor, the island arc and continent. I have also been interested in the geological aspects of emplacement of mantle materials.

List of Publication (selected from 253 peer-reviewed papers)

Akizawa, N., Arai, S. and Tamura, A. (2012) Behavior of MORB magmas at uppermost mantle beneath a fast-spreading axis: an example from Wadi Fizh of the northern Oman ophiolite. Contrib. Mineral. Petrol., 164, 601-625.

Arai, S., Ishimaru, S. and Mizukami, T. (2012) Methane and propane micro-inclusions in olivine in titanoclinohumite-bearing dunites from the Sanbagawa high-P metamorphic belt, Japan: hydrocarbon activity in a subduction zone and Ti mobility. Earth Planet. Sci. Lett., 353-354, 1-11.

Gahlan, H.A., Arai, S., Abu El-Ela, F.F. and Tamura, A. (2012) Origin of wehrlite cumulates in the Moho Transitio Zone of the Neoproterozoic Ras Salatit Ophiolite, Central Eastern Desert, Egypt. Contrib. Mineral. Petrol., 163, 225-241.

Ishimaru, S. and Arai, S. (2011) Peculiar Ca-Mg-Si metasomatism along a shear zone within the mantle wedge: inference from fine-grained xenoliths from Avacha volcano, Kamchatka. Contrib. Mineral. Petrol., 161, 703-720.

Santosh, M., Rajesh, V. J., Tsunogae, T. and Arai, S. (2010) Diopsidites from a Neoproterozoic-Cambrian

suture in southern India. Geol. Mag., 147, 777-788.

Khedr, M. Z., Arai, S., Tamura, A. and Morishita, T. (2010) Clinopyroxenes in high-P metaperidotites from Happo-O'ne, central Japan: implication for wedge-transversal chemical change of slab-derived fluids. Lithos, 119 439-456.

Rajesh, V.J., Arai, S., Santosh, M. and Tamura, A. (2010) LREE-rich hibonite in ultrapotassic rocks in southern India. Lithos, 115, 40-50.

Khedr, M.Z. and Arai, S. (2010) Hydrous peridotites with Ti-rich chromian spinel as a low-temperature forearc mantle facies; evidence from the Happo-O'ne metaperidotites (Japan). Contrib. Mineral. Petrol., 159, 137-157.

Arai, S. (2010) Possible recycled origin for ultrahigh-pressure chromitites in ophiolites. J. Mineral. Petrol.Sci., 105, 280-285.

Payot, B.D., Arai,, S., Tamayo, R.A., Jr. and Yumul, G.P., Jr. (2009) What underlies the Philippine Island Arc?: Clues from the Calaton Hill, Tablas Island, Romblon (central Philippines). Jour. Asian Earth Sci., 36, 371-389.

Ishimaru, S, Arai, S & Shukuno, H (2009) Metal-saturated peridotite in the mantle wedge inferred from metal-bearing peridotite xenoliths from Avacha volcano, Kamchatka. Earth Planet Sci Lett, 284, 352-360.

Arai, S. & Ishimaru, S. (2008) Insights into petrological characteristics of the lithosphere of mantle wedge beneath arcs through peridotite xenoliths: A review. Jour. Petrol., 49 (D.H. Green vol.), 665-695.

Tamura, A., Arai, S., Ishimaru, S. and Andal, E.S. (2008) Petrology and geochemistry of peridotites from IODP Site U1309 at Atlantis Massif, MAR 30oN: micro- and macro-scale melt penetrations into peridotites. Contrib. Mineral. Petrol., 155, 491-509. (doi: 10.1007/s00410-007-0254-0)

Arai, S., and Y. Takemoto (2007) Mantle wehrlite from Hess Deep as a crystal cumulate from an ultra-depleted primary melt in East Pacific Rise, Geophys. Res. Lett., 34, L08302, doi:10.1029/2006GL029198.

Python, M., Ceuleneer, G., Ishida, Y., Barrat, J.-A. and Arai, S. (2007) Oman diopsidites: a new lithology diagnostic of very high temperature hydrothermal circulation in mantle peridotite below oceanic spreading centres. Earth Planet. Sci. Lett., 255, 289-305.

Ishimaru, S., Arai, S., Ishida, Y., Shirasaka, M., and Okrugin, V.M. (2007) Melting and multi-stage metasomatism in the mantle wedge beneath a frontal arc inferred from highly depleted peridotite xenoliths from the Avacha volcano, southern Kamchatka. Jour. Petrol., 48, 395-433.

Arai, S. (1994) Characterization of spinel peridotites by olivine-spinel compositional relationships: Review and interpretation. Chem. Geol., 113, 191-204.

Arai, S. and Yurimoto, H. (1994) Podiform chromitites of the Tari-Misaka ultramafic complex, southwestern Japan, as mantle-melt interaction products. Econ. Geol., 89, 1279-1288.

Arai, S. (1992) Chemistry of chromian spinel in volcanic rocks as a potential guide to magma chemistry. Mineral. Mag., 56, 173-184.

Arai, S. & Hirai, H. (1985) Relics of H_2O fluid inclusions in mantle-derived olivine. Nature, 318, 276-277.

Arai, S. (1975) Contact metamorphosed dunite-harzburgite complex in the Chugoku district, western Japan. Contrib. Mineral. Petrol., 52, 1-16.

CV and list of publications
Wolfgang Bach

Affiliation: University of Bremen
Geoscience Department
Klagenfurter Str., 28359 Bremen
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Academic education and career

1991: Diploma in Mineralogy (University of Giessen)
1996: PhD (Dr. rer.nat.) in Geochemistry (University of Giessen)

Employment

1995 - 1996 Scientific Associate, University of Potsdam
1996 – 1999 Postdoctoral Scholar, Woods Hole Oceanographic Institution
1999 – 2003 Assistant Scientist, Woods Hole Oceanographic Institution
2003 – 2005 Associate Scientist, Woods Hole Oceanographic Institution
2005 – present Professor (W3), University of Bremen

Major Research Interests

- Geochemical and isotopic evolution of the Earth's crust and mantle
- Ocean-lithosphere exchange budgets
- Seafloor hydrothermal systems
- Thermodynamics and kinetics of fluid-rock interactions
- Bioenergetics of chemosynthesis-based ecosystems

Expert Activities

- Reviewer for Nature, Science, PNAS, Geology, Earth and Planetary Science Letters, Journal of Petrology, Geochimica et Cosmochimica Acta, Chemical Geology, Lithos, Astrobiology, Geobiology,
- Referee for DFG, NSF, NERC, SNSB, IODP
- Associate Editor for Geochimica et Cosmochimica Acta
- Organization of the ECORD Summer School on Mid-Ocean Ridge Processes in 2009
- Participation as lecturer in four Ridge/InterRidge Summer Schools
- Associate Partner of Coordination Action for Research Activities on life in Extreme Environments (CAREX)
- Member of Scientific Committee for Oceanic Research (SCOR) Working Group on HydrothermalEnergy Transfer and its Impact on the Ocean Carbon Cycles
- Senior Personnel of the Seamount Biogeoscience Network
- Participant of the Deep Sea & Subsea Frontier (DS^3F); Working Package 1: Lithosphere – biosphere interaction and resources
- Co-chair of Steering Committee IODP New Ventures in Exploring Scientific Targets
- Chair of Academic Programs, Geoscience Department (2008-2010)
- Member of the InterRidge Workgroup Deep Earth Sampling
- Session and Theme convenor in numerous Goldschmidt and AGU conferences
- Representative of the IODP Science Steering and Evaluation Panel (2003-2005)
- Participant in five ODP cruises and co-chief scientist of one IODP cruise; participant in nine other cruises and chief scientist of three.
- Supervisor of five completed Ph.D. Theses and three pending ones

Relevant Recent Publications

Bach W, Jöns N, and Klein F (2012) Metasomatism of the Ocean Crust. In: Metasomatism and Metamorphism (Harlov D, Austrheim H, editors) *Lecture Notes in Earth Sciences*, Springer, 253-288, DOI: 10.1007/978-3-642-28394-9_8

Ziebis W, McManus J, Ferdelman T, Schmidt-Schierhorn F, Bach W, Muratli J, Edwards K, Villinger H (2012) Interstitial fluid chemistry of sediments underlying the North Atlantic Gyre and the influence of subsurface fluid flow. *EPSL* 323-324, 79-91

Berndmeyer C, Birgel D, Brunner B, Wehrmann L, Jöns N, Bach W, Arning E, Föllmi K, Peckmann J (2012): The influence of bacterial activity on phosphorite formation in the Miocene Monterey Formation, California. *Palaeogeography, Palaeoclimatology, Palaeoecology* 317-318, 171-181

Hentscher M, Bach W (2012) Geochemically induced shifts in catabolic energy yields explain past ecological changes of diffuse vents in the East Pacific Rise 9°50'N area. *Geochem. Trans.* 13:2. doi:10.1186/1467-4866-13-2

Bach W, Rosner M, Jöns N, Rausch S, Robinson LF, Paulick H, Erzinger J (2011) Carbonate veins trace subseafloor circulation of seawater during uplift of mantle rocks: ODP Leg 209. *EPSL* 311: 242-252.

Petersen JM, Zielinski FU, Pape T, Seifert R, Moraru T, Amann R, Hourdez S, Girguis PR, Wankel SD, Barbe V, Pelletier E, Fink D, Borowski C, Bach W, Dubilier N (2011) Hydrogen is an energy source for hydrothermal vent symbioses. *Nature* 476: 176-180

Amend JP, McCollom TM, Hentscher M, Bach W (2011) Metabolic Energy for Chemolithoautotrophs in Peridotite-Hosted and Basalt-Hosted Hydrothermal Systems *Geochim. Cosmochim. Acta* 75: 5736-5748

John T, Scambelluri M, Frische M, Barnes JD, Bach W (2011) Dehydration of subducting serpentinite: implications for halogen mobility in subduction zones ... *Earth Planet Sci Lett* 308: 65-76

Edwards KJ, Glazer BT, Rouxel OJ, Bach W, Emerson D, Davis RE, Toner BM, Chan CS, Tebo BM, Staudigel H, Moyer CL (2011) Ultra-diffuse Hydrothermal Venting Supports Fe-oxidizing Bacteria ... *The ISME Journal: Multidisciplinary J. Microbial Ecol.* doi:10.1038/ismej.2011.48

Orcutt BN, Bach, W, Becker K, Fisher AT, Hentscher M, Toner BM, Wheat CG, and Edwards KJ (2010) Colonization of subsurface microbial observatories deployed in young ocean crust *The ISME Journal: Multidisciplinary Journal of Microbial Ecology* doi:10.1038/ismej.2010.157

Jöns N, Bach W, and Klein F (2010) Magmatic influence on reaction paths and element transport during serpentinization. *Chemical Geology* 274: 196-211

Bach W, and Früh-Green GL (2010) Alteration of the Oceanic Lithosphere ... *Elements* 6: 173-178.

Santelli CM, Banerjee N, Bach W, & Edwards KJ (2010) Tapping the Subsurface Ocean Crust Biosphere: Low Biomass and Drilling-Related Contamination Calls for Improved Quality Controls. *Geomicrobio J. l* 27: 158-169

Bach W, Ravelo C, Behrmann J, Camoin G, Duncan R, Edwards K, Gulick S, Inagaki F, Pälike H, and Tada R (2010) IODP New Ventures in Exploring Scientific Targets (INVEST): Defining the New Goals of an International Drilling Program. *Scientific Drilling* 5: 54-64

Eickmann B, Bach W, Kiel S, Reitner J, and Peckmann J (2009) Evidence for cryptoendolithic life in … pillow basalts of Variscan orogens, Germany. *Palaeoceanog, Palaeoclimat, Palaeoeco* 283: 120–125

Klein F, Bach W, Jöns N, McCollom TM, Moskovitz B, and Berquo T (2009) Iron partitioning and hydrogen generation during serpentinization of abyssal peridotites from 15°N on the Mid-Atlantic Ridge *Geochimica et Cosmochimica Acta* 73(22): *6868-6893*

Klein F & Bach W(2009) Fe-Ni-Co-O-S phase relations in peridotite-seawater interaction *J. Petrol.* 50: 37-59

Bach W & Klein F (2009) Petrology of rodingites: Insights from geochemical reaction path modeling, *Lithos* 112: 103-117

Jöns N, Bach W, and Schroeder T (2009) Formation and alteration of plagiogranites in an ultramafic-hosted detachment fault at the Mid-Atlantic Ridge (ODP Leg 209), *Contrib. Mineral. Petrol.* 157: 625-639

McCollom TM, and Bach W (2009) Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks, *Geochim. Cosmochim. Acta* 73: 856-879

Santelli CM, Orcutt BN, Banning E, Bach W, Moyer CL, Sogin ML, Staudigel H, and Edwards KJ (2008) Abundance and diversity of microbial life in ocean crust, *Nature* 453: 653 - 656

KEIR BECKER

I. Education and Appointments: A.B., 1975, Physical Sciences, cum laude, Harvard College Ph.D., 1981, Oceanography, Scripps Institution of Oceanography, UC San Diego Assistant Research Geophysicist, Scripps Institution of Oceanography, and Staff Scientist, Deep Sea Drilling Project, 1981-1985 Assistant Professor, RSMAS - MGG, University of Miami, 1985-1987 Associate Professor, RSMAS - MGG, University of Miami, 1987-1994 Professor, RSMAS - MGG, University of Miami, 1994-present

II. Activities Related to Scientific Ocean Drilling:

A. Shipboard Participant, Scientific Ocean Drilling (* = Chief or Co-Chief Scientist): DSDP Legs 70, 78B, 83, 92 ODP Legs 102, 109, 111*, 118, 137*, 139, 148, 158, 168, 174B*, 190, 196* IODP Expeditions 301, 327, 336 (Participant in 33 other oceanographic cruises since 1978; total time at sea ~5 yrs)

B. JOI-USSAC Distinguished Lecturer, 1994-1995

C. DSDP/ODP/IODP Panel Service and Workshop Co-Convener/Steering Committees JOIDES Downhole Measurements Panel (liaison or member), 1982-1990 JOIDES Tectonics Panel, 1984-1986 JOIDES Lithosphere Panel, 1986-1990 USSAC, 1988-1990 USSAC Executive Committee, 1989-1990 JOIDES Planning Committee, 1990-1994 Chairman, JOIDES Engineering Development Review Committee, 1993-1994 Co-convener, SCORE (Sediment-Covered Ocean Ridges) Workshop, Portland, 1994 Co-convener, BOREHOLE Observatory Workshop, Miami, 1994 Steering Committee, ION/ODP Workshop, Marseilles, 1995 COMPOST-II (host), Miami, 1997 Co-chair, JOIDES Long-Term Observatories PPG, 1997-1999 Co-convener, Advanced CORKs Workshop, Scripps, 1997 and College Station, 1998 Co-convener, Hydrogeology of Oceanic Lithosphere Workshop, Santa Cruz, 1998 Chairman, JOIDES/ODP Science Committee (SCICOM), 2001-2003 Chairman, JOIDES/ODP Operations Committee (OPCOM), 2001-2003 Chairman, IODP Arctic Scoping Group (for ACEX Expedition 302), 2003 IODP Science Planning Committee (SPC), 2003-2007 (Vice-chair, 2004-2005) Chairman, IODP Science Planning Committee (SPC), 2005-2007 IODP Science Advisory Structure Executive Committee (SASEC), 2006-07, 2008-11 IODP-MI Thematic Review Committee, Deep Biosphere & Subseafloor Ocean, 2009 IODP-MI Second Triennial Review Committee, 2010 IODP Science Implementation and Policy Committee (SIPCom), 2012-present

D. Director, final rotation of JOIDES Office, 2001-2003

E. Co-originator, ODP/IODP CORK hydrogeological observatories, with E. Davis, B. Carson, and T. Pettigrew. Participant in 7 ODP/IODP CORK-installation and 21 submersible CORK-servicing expeditions (2 of 7 and 12 of 21 as chief scientist)

F. ODP third-party downhole tool developer: Drillstring packer (1984-1991; transferred to ODP-TAMU, 1991) Downhole flowmeter, 1990-1991 High-temperature, memory temperature logging tool, 1993-1994

G. Principal Investigator, 18 NSF-ODP grants for CORKS and downhole tools since 1984

III. Other Significant National/International Committee Service

RIDGE Steering Committee, 1994-1997 Co-Chairman, DEOS Steering Committee (predecessor to OOI), 1997-2000 NAS/NRC Committee on Seafloor Observatories, 1999-2000 NAS/NRC Committee on Future Needs in Deep Submergence Science, 2003 ORION Science and Technology Advisory Committee (STAC), 2005-2007 NSF/WHOI Replacement HROV Oversight Committee (RHOC), 2005-present ESF EUROMARC Review Panel, 2006-2011 NSF-OCE Integrative Programs Section Committee of Visitors, 2008

IV. Ten Significant DSDP/ODP/IODP-related Publications (out of nearly 100 drilling publications)

Becker, K., R.P. Von Herzen, T.J.G. Francis, R.N. Anderson, J. Honnorez, A.C. Adamson, J.C. Alt, R. Emmermann, P.D. Kempton, H. Kinoshita, C. Laverne, M.J. Mottl, and R.L. Newmark, 1982, In situ electrical resistivity and bulk porosity of the oceanic crust, Costa Rica Rift, Nature, 300, 594-598.

Becker, K., M.G. Langseth, R.P. Von Herzen, and R.N. Anderson, 1983, Deep crustal geothermal measurements, Hole 504B, Costa Rica Rift, J. Geophys. Res., 88, 34473457.

Becker, K., et al., 1989, Drilling deep into young oceanic crust at Hole 504B, Costa Rica Rift. Rev. Geophys., 27, 79-102.

Davis, E., Becker, K., Pettigrew, T., Carson, B., and MacDonald, R., CORK: a hydrologic seal and downhole observatory for deep ocean boreholes, in Davis, E., Mottl, M., et al., Proc. ODP. Init. Repts., 139, 43-53.

Becker, K., and Fisher, A.T., 2000, Permeability of upper oceanic basement on the eastern flank of the Juan de Fuca Ridge determined with drill-string packer experiments, J. Geophys. Res., 105, 897-912.

Becker, K., and Davis, E.E., 2003, New evidence for age variation and scale effects of permeabilities of young oceanic crust from borehole thermal and pressure measurements, Earth Planet. Sci. Lett., 210, 499-508.

Becker, K., Davis, E.E., Spiess, F.N., deMoustier, C.P., 2004, Temperature and video logs from the upper oceanic crust, Holes 504B and 896A, Costa Rica Rift flank: implications for the permeability of upper oceanic crust, Earth Planet. Sci. Lett., 222, 881-896.

Becker, K., and Davis, E.E., 2005, A review of CORK designs and operations during the Ocean Drilling Program, Proc. IODP, Exp. Rept., 301, doi:10.2204/iodp.proc.301.104.2005.

Becker, K., and A. T. Fisher, 2008, Borehole packer tests at multiple depths resolve distinct hydrologic intervals in 3.5-Ma upper oceanic crust on the eastern flank of Juan de Fuca Ridge, J. Geophys. Res., 113, B07105, doi:10.1029/2007JB005446.

Orcutt, B.N., W. Bach, K. Becker, A.T. Fisher, M. Hentscher, B.M. Toner, C.G. Wheat, K.J. Edwards, 2010, Colonization of subsurface microbial observatories deployed in young ocean crust, Intl. Soc. Microbial Ecology Journal, 5, 692-703, doi: 10.1038/ismej.2010.157.2011.

Françoise, Irène BOUDIER

Born : March 4th, 1938, Fontenay-sous-Bois (94) (France)
Unmaried, no child
Professional Address : **Université Montpellier2,**
Laboratoire de Tectonophysique, Place eugene Bataillon,
CC049, 34095 Montpellier cedex 5, France

STUDIES

Baccalauréat, 1956, Clermont-Ferrand, (France)
Graduation in Earth Sciences, 1959, Clermont-Ferrand, (France)
DEA (Master), in Petrology, 1962, Clermont-Ferrand, (France)
Doctorat IIIè cycle, in Structural Geology and Petrofabrics, 1972, Nantes, (France)
Doctorat d'Etat, in Structural Petrology and Petrofabrics, 1976, Nantes, (France)

LANGUAGES

French : native language
English : fluent
Arabic : poor

UNIVERSITY POSITIONS

Assistant lecturer at University of Nantes, Earth Sciences Department, 1964-1975
Lecturer at University of Nantes, Earth Sciences Department, 1975-1981
Professor at University of Nantes, 1981-1986
Professor at University of Montpellier, since 1986
Prefessor Emeritus at University of Montpellier, since feb 2003

ADMINISTRATIVE INVOLVEMENTS

Organization of the newly created Department of Earth Sciences of University of Nantes, 1964-1967
Member of the University Council, University of Nantes, 1976-1978
Secretary of the Third International Conference on Kimberlites hold in Clermont-Ferrand, 1982
Member of National Committee of Earth Sciences of the CNRS, 1982-1985
Head of Second Cycle Studies, University of Montpellier, 1989-1993

TEACHING

Pratical Teaching in Mineralogy, Fondamental Geology, Petrography, Structural Geology, University of Nantes, 1964-1981
Magistral Teaching
  1978-1986, Fondamental Geology (1st cycle), University of Nantes
  1981-1986, Tectonophysics (3rd cycle), University of Paris XI
  since 1986, Mineralogy, Petrology (1st cycle), University of Montpellier
    Geodynamics, Tectonophysics (2nd and 3rd cycles), University of Montpellier

SCIENTIFIC ACTIVITY

Covers the domain of Structural geology and Petrofabrics. Co-discovery in 1971 of the principles of kinematic analysis in plastically deformed rocks, mechanisms of ductile deformation and recrystallization, application to mantle flow and anisotropy, oceanic lithosphere (involvement in oceanographic cruises), mechanisms of sea-floor spreading as deduced from structural studies in ophiolites, particularily the Oman Ophiolite (20 years of continuous involvement).

86 scientific publications in international scientific journals
CITATION REPORT 2393 (web of science 2012)
Co-editor of Three Special Issues of International Journals:
'The ophiolites of Oman', *Tectonophysics,*1988.
'Adolphe Nicolas Volume', *Tectonophysics,* 1997
'The ophiolite of Oman and United Arab Emirates', *Journal of Geophysical Researches,* 2000.

BIBLIOGRAPHY F. BOUDIER SINCE 2000

Nicolas A. and **F. Boudier**, Large mantle upwellings and related variations in crustal thickness in the Oman ophiolite, Geological Society America Bulletin, 349, 67-73, 2000.

Boudier F., M. Godard and C. Armbruster, Significance of noritic gabbros in the gabbro section of the Oman ophiolite., Marine Geophysical Researches, 21, 307-326, 2000.
Nicolas A., **F. Boudier**, K. Michibayashi and L. Gerbert-Gaillard, Aswad massif (United Arab Emirates), Archetype of the Oman-UAE ophiolite belt, Geological Society America Bulletin, 349, 499-512, 2000.
Nicolas A., B. Ildefonse, **F. Boudier** and W. Ben Ismail, Dikes in Oman-United Arab Emirates ophiolite, Marine Geophysical Researches, 21, 269-287, 2000.
Boudier F. and T. Juteau, ed. The ophiolite of Oman and United Arab Emirates, Kluwer. 2000
Dewandel B., **F. Boudier,** H. Kern, W. Warsi and D. Mainprice, Seismic wave velocity and anisotropy of serpentinized peridotite in the Oman ophiolite, Tectonophysics, 370, 77-94, 2003.
Nicolas, A., and **F. Boudier**, Where ophiolites come from and what do they tell us, Geological Society America Bulletin, 273 : 137-152, 2003.
Nicolas, A., D. Mainprice, and **F. Boudier**, High temperature seawater circulation throughout crust of oceanic ridges : A model derived from the Oman ophiolite, J. Geophys. Res., 108 : 2371, on line, 2003.
Bosch, D., M. Jamais, **F. Boudier**, A. Nicolas, J.-M. Dautria, and P. Agrinier, Deep and high temperature hydrothermal circulation in the Oman ophiolite-Petrological and isotopic evidence, J. Petrology., 45 (6), pp. 1181-1208, 2004.
Dewandel B., P. Lachassagne, **F. Boudier**, S. Al-Hattali, B. Ladouche, JL. Pinault, Z. Al-Suleimani. A conceptual hydrogeological model of ophiolite hard-rock aquifers in Oman based on a multiscale and multidisciplinary approach. Hydrogeology Journal, 13, 708-726. 2005.
Boudier , F., A. Nicolas, and D. Mainprice, Does anisotropy of thermal contraction control hydrothermal circulation at the Moho level below fast spreading oceanic ridges?, in International Geology Review, edited by C. Coleman, pp. 101-112, GSA Robert, G., 2005.
Boudier, F and A. Nicolas. Comment on « dating the geologic history of Oma,'s Semail ophiolite : insight from U-Pb geochronology » by C.J. Warren, R.R. Parrish, D.J. Waters and M.P. Searle. Contrib. Miner. Petrol. 154, 11-113, 2007.
Nicolas A., and **Boudier F.** (2008) Large shear zones with no relative displacement. Terra Nova 3, 200-205, doi:10.1111/j.1365-3121.2008.00806.x
Nicolas A., **Boudier F.**, Koepke J., France L., Ildefonse B., and Mével C. (2008) Root zone of the sheeted dike complex in the Oman ophiolite. Geochemistry, Geophysics and Geosystems 9, Q05001, doi:10.1029/2007GC001918.
Boudier F., Baronnet A., and Mainprice D. (2009) Oriented Serpentine Minerals Replacements of Natural Olivine and their seismic implications: Oceanic Lizardite versus Subduction-Related Antigorite. J. Petrol. 51, 495-512. doi:10.1093/petrology/egp049.
Burg J.P., Bodinier J.L., Gerya T., Bedini R.M., **Boudier F.**, Dautria J.M., Prikhodko A., Efimov A., Pupier E. and Balanec J.L. (2009) Translithospheric mantle diapirism: geological evidence and numerical modelling of the Kondyor zoned ultramafic complex (Russian Far-East). J. Petrol. 50, 289-321. doi:10.1093/petrology/egn083
Koepke J., Schoenborn S., Oelze M., Wittmann H., Feig S.T., Hellebrand E., **Boudier F.**, and Schoenberg R. (2009) Petrogenesis of crustal wehrlites in the Oman ophiolite: Experiments and natural rocks, Geochem. Geophys. Geosyst., 10, Q10002, doi:10.1029/2009GC002488
Nicolas A., **Boudier F.**, France L. (2009) Subsidence in magma chamber and the development of magmatic foliation in Oman ophiolite gabbros. Earth Planet. Sc. Lett. 284, 76-87. doi:10.1016/j.epsl.2009.04.012.
Boudier F., Baronnet A., and Mainprice D. (2009) Oriented Serpentine Minerals Replacements of Natural Olivine and their seismic implications : Oceanic Lizardite versus Subduction-Related Antigorite. J. Petrol. 51, 495-512. doi:10.1093/petrology/egp049.
Meshi A., **Boudier F.**, Nicolas A., and Milushi I. (2009) Structure and tectonics of lower crustal and upper mantle rocks in the Jurassic Mirdita ophiolites, Albania. International Geology Review,52: 117 - 141, doi:10.1080/00206810902823982.
Menzies, M. ; Kelemen, P. ; Dick, H. ; Bodinier, J.L. ; **Boudier, F.** ; Hirth, G. ; Grove, T. ; Tommasi, A. and Takazawa E. (2010) Shallow Mantle Composition and Dynamics : Fifth International Orogenic Lherzolite Conference : Foreword. J. Petrol., 51 : 3-7 ; doi:10.1093/petrology/egp098
Morales, L. F. G., **Boudier F.**. and Nicolas A. (2011) Microstructures and crystallographic preferred orientation of anorthosites from Oman ophiolite and the dynamics of melt lenses, Tectonics, 30, TC2011 doi:10.1029/2010TC002697
Boudier, F. & Nicolas, A. (2011) Axial melt lenses at oceanic ridges – A case study in the Oman ophiolite. Earth Planet. Sci. Lett., 304, 313-325, doi:10.1016/j.epsl.2011.01.029.
Nicolas, A. & **Boudier, F**. (2011) Structure and dynamics of ridge axial melt lenses in the Oman ophiolite. J. Geophys. Res., 116, B03 103, doi:10.1029/2010JB007934.

Georges Ceuleneer - Director of Research – CNRS - France

PERSONAL INFORMATION

Date of birth: December 10th, 1959 - Place of birth: Brussels (Belgium)
Nationality: Belgian - Family situation : Married, 3 children.
Office Address: " GET" Observatoire Midi-Pyrénées - 14, av. E. Belin, 31400 Toulouse, FRANCE.
Tél. + 33 (0)5 61 33 29 60 - e-mail: Georges.Ceuleneer@get.obs-mip.fr

EDUCATION + EMPLOYMENT HISTORY

1977-81: Graduate studies in Geology, Université Libre de Bruxelles, Belgium.
1981-82: Master in Geophysics - Université de Paris XI, Orsay, France.
1982-86: PhD (Lab. Tectonophysics, Nantes). Structural study of the Oman ophiolite.
1986: Military duty in the Belgian Navy (1 year).
1987-88: Post-Doc in the National Space Agency (Toulouse, France), ESA scholarship.
1988: Engaged as Researcher by the CNRS.
1999: Director of Research (Senior Scientist) in the CNRS.

INVOLVMENT IN DRILLING EXPEDITIONS AND ADMINISTRATION

Cruises:
. ODP-LEG-153 (Mantle peridotites along the MAR 22°N).
. IODP-Expedition 345 (Hess Deep Crust)
. Site survey (Dives with Shinkaï-6500) for LEG 209 (MAR Peridotites 15°N).

Committees:
. Chair of IODP-France and alternated of ESSAC French Representative since 2011.
. Co-author of the Thematic Review "Oceanic crustal structure and formation", 2009.
. ODP Science Steering and Evaluation Committee from 1997 to 1999.
. Speaker at the European Ocean Drilling Forum. Edinburgh, 1998.

RESEARCH INTEREST

. Melt migration in the oceanic mantle and genesis of the oceanic crust.
. Modelling of mantle convection and of melt migration in the Earth's mantle.
. Geological mapping using remote sensing hyperspectral techniques (Earth and Planets).

Other oceanographic cruises:
. Several dives with the submersibles *Nautile* and *Shinkaï-6500*.
. Geophysical surveys of the Mid-Atlantic Ridge (*L'Atalante*).

Field work in ophiolites:
. About 25 field seasons in Oman, USA, Venezuela and Europe.

OTHER COMMITTEES and RESPONSABILITIES

. Director and deputy director of a CNRS lab (2007 – 2010).
. Member of the French oceanographic cruises projects committee (2003-2010).
. Member and Chair of « Groupe Ocean » (Post-cruise funding of french cruises) (2000-2002).
. "Chargé de mission" for the french Ministry of Research (2007-2008); evaluation of labs, international funding applications, etc…

PhD supervised in Toulouse University (all about the Oman ophiolite)

Isma Amri (1992-1995)
Mathieu Benoit (1994-1997)
Marie Python (1998-2002)
Harold Clénet (2005-2009)
Bénédicte Abily (2007-2011)

Teatching and diffusion of knowledge

. Lectures in petrology in master classes and lessons for college teachers in natural sciences.
. Organiser of annual summer schools for researchers and PhD student.
. Conferences (Clubs of mineralory, Museums, “Free Time Universities”, Schools, Jails, …).
. Contributions to newspapers (La Recherche, etc…).
. Leader of field trips in the Oman ophiolites, for researchers and teatchers.

Publications (selection)

Ceuleneer G., Monnereau M. and Amri I. Thermal structure of a fossil mantle diapir inferred from the distribution of mafic cumulates. **Nature**, 379, 149-153, 1996.

Benoit M., Ceuleneer G. and Polvé M. The remelting of hydrothermally altered peridotite at mid-ocean ridges by intruding mantle diapir. **Nature**, 402, 514-518, 1999.

Abily B., Ceuleneer G. and Launeau P. Syn-magmatic normal faulting in the lower oceanic crust: evidence from the Oman ophiolite. **Geology**, 39, 391-394, 2011.

Abily B. and Ceuleneer G. The dunitic mantle/crust transition zone in the Oman ophiolite: Residue of melt rock-interaction, cumulates from high-MgO melts, or both? **Geology**, in press, 2013.

Borisova A., Ceuleneer G., Kamenetsky V., Arai S., et al. A new view on the petrogenesis of the Oman ophiolite chromitites from microanalyses of chromite-hosted inclusions. **J. Pet**., 53, 2411-2440, 2012.

Dantas C., Ceuleneer G., Grégoire M., Python M., Freydier R., Warren J. and Dick H.J.B. Pyroxenites from the southwest indian ridge, 9°-16°E : cumulates from incremental melt fractions produced at the top of a cold melting regime. **J. Petrol**., 48, 647-660, 2007.

Python M. and Ceuleneer G. Nature and distribution of dykes and related melt migration structures in the mantle section of the Oman ophiolite. **Geochem. Geophys. Geosyst.,** 4(7), 8612, doi :10.1029/2002GC000354, 2003.

Ceuleneer G. and Rabinowicz M. Mantle flow and melt migration beneath ocean ridges: models derived from observations in ophiolites, in Mantle flow and melt generation at mid-ocean ridges, **AGU Geophys. Monograph 71**, J.P. Morgan, D.K. Blackman and J. M. Sinton editors, 123-154, 1992.

Dannowski A., Grevemeyer I., Ranero C.R., Ceuleneer G., Maia M., Phipps Morgan J. and Gente P. Seismic structure of an oceanic core complex at the Mid-Atlantic Ridge, 22°19’N. **J. Geophys. Res.,** 115, B07106, doi:10.1029/2009JB006943, 2010.

Clénet H., Ceuleneer G., Pinet P., Abily B., Daydou Y., Harris E., Amri I. and Dantas C. Thick sections of layered ultramafic cumulates in the Oman ophiolite revealed by an airborne hyperspectral survey: ... **Lithos**, 114, 265-281, doi:10.1016/j.lithos.2009.09.002, 2010.

Nonnotte P., Ceuleneer G. and Benoit M. Genesis of andesitic-boninitic magmas at mid-ocean ridges by melting of hydrated peridotites : geochemical evidence from DSDP Site 334 gabbronorites. **Earth Planet. Sci. Lett**., 236, 632-653, 2005.

Ceuleneer G. and Cannat M. High temperature ductile deformation of the site 920 peridotites. In : Karson J.A., Cannat M., Miller D.J. and Elthon D., Eds., **Proc. Ocean Drilling Progam, Scientific Results, 153**, College Station, Texas, U.S.A., 23-34, 1997.

Cannat M., Ceuleneer G. and Fletcher J. Localization of ductile strain and the magmatic evolution of gabbroic rocks at the Mid-Atlantic Ridge (23°N). In : Karson J.A., Cannat M., Miller D.J. and Elthon D., Eds., **Proc. ODP, Scientific Results, 153,** College Station, Texas, U.S.A., 77-98, 1997.

Ceuleneer G. and le Sueur E. The Trinity ophiolite (California) : the strange association of fertile mantle peridotite with ultra-depleted crustal cumulates**. Bull. Soc. Geol. France**, t. 179, n° 5, 503-518, 2008.

Python M., Ceuleneer G., Ishida Y., Barrat J.-A. and Arai S. Oman diopsidites : a new lithology diagnostic of very high temperature hydrothermal circulation in mantle peridotite below oceanic spreading centres. **Earth Planet. Sci. Lett.**, 255, 289-305, 2007.

Rabinowicz M. and Ceuleneer G. The effect of sloped isotherms on melt migration in the shallow mantle : … based on observations in the Oman ophiolite. **Earth Planet. Sci. Let**., 229, 231-246, 2005.

Amri I., Benoit M. and Ceuleneer G. Tectonic setting for the genesis of oceanic plagiogranites: evidence from a paleo-spreading structure in the Oman ophiolite. **Earth Planet. Sci. Lett**., 139, 177-194, 1996.

CURRICULUM VITAE

LAURENCE A. COOGAN

School of Earth and Ocean Sciences
University of Victoria
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Canada

Phone 250 472 4018
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Professional Preparation:

University of Leicester (UK) PhD (1998) University of Liverpool (UK) BSc. (1993)

Appointments:

2008-present: Associate Prof. (University of Victoria)
2004-2008: Assistant Prof. (University of Victoria)
2002-2004: NERC Post-doctoral Research Fellow (Leicester University)
1998-2002: Post-doctoral Researcher (Cardiff University)

Awards:

2011: UVic Faculty of Science Teaching Award
2007: Mineralogical Association of Canada Young Scientist Award
2002: NERC Post Doctoral Fellowship

Five publications relevant to this proposal:

Coogan, L.A. and Dosso, S. (2012) An internally consistent, probabilistic, determination of ridge-axis hydrothermal fluxes, Earth and Planetary Science Letters v. 323-4 p 92-101.

Coogan, L.A., (2007), The lower oceanic crust, *in* Turekian, K., and Holland, H.D., eds., Treatise on Geochemistry, Elsevier. (Revised version in press in forthcoming 2nd edition).

Coogan, L.A., Jenkin, G.R.T. and Wilson, R.N., 2007. Contrasting cooling rates in the oceanic lithosphere at fast- and slow-spreading mid-ocean ridges derived from geospeedometry. Journal of Petrology, 48: 2211-2231.

Perk, N., Coogan, L.A., Karson, J.A., Klein, E.M. and Hanna, H., 2007. Primitive cumulates from the upper crust formed at the East Pacific Rise. Contributions to Mineral Petrology: DOI:10.1007/s00410-007-0210-z.

Coogan, L.A., Howard, K.A., Gillis, K.M., Bickle, M.J., Chapman, H.J., Boyce, A.J., Jenkin, G.R.T., and Wilson, R.N., (2006), Chemical and thermal constraints on focused fluid flow in the lower oceanic crust: American Journal of Science.

Five other significant research publications:

Coogan, L.A., (2008) Reconciling temperatures of metamorphism, fluid fluxes and heat transport in the upper crust at intermediate- to fast-spreading mid-ocean ridges. *Geochemistry Geophysics Geosystems,* DOI: 10.1029/2007GC001787

Gillis, K.M. and Coogan, L.A., (2011). Secular variation in carbon uptake into the ocean crust. Earth and Planetary Science Letters, v302, p 385-392

Coogan, L.A. and Hinton, R.H., 2006. Do the trace element compositions of detrital zircons require

Hadean continental crust? Geology, 34(8): 633-636.
Coogan, L.A., Kasemann, S., and Chakraborty, S., 2005, Rates of hydrothermal cooling of new oceanic upper crust derived from Li-geospeedometry: Earth Planet. Sci. Lett., v. 240, p. 415-424.
Costa, F., Coogan, L.A., and Chakraborty, S. (2009) The time scales of magma mixing and mingling involving primitive melts and melt-mush interaction at Mid-ocean ridges: Contributions to Mineral Petrology, DOI 10.1007/s00410-009-0432-3

Recent collaborators:

A. Barker (Upsala), S. Chakraborty (U. Bochum), F. Costa (Singapore), R. Dohmen (U. Bochum), S. Dosso (UVic), K. Gillis (UVic), R. Hinton (Edinburgh), G. Jenkin (Leicester), S. Kasemann (Edinburgh), J. Naden (BGS), N. Pester (U.Min), A. Saunders (Leicester – PhD advisor), W. Seyfried (U.Min), R. Wilson (Leicester),

Graduate Students supervised:

Archana Shejwalkar, (PhD – in progress, UVic), Brock Anderson (PhD – in progress, UVic), Casey Brant (PhD – in progress, UVic), Simon Jowitt (PhD, Leicester), Graham Banks (PhD, Cardiff), Kathi Faak (PhD, U. Bochum), Richard Thomas (PhD, Cardiff), Zhihuan Wan (MSc, UVic.), Lisa Worrell (PhD, Liverpool)

Field experience:

Numerous field seasons in both the Oman and Troodos ophiolites. Seagoing experience with submersible, ROV, portable rock-drills and dredging.

Synergistic Activities:

2007-present: member of the editorial board of LITHOS
2004-present: NEPTUNE Canada 'ridge-fluids' science planning committee member

KATHRYN M. GILLIS

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Professional Preparation

B.Sc. (Hons.), Geology, Queen's University, Kingston, Ontario, 1981

Ph.D., Geology, Dalhousie University, Halifax, Nova Scotia, 1987

NSERC Postdoctoral Scholar, Université de Montréál and Woods Hole Oceanographic Institution, 1986-1989

Positions Held

2011 - present	Associate Dean, Faculty of Science and Professor, School of Earth and Ocean Sciences, University of Victoria
2004 - 2011	Professor and Director, School of Earth and Ocean Sciences, University of Victoria
1997 - 2004	Associate Professor, School of Earth and Ocean Sciences, University of Victoria
1994 - 1997	Assistant Professor, School of Earth and Ocean Sciences, University of Victoria
1993 -1994	Associate Scientist, Dept. of Geology and Geophysics, Woods Hole Oceanographic Institution
1989 - 1993	Assistant Scientist, Dept. of Geology and Geophysics, Woods Hole Oceanographic Institution

Five Most Relevant Publications:

Kirchner, T. and Gillis, K.M., 2012. Mineralogical and strontium isotopic record of hydrothermal processes in the lower ocean crust at and near the East Pacific Rise, Contrib. Mineral. Petrol., doi:10.1007/s00410-012-0729-5.

Gillis, K.M., 2008, The roof of an axial magma chamber: a hornfelsic heat exchanger, *Geol*, 36, 299-302.

Gillis, K.M., Coogan, L.A., and Pedersen, R., 2005. Strontium isotope constraints on fluid flow in the upper oceanic crust at the East Pacific Rise, *Earth Planet. Sci. Lett*. 232, 83-94.

Gillis, K.M., Coogan, L.A. and Chaussidon, M., 2003. Volatile behavior (Cl, F, B) in the roof of an axial magma chamber from the East Pacific Rise, *Earth Planet. Sci. Lett*. 213, 447-462. Gillis, K.M., Muehlenbachs, K., Stewart, M., and Gleeson, T., 2001. Fluid flow patterns in fast-spreading East Pacific Rise crust. *J. Geophys. Res*. **106**, 26,311-26,329.

Gillis, K.M., Muehlenbachs, K., Stewart, M., and Gleeson, T., 2001. Fluid flow patterns in fast-spreading East Pacific Rise crust. *J. Geophys. Res*. **106**, 26,311-26,329.

Gillis, K.M., 1995. Controls on hydrothermal alteration in fast-spreading oceanic crust, *Earth Planet. Sci.* Lett., 134, 473-489.

Five Other Significant Publications:

Barker, A.K., Coogan, L.A., Gillis, K.M., Hayman, N., and Weis, D., 2010. Direct observation of a fossil high temperature, fault–hosted hydrothermal upflow zone in crust formed at a fast-spereading East Pacific Rise, *Geology*, 38, 379-382, doi: 10.1130/G30542.1.

Heft, K., Gillis, K.M., Pollock, M., Karson, K., and Klein, E., 2008, Constraints on the nature of axial hydrothermal systems from the sheeted dike complex exposed at Pito Deep, *Geochem, Geophys., Geosys*., *9*, doi:10.1029/2007GC001926).

Barker, A., Coogan, L.A., Gillis, K.M., and Weis, D., 2008. Strontium isotopic constraints on fluid flow in the sheeted dike complex of fast-spreading crust: Part I – pervasive fluid flow at Pito Deep, *Geochem, Geophys., Geosys*., *9*, doi:10.1029/2007GC001901.

Coogan, L.A., Howard, K.A., Gillis, K.M., Bickle, M.J., Chapman, H.J., Boyce, A.J., Jenkin, G.R.T., and Wilson, R.N., 2006, Chemical and thermal constraints on focused fluid flow in the lower oceanic crust: *Am. J. Sci.*, 306, 389-427.

Coogan, L.A., Gillis, K.M., MacLeod, C.J., Thompson, G.M., and Hékinian, R., 2002. Petrology and geochemistry of the lower ocean crust formed at the East Pacific Rise and exposed at Hess Deep: a synthesis and new results. *Geochem., Geophys., Geosys.,* **3**, Paper Number 2001GC000230.

Synergistic Activities

Research results are routinely incorporated into undergraduate and graduate courses at U. Victoria; supervision of undergraduate research projects that involve deep sea samples; Member, NEPTUNE Canada SAC; Member, Canadian Consortium for Ocean Drilling.; co-chief scientists for IODP Exp 345 to Hess Deep.

Recent Collaborators (last 48 months): L. Coogan (U. Victoria), J. Karson (Syracuse U.), E. Klein (Duke U.), D. Weis (UBC), A. Barker, C. MacLeod (Cardiff U.), D. Teagle (U. Southampton), D. Shillington (LDEO), J. Snow (Houston).

Graduate & Postdoctoral Advisors

Graduate Advisor (Dalhousie): P. Robinson (Dalhousie, retired)
Post-doctoral Supervisor (U. Montréal): J. Ludden (British Geological Survey)
Post-doctoral Supervisor (WHOI): G. Thompson (WHOI, retired)

Thesis Advisor and Postgraduate-Scholar Sponsor (*last 5 years; *=current*)

Graduate students: B. Anderson (PhD)*, C. Brant (PhD)*, C. Fitzgerald (Ashton Mining), K. Heft (Mineral Exploration consultant), A. Klumb (Mineral Exploration consultant), H. Paul (IODP Technician), T. Kirshner (MSc), K. Zoeller*.

Postdoctoral Advisor for: A. Barker (Assist. Professor, Uppsala Universitet).

Marguerite Godard **Geochemistry**
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Senior Researcher CNRS
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Tel : + (0) 467 14 36 03
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DEGREES :
1993 : Thèse de Doctorat « Physique et chimie de la Terre » (PhD), Univ. Montpellier 2, France.
2010 : Habilitation à Diriger les Recherches « Sciences de l'Univers », Univ. Montpellier 2, France.

POSITIONS :
1990-1993: Fellowship, French Ministry of Research and Technology, Univ. Montpellier 2, France.
1994: Associate Researcher, Water ResourceS Research Unit, University of Newcastle, UK.
1994-today: Chargée de Recherche CNRS (1994-2012), Directeur de Recherche CNRS (2012-…) Univ. Montpellier 2, France

PROFESSIONAL ACTIVITIES, TEACHING, SYNERGISTIC ACTIVITIES AND SERVICES

• Co-chair of IODP/ICDP workshop "Geological carbon capture & storage in mafic and ultramafic rocks" (2011); Chair of WG "CO_2 sequestration" at conference on IODP New Ventures in Exploring Scientific Targets (2009).
• Participation to Scientific Drilling proposals: IODP Proposal 758-Full2 "Serpentinization and life: Biogeochemistry and tectono-magmatic processes in young mafic and ultramafic seafloor" – PI: G. Frueh-Green (status : sent to OTF); ICDP Workshop "Oman Ophiolite Drilling Project" – PI : P. Kelemen (status : accepted).
• Co-chair of sessions at EGU, AGU and Goldschmidt conferences; Invited speaker at EGU; lecturer at ECORD summer school.
• Member of the governing board for Doctoral Studies SIBAGHE, Université Montpellier 2 (2011-…); Co-direction of the Master of Geology, Université Montpellier 2 (2003 -2007).
• Teaching in Master Courses (12h/year); Supervision of 10 Master (DEA) research projects – Université Montpellier 2 (1998-…).
• Supervision and participation to the supervision of 6 PhD projects.
• Referee for: INSU, ANR & NSF research proposals and manuscripts submitted to *Earth and Planetary Science Letters, Geochimica et Cosmochimica Acta, Swiss Journal of Geosciences, G-cubed, Terra Nova, Journal of Petrology, Journal of Asian Earth Sciences, Journal of Greenhouse Gas Control, Lithos.*

Publications *(http://www.researcherid.com/rid/A-7127-2008)*: **34**
Meetings: 102

PUBLICATIONS (2008-2012)

Godard, M., Lagabrielle, Y., Alard, O. and Harvey, J., **2008**, Geochemistry of the highly depleted peridotites drilled at ODP Sites 1272 and 1274 (Fifteen-Twenty Fracture Zone, Mid-Atlantic Ridge): Implications for mantle dynamics beneath a slow spreading ridge. *Earth Planet. Sci. Lett.*, 267(3-4): 410-425, doi:10.1016/j.epsl.2007.11.058.

Andreani, M., Luquot, L., Gouze, P., Godard, M., Hoise, E. and Gibert, B., **2009**. Experimental study of carbon sequestration reactions controlled by the percolation of CO_2-rich brine through peridotites. *Environ. Sci. Technol.*, 43(4): 1226-1231; doi: 10.1021/es8018429.

Drouin, M., Godard, M., Ildefonse, B., Bruguier, O. and Garrido, C., **2009**. In situ geochemistry of olivine-rich troctolites (IODP Hole U1309D, Atlantis Massif, Mid-Atlantic Ridge, 30°N): a record of magmatic impregnation in the lower oceanic lithosphere. *Chem. Geol.*, 264: 71-88, doi:10.1016/j.chemgeo.2009.02.013.

Godard, M., Awaji, S., Hansen, H.-E., Hellebrand, E., Brunelli, D., Johnson, K.T.M., Yamasaki, T., Maeda, J., Abratis, M., Christie, D., Kato, Y., Mariet, C. and Rosner, M., **2009**. Geochemistry of a long in-situ section of intrusive slow-spread lithosphere: Results from IODP Site U1309 (Atlantis Massif, 30°N Mid-Atlantic-Ridge). *Earth Planet. Sci. Lett.*, 279: 110-122, doi:10.1016/j.epsl.2008.12.034.

Lorand, J.-P., Alard, O. and Godard, M., **2009**. Platinum-group element signature of the Primitive Mantle rejuvenated by melt-rock reactions : evidence from Sumail peridotites (Oman Ophiolite). *Terra Nova*, 21(1): 35-40, doi: 10.1111/j.1365-3121.2008.00850.x.

Marchesi, C., Garrido, C., Godard, M., Belley, F. and Ferré, E., **2009**. Migration and accumulation of ultra-depleted subduction-related melts in the Massif du Sud ophiolite (New Caledonia). *Chem. Geol.*, 266: 180–195. doi:10.1016/j.chemgeo.2009.06.004.

Deschamps, F., Guillot, S., Godard, M., Chauvel, C., Andreani, M. and Hattori, K., **2010**. In situ characterization of serpentinites from forearc mantle wedges: Timing of serpentinization and behaviour of fluid-mobile elements in subduction zones. *Chem. Geol.*, 269(3-4): 262-277; doi:10.1016/j.chemgeo.2009.10.002.

Hanghoj, K., Kelemen, P., Hassler, D. and Godard, M., **2010**. Composition and genesis of depleted mantle peridotites from the Wadi Tayin massif, Oman ophiolite. Major and trace element geochemistry, and Os isotope and PGE systematics. *J. Petrol*, 51(1&2), 201-227, doi:10.1093/petrology/egp077.

Drouin, M., Ildefonse, B. and Godard, M., **2010**. A microstructural imprint of melt impregnation in slow-spread lithosphere: olivine-rich troctolites from the Atlantis Massif (Mid-Atlantic Ridge 30°N, IODP Hole U1309D). Geochem. Geophys. Geosyst. 11, Q06003, doi:10.1029/2009GC002995.

Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., Abe, N., Abratis, M.W., Andal, E.S., Andreani, M., Awaji, S., Beard, J.S., Brunelli, D., Charney, A., Christie, D., Delacour, A.G., Delius, H., Drouin, M., Einaudi, F., Escartin, J., Frost, B.R., Fryer, P.B., Gee, J.S., Godard, M., Grimes, C.B., Halfpenny, A., Hansen, H.-E., Harris, A.C., Tamura, A., Hayman, N.W., Hellebrand, E., Hirose, T., Hirth, J.G., Ishimaru, S., Johnson, K.T.M., Karner, G.D., Linek, M., Maeda, J., Mason, O.U., MacLeod, C.J., McCaig, A.M., Michibayashi, K., Morris, A., Nakagawa, T., Nozaka, T., Rosner, M., Searle, R.C., Suhr, G., Tominaga, M., von der Handt, A., Yamasaki, T. and Zhao, X., **2011**. Drilling constraints on lithospheric accretion and evolution at Atlantis Massif, Mid-Atlantic Ridge 30°N. J. Geophys. Res., 116(B07103): doi:10.1029/2010JB007931.

Deschamps, F., Guillot, S., Godard, M., Andreani, M. and Hattori, K., **2011**. Serpentinites act as sponges for fluid-mobile elements in abyssal and subduction zone environments. Terra Nova: doi: 10.1111/j.1365-3121.2011.00995.x.

Debret, B., Nicollet, C., Andreani, M., Schwartz, S., Godard, M., **2012**. Three steps of serpentinization in an eclogitized oceanic serpentinization front (Lanzo Massif - Western Alps). J. Metam. Pet., doi:10.1111/jmg.12008.

Deschamps, F., Godard, M., Guillot, S., Chauvel, C., Andreani, M., Hattori, K., Wunder, B., France, L., **2012**. Behavior of fluid-mobile elements in serpentines from abyssal to subduction environments: Examples from Cuba and Dominican Republic. Chem. Geol. 312, 93-117.

Lafay, R., Deschamps, F., Schwartz, S., Guillot, S., Godard, M., Nicollet, C., ***in press***. High-pressure serpentinites, a trap-and-release system controlled by metamorphic conditions: Example from the Piedmont zone of the western Alps. Chem. Geol.

Lissenberg, C.J., MacLeod, C.J., Howard, K.A., Godard, M., ***in press***. Pervasive Reactive Melt Migration Through Fast spreading Lower Oceanic Crust (Hess Deep, equatorial Pacific Ocean). Earth Planet. Sci. Lett.

Biographical Sketch

Steven L. Goldstein

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(A) Professional Preparation:

BA	Columbia University, New York, NY	Chemistry	1976.
MA	Harvard University, Cambridge, MA	Geological Sciences	1978.
PhD	Columbia University, New York, NY	Geological Sciences	1986.

(B) Appointments:

2005- present	Professor, Columbia University.
1998- 2005	Associate Professor, Columbia University.
1996-98	Assistant Professor, Department of Earth and Environmental Sciences, Columbia University, Palisades, NY 10964.
1985-96	Staff Scientist, Max-Planck-Institut für Chemie, Mainz, Germany.

(C) Publications

(i) Five recent mantle geochemistry publications

Straub, S,M., Goldstein, S.L., Class, C., and Schmidt, A., "Mid-ocean ridge basalt of Indian type in the northwest Pacific Ocean basin", Nature Geoscience, 2, 286-289, 2009.

Class, C., Goldstein, S.L., and Shirey, S.B., "Osmium isotopes in Grande Comore lavas: a new extreme among a spectrum of EM-type endmembers" Earth and Planetary Science Letters, 284, 219-227, 2009.

Goldstein, S.L., Soffer, G., Langmuir, C.H., Lehnert, K.A., Graham, D.W., and Michael, P.J., "Origin of a 'Southern Hemisphere' geochemical signature in the Arctic upper mantle", Nature 453, 89-93; doi:10.1038/nature06919, 2008.

Zhang, H.F., Goldstein, S.L., Zhou, X-H., Sun, M., Zheng, J.-P., Cai, Y., "Transformation of ancient sub-continental lithospheric mantle beneath Archean blocks, eastern China: Re-Os isotopic evidence from mantle xenoliths of Paleozoic kimberlites and Mesozoic basalts", Contributions to Mineralogy and Petrology 155, 271-293, 2008.

Class, C. and Goldstein, S.L., "Evolution of helium isotopes in the Earth's mantle", Nature, 436, 1107-1112, 2005.

(ii) Five other recent publications

Cole, J.M., Goldstein, S.L., deMenocal, P.B., Hemming, S.R., and Grousset, F.E., "Contrasting compositions of Saharan dust in the eastern Atlantic Ocean during the last deglaciation and African Humid Period, Earth and Planetary Science Letters, 278, 257-266, 2009.

Pahnke, K., Goldstein, S.L., and Hemming, S.R. "Abrupt changes in Antarctic Intermediate Water circulation over the past 25,000 years", Nature Geoscience, 1, 870-874, 2008.

van de Flierdt, T., Goldstein, S.L., Hemming, S.R., Roy, M. Frank, M., and Halliday, A.N., "Global neodymium-hafnium isotope systematics–revisited", Earth and Planetary Science Letters, 259, 432-441, 2007.

Thompson, W.G. and Goldstein, S.L. "Open system coral ages reveal persistent suborbital sea-level cycles", Science, 308, 401-404, 2005.

Piotrowski, A.M., Goldstein, S.L., Hemming, S.R., and Fairbanks, R.G., "Temporal relationships between ocean circulation and carbon cycling during glacial-interglacial transitions", Science 307, 1933-

1938, 2005.

(D) Synergistic Activities:

Journal Editor: Chemical Geology, Editorial Advisory Board (1990-2002); Earth and Planetary Science Letters, Editorial Advisory Board (1991-present); Journal of Geophysical Research-Solid Earth, Associate Editor (1995-1997), Geochimica et Cosmochimica Acta, Associate Editor (2000-2002), Chemical Geology, Editor-in-Chief (2002-2008).

Professional Service: AGU Hess Medal Committee (1998-1999). Co-Organizer: *ICDP Workshop on a Deep Drill Hole in the Dead Sea*, 2002; *Workshop on Curation of Terrestrial Scientific Cores, Samples, and Collections*, Houston, 2004; *Workshop on Linking Information Systems in Marine and Terrestrial Geosciences: Sediment Geochemistry*, Washington, D.C., June 2004, '*SESAR: Designing Interoperability for Sample-based Data Management via the International Geo Sample Number IGSN*', San Diego; *GERM (Geochemical Earth Reference Model) Workshop*, New York, 2006. Oversight Committee, Northeast National Ion Microprobe Facility (NENIMF), 2004-present; AGU VGP Nominations Committee, 2009-present; Visiting Committee, Korean Basic Science Institute, 2010; Chair or Vice Chair, Dept. of Earth and Environmental Sciences, Columbia University, 2006-2012.

Teacher Education: Goldstein, S.L. "Hawaii and hotspots; a window to the deep mantle" in "Earth; Inside and Out", ed. by E. Mathez, New Press. New York, NY, p. 93-99; essays on the Earth for K-12 teachers; 2001. Lecturer, Earth2Class Program for K-12 teachers.

Undergraduate Research: Advisor for LDEO Summer Intern Program and Columbia undergraduates (1996-present).

Public Outreach: Lamont-Doherty Earth Observatory Annual Open House (1996-present), public lectures laboratory tours and demonstrations; geological field trips for Boy Scouts; Columbia University Alumni Association Lectures, Lamont-Doherty Earth Observatory Public Lecture Series, Public School Lectures on Earth Science, Science Clubs in Retirement Communities, lecturer in Earth2Class Program middle and high school teachers.

(E) Collaborators and Other Affiliations:

(i) Collaborators Over the Past Four *Years*: *B. Haley (OSU), M. Dungan (U Oregon), E. Ito (U Minn.); C. Langmuir (Harvard), K. Pahnke (Max-Planck Inst., Oldenburg), H. Scher (U S. Carolina), M. Stein (Geol. Survey of Israel).*

(ii) Graduate Advisors: *R.K. O'Nions (Pres., Imperial Coll.), C. Langmuir (Harvard), A. Zindler.*

(iii) Primary thesis advisor to the following graduate students:

At MPI: *C. Class (LDEO), K. Haase (U of Erlangen), A. Haase-Schramm (private sector); G. Loock (3 women, 1 man).*

At Columbia: *Y. Cai (LDEO), K. Jones (Exxon-Mobil), A. Hartman (PhD student, Columbia U), J. Jweda (PhD student, Columbia U), W. Jacobson (Ph.D. student, Columbia U), A. LaGatta (Adjunct Professor, St. Mary's College, California), A. Piotrowski (Lecturer, Cambridge U), R. Rutberg (Associate Professor, Hunter College, CUNY), K. Simons (Exxon-Mobil), W. Thompson (Associate Scientist, WHOI), Y. Wu (PhD student, Columbia U). (6 women, 5 men).*

Curriculum Vitae – Philippe Gouze
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PROFESSIONAL PREPARATION:
1989 M.Sc., Université de Montpellier, Centre de Geology et Geophysique
1993 Ph.D. degree (modelling transport in porous media) University of Paris VI

APPOINTMENTS:
1994 EC grant (Postdoc), *Water Resource Systems Research Unit*, Department of Civil Engineering, University of Newcastle upon Tyne, UK,
1995 – present CNRS researcher at the University of Montpellier.
2003-2006 Vice-director of the *Tectonophysic* research Unit (CNRS UMR 5568)
2010 – present Head of the *Transport in Porous Media* group at *Geosciences Montpellier* research Unit (CNRS UMR 5243).

5 publications most closely related to this proposal, 2008-2010:

Andreani M., P. Gouze, L. Luquot, P. Jouanna (2008), Changes in seal capacity of fractured claystone caprocks induced by dissolved and gaseous CO2 seepage, Geophys. Res. Lett., 35, L14404, doi:10.1029/2008GL034467.
Andreani M., L. Luquot, P. Gouze, M. Godard, E. Hoisé, B. Gibert (2009) Experimental study of carbon sequestration reactions controlled by the percolation of CO2-rich brine through peridotites, Environ. Sci. Technol., 43 (4), pp 1226–1231
Gouze P., Y. Melean, T. Le Borgne, M. Dentz, J. Carrera (2008), Non-Fickian dispersion in porous media explained by heterogeneous microscale matrix diffusion, Water Resour. Res., 44, W11416, doi:10.1029/2007WR006690.
Gouze P. and L. Luquot (2011), On the characterization of porosity-permeability relationships and reactive surface areas during heterogeneous dissolution induced by CO2 injection in limestone reservoir, Journal of Contaminant Hydrology, 120–121, 45–55, doi:10.1016/ j.jconhyd.2010.07.004.
Luquot L., P. Gouze (2009) Experimental determination of porosity and permeability changes induced by massive injection of CO_2 into carbonate reservoirs, Chemical Geology 265, 148–159, doi:10.1016/j.chemgeo.2009.03.028.

REASEARCH ACTIVITIES

1. Groundwater hydrology. This includes conceptual, mathematical and numerical modelling of groundwater flow and contaminant transport in heterogeneous aquifers, sea water intrusion into coastal aquifers, pumping tests to determine aquifer coefficients, (non-Fickian) dispersion measurements from laboratory to borehole scale, flow and transport in fractures, and borehole geophysics for application to hydrogeology.

2. Fluid-rock mass transfer in reservoir. This research focuses on experimental characterization and modelling hydrodynamical properties (porosity, permeability, reaction surface area) changes induced by dissolution-precipitation processes in the course of reservoir diagenesis and underground CO2 storage, with emphasis on carbonation processes.

3. Geothermal energy & hydrothermal processes in low enthalpy environments. This includes laboratory scale experimental characterization and modelling of flow, transport and fluid-rock-gas reactions

associated with natural hydrothermal cycles at the mid-ocean ridges and forced borehole extraction of heat in geothermal areas (ex: Iceland).

4. Diffusion in low permeability media, for applications to nuclear waste disposal in claystones. This research concerns for example the measure of diffusion coefficient and sorption of the radioelements (iodine) in natural conditions.

5. Microstructure and macroscopic properties of heterogeneous materials. This research focuses on the development of numerical tools for deterministic and statistical characterization of the heterogeneity from X-ray micro-tomography imagery.

COLLABORATORS : M. Dentz, R. Carrera, L. Luquot (CSIC, SP); A. Guadagnini (Politechnico di Milan, IT), A. Neimi (Upsala University, S); J. Bensabat (EWRE, IS); S. Savoye (CEA, FR), C. Wittebroodt (IRSN, FR), J. Bear (Technion, IS); S. Gilfillan, C. McDermott (U. Edinburg); P. Besse (Bureau Veritas, FR); O. Silva (CIUEDEN, SP); R. Zimmerman, A. Gringarten (Imperial College, UK); A. Hauradou (FAST, FR); M. Andréani (U. Lyon, FR); P. Benezeth, O. Pokrovsky (U. Toulouse, FR); B. Menez (IPGP, FR); P. Kelemen, J Mattre (DEO, US); D. Tartakovsky (UCSD, US); I. Battiato (Clemson U., US); P. Lichtner (LANL, US); M. Lescane (TOTAL, FR); T. Dutta (U. Kolkata Jadavpur, IN); D. Guerillot, J. Nunes (Petrobras, BR);

ON-GOING PROJECT closely related to this proposal:
FP7-MUSTANG, A multiple space and time scale approach for the quantification of deep saline formations for CO2 storage (2009 -2013);
FP7-PANACEA, Predicting and monitoring the long-term behavior of CO2 injected in deep geological formations (2011-2014);
FP7 TRUST, High resolution monitoring, real time visualization and reliable modeling of highly controlled, intermediate and up-scalable size pilot injection tests of underground storage of CO2 (2012-2015);

MEETING CONVENOR : December 2011, AGU, December 2012, AGU,

GOUZE'S ADVISORS: Professor G. de Marsily (college de France); Professor R. Carrera (CSIC Barcelone Darcy's Medial).

ADVISOR:
PhD: Alain Cartalade (-2001), Catherine Noiriel (-2005), Sandra Tenchine (-2004), Linda Luquot (-2007), Charles Wittebrodt (-2010) Charlotte Garing (-2011); Halidi Abdoulgafour (-2012), Mohamed Kassab (Collaboration Polytechn. Milan, -2011); Ousmane Papa Mangane (-), Filip Gjevaj (-), Ikram Fatnassi (-)
PostDoc: Muriel Andréani (2007-2008), Yasmin Melean (2004-2006), Linda Luquot (2009-2011), Jallal Dweik (2010- 2011), Olivier Rodriguez (2010-2011), C. Garing (2011-), S. Sadhukhan (2011-), C. Blitz (2012-), A. Russian (2012-).

GREG HIRTH

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Experience:

Brown University, Department of Geological Sciences
2010-present Professor 2007-2009 Associate Professor
2002-2007 Adjunct Associate Professor

Woods Hole Oceanographic Institution, Department of Geology and Geophysics
1998-2007 Associate Scientist (Tenured in 2001) 1994-1998 Assistant Scientist 1993 Postdoctoral Scholar

Rice University, Department of Earth Science
Spring 2010 Weiss Visiting Professor

University of Montpellier, Laboratoire de Tectonophysique
Spring 2007 Visiting Scientist

Massachusetts Institute of Technology, Dept. Earth, Atmospheric, and Planetary Sciences
1993-2007 Research Affiliate,

California Institute of Technology, Division of Geological and Planetary Sciences Fall 1999 Visiting Professor of Geophysics,

University of Minnesota, Dept. of Geology and Geophysics
1991-1992 Postdoctoral Research Associate

Brown University, Department of Geological Sciences
1985-1991 Graduate Research Assistant

Education:

Ph.D. Geological Sciences, Brown University, 1991 Sc.,
M. Geological Sciences, Brown University, 1987
B.S. Geological Sciences, Indiana University, 1985

Professional and Synergistic Activities:

Fellow MSA (2006) and AGU (2008) Panelist, NSF MARGINS (OCE), 2000; Tectonics (2001-2004) Co-convener, Rock Deformation GRC 2008 President-Elect, Tectonophysics Section, AGU, 2010-present Co-convener, Earthscope Institute on the Lithosphere-Asthenosphere Boundary, 2011

Five publications relevant to proposed research

Homburg, J.M., G. Hirth and P.B. Kelemen, Investigation of the strength contrast at the Moho: A case study from the Oman Ophiolite, *Geology*, 38, DOI:10.1130/G30880.1, 679-682, 2010.

Roland, E., M. Behn and G. Hirth, Thermal-mechanical behavior of oceanic transform faults- Implications for the spatial distribution of seismicity, *Geochemistry, Geophysics, and Geosystems (G-cubed),* 11, Q07001, DOI: 10.1029/2010GC003034, 2010.

Kelemen, P.B., and G. Hirth, Reaction-driven cracking during retrograde metamorphism: Olivinehydration and carbonation, *Earth Planet. Sci. Lett.*, vol 345-348, 81-89, http://dx.doi.org/10.1016/j.epsl.2012.06.018, 2012.

Mehl, L., and G. Hirth, Plagioclase recrystallization and preferred orientation in layered mylonites: Evaluation of flow laws for the lower crust, *J. Geophys. Res.*, 113, B05202, doi:10.1029/2007JB005075, 2008.

deMartin, B., G. Hirth, B. Evans, Experimental Constraints on Thermal Cracking of Peridotite at Oceanic Spreading Centers, in J. Lin, ed., *The Thermal Structure of the Oceanic Crust and Dynamics of Hydrothermal Circulation*, Geophysical Monograph 148, American Geophysical Union, Washington, D.C., 148, 167-185, 2004.

Five other recent publications

Kohli, A. H., D. L. Goldsby, G. Hirth, and T. E. Tullis, Flash weakening of serpentinite at near-seismic slip rates, *J. Geophys. Res.*, doi:10.1029/2010JB007833, 116, B03202, 2011.

Hirth, G., and D. Kohlstedt, Rheology of the Upper Mantle and the Mantle Wedge: A View From the Experimentalists, in Inside the Subduction Factory, John Eiler (ed.), Geophysical Monograph 138, 83-105, American Geophysical Union, Washington, D.C., 2003.

Freed, A.M, G. Hirth, and M.D. Behn, Using short-term postseismic displacements to infer the ambient deformation conditions of the upper mantle, *J. Geophys. Res.*, 117, B01409, doi:10.1029/2011JB008562, 2012.

Chernak, L., G. Hirth, J. Selverstone, and J. Tullis, The effect of aqueous and carbonic fluids on the dislocation creep strength of quartz, *J. Geophys. Res.*, 114, B04201, doi:10.1029/2008JB005884, 2009.

Boettcher, M., G. Hirth, and B. Evans, Olivine friction at the base of oceanic seismogenic zones, *J. Geophys. Res.*, 112, B01205, doi:10.1029/2006JB004301, 2007.

Graduate Advisor: Jan Tullis, Brown University

Postdoctoral Advisor: David Kohlstedt, University of Minnesota

Collaborators (non-Brown Univ., last 48 months): G. Abers (Lamont), M. Behn (WHOI), J.Collins (WHOI), J. Escartin (IPG Paris), B. Evans (MIT), R. Evans (WHOI), A. Freed (Purdue), J.Gaherty (Lamont), B. Hacker (UCSB), B. Hager (MIT), B. Holtzman (Lamont), P. Kelemen(Lamont), D. Kohlstedt (U. Minn.), D. Lizarralde (WHOI), P. Molnar (U. Colorado), A. Sheehan (U. Colorado), H. Stuntiz (Tromso), C. Teyssier (U. Minn), D. Whitney (U. Minn). **Students, Post-docs and recent collaborators (last 48 months):** W. Behr (U. Texas), M. Billen (UC Davis), M. Boettcher (UNH), M. Braun (ExxonMobil), L. Chernak (U. Rochester), B. deMartin (ExxonMobil), J. Escartin (IPG Paris), E. Goergen (FEI), J. Homburg (ExxonMobil), J.Hustoft, G. Jaroslow (SEA), A. Kohli (Stanford), L. Mehl (Alaska Pacific Univ.), L. Montesi (Maryland), J. Muto (Tohoku U.), J. Pikser (Lamont), J. Precigout (ETH), E. Roland (USGS), P Skemer (WUSTL), M. Sundberg (ExxonMobil), J. Warren (Stanford), W. Zhu (Maryland).

Curriculum Vitae

Albrecht Werner Hofmann

Date of birth: 11 March 1939 in Zeitz (Germany)

Marital status: Married, 2 children

Citizenship: German

Education:
- Elementary: 1945-46 Schlitz (Germany); 1946-49 Stuttgart
- Secondary: 1949-52 Stuttgart; 1952-58 Ravensburg
- University: 1958-59 Duke University, Durham, North Carolina, USA; 1959-62 Universität Freiburg i.Br., Germany; 1962-68 Brown University, Providence, R.I., USA
  - 1965 M.Sc.
  - 1968 Ph.D. Major: Geochemistry, minors mineralogy and thermodynamics (advisor B.J. Giletti).

Professional Career:

1968-70	Assistant, Laboratorium für Geochronologie, Heidelberg
1970-72	Postdoctoral Fellow, Geophysical Laboratory, Carnegie Institution of Washington
1972-80	Scientific Staff Member, Department of Terrestrial Magnetism, Carnegie Institution of Washington
1980-2007	Director, Geochemistry Division, Max-Planck-Institut für Chemie, Mainz
1987-	Adjunct professor at the University of Mainz
1989-91; 98-2000	Managing Director of the Max-Planck-Institut für Chemie.
Since 04/07	Max Planck Emeritus Visiting Senior Research Scientist at Lamont-Doherty Earth Observatory, Columbia University, New York. Adjunct Professor at the University of Nanjing, China.

Honors:

1987	Jaeger-Hales Lectureship at the Australian National University;
1994	Fellow of the American Geophysical Union;
1994	Chevalier de l'Ordre des Palmes Académiques;
1995	Sherman-Fairchild Scholarship at California Institute of Technology;
1996	MESR/Humboldt Award of the Ministère de l'Enseignement Supérieur et de la Recherche and the Alexander-von-Humboldt-Foundation;
1996	V.M. Goldschmidt Medal of the Geochemical Society;
1996	Geochemistry Fellow of the European Association of Geochemistry and the Geochemical Society.
1999	U.S. National Academy of Sciences (Foreign Associate)
1999	Fellow of the Geological Society of America
2001	Harry H. Hess Medal of the American Geophysical Union
2003	ISI "Highly Cited Researcher" in Geoscience
2010	Hamilton Visiting Scholar, Southern Methodist University, Dallas, Texas.

2011 Horace Mann Medal by Brown University, Providence, Rhode Island.

Editing (at various times):

Chemical Geology, Editor;
Geochimica et Cosmochimica Acta, Associate Editor;
Contributions to Mineralogy and Petrology, Associate Editor.
Editor of "Frontiers Section" of Earth & Planetary Science Letters (2008-09)

Memberships and Offices in scientific organizations:

Max-Planck-Gesellschaft, Member;
European Union of Geosciences , Founding Council Member, President 1997-99;
European Association of Geochemistry, President 1999-2000;
Geochemical Society, Member, Member of Board of Directors 1998-2001;
American Geophysical Union, Member;
Geological Society of America, Member;
Deutsche Mineralogische Gesellschaft, former Council Member;
Geologische Vereinigung, former Council Member
Forschungskollegium Geochemie e.V., Founder and Member;
Forschungskollegium Mineralogie, Member;
Comité Scientifique, France (Member 1989-1993).

Service in Committees: Member of visiting/evaluation committees at:

ETH Zurich
Harvard University,
Wood Hole Oceanographic Institute,
U.S. Geological Survey in Washington,
Department of Terrestrial Magnetism of the Carnegie Institution of Washington,
University of Munich,
GEOMAR (University of Kiel, Germany),
University of Bremen, Germany;
Member and chairman of AGU Fellows Committee,
Member and chairman of the Harry Hess Medal Committee of the AGU, 2011-2012
Member of search committee for director to the Department of Terrestrial Magnetism, Carnegie Institution for Science, 2011
Member of medal nominations committee of the Geochemical Society, 2011
Member of the Vetlesen Prize Committee 2004 and 2012
Organized or helped organize two major meetings of the European Union of Geosciences in Strasbourg (1983 and 1999)
Co-organizer of two Goldschmidt Conferences (Heidelberg 1996 and Cologne 2006) and several smaller conferences such as Mantle Plume conferences in Schloss Ringberg, Germany, and in Hawaii.

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Education :
• 2002 : "Habilitation à diriger des recherches", Université Montpellier 2
• 1987 : "Thèse de doctorat" (PhD), Université Lyon 1
• 1985 : DEA Pétrologie et Minéralogie. Université Lyon I

Academic employment :
• 2008-present : "Directeur de Recherches" (Senior Research Scientist) CNRS, France
• 1991-2008 : "Chargé de Recherches" CNRS, France
• 1989-1991 : Swiss National Fond fellowship, ETH Zürich, Switzerland

Main research topic :
Formation and evolution of the oceanic lithosphere

Scientific animation, management, and outreach
• Head of "Manteau & Interfaces" Research Team in CNRS UMR5243 (Géosciences Montpellier) (2011-)
• Member of French "Commission Nationale Flotte Hauturière" (2011-)
• Member of ISSEP (1999-2002), SciCom et ExCom (2003), iPC/SPC (2003-2006), OTF (2005-2006), ESSAC (2003-2010) in ODP & IODP; alternate member of SASEC (2007-2011)
• Chairman of IODP-France (Oct 2003-2010); Vice-chairman of ODP-France (Oct 2001-2003)
• Chairman of InterRidge "Deep Earth Sampling" Working Group (2004-2010)
• Lead Proponent of "Mission Moho" proposal (2007; http://missionmoho.org)
• Co-Lead Proponent of "MoHole to the Mantle" proposal (2012; http://mohole.org)
• ECORD Distinguished lecturer, 2007-2008, 2013-2014
• Co-chairman/organizer of workshops:
  - "Mission Moho", Portland, Oct. 2006 (http://missionmoho.org)
  - "Melting, Magma, Fluids and Life", Southampton, July 2009 (http://www.interridge.org/WG/DeepEarthSampling/workshop2009)
  - "The MoHole, a crustal journey and mantle quest", Kanazawa, June 2010 (http://mohole.org)
• Steering Committees:
  - IODP-DCO "Reaching the Mantle Frontier" Workshop, Carnegie Inst., Washington DC (2010; https://dco.gl.ciw.edu/september2010mohoworkshop)
  - Geologic carbon capture and storage in mafic and ultramafic rocks. IODP/ICDP Workshop, Suktan Qaboos University, Oman (2011; http://ccs-oman2011.org/)
  - ICDP-DCO Workshop : Oman Drilling project, Palisades, New York (2012, https://dco.gl.ciw.edu/icdp-workshop-oman-drilling-project)
  - CHIKYU+10 Steering Committee (2012-)

Fieldwork and Cruises
• 1985 to 1990 : Fieldwork in Italian and French Alps
• 1991 to 1999, 2007-2008 : Fieldwork in the Oman Ophiolite
• 1997 and 2003: ODP Legs 176 and 209 (D/V JOIDES Resolution)
• 2000 : MANAUTE cruise (R/V L'Atalante + Nautile). Manus Basin. New Starmer Program.
• 2001 : SWIFT cruise (R/V Marion Dufresne). SouthWest Indian Ridge
• 2005 : IODP Expedition 305 (D/V JOIDES Resolution), *Co-chief Scientist*

• 2007 : MoMAR-DREAM cruise (R/V Pourquoi Pas ? + Nautile). MAR, Rainbow Massif
• 2008 : JC21 cruise (RRS James Cook + ROV Isis). Sampling & mapping at Hess Deep
• 2008 : MoMAR−DREAM 2 cruise (R/V Atalante + ROV Victor). MAR, Rainbow Massif
• 2011 : IODP Expedition 335 (D/V JOIDES Resolution), *Co-chief Scientist*
• 2012-2013 : IODP Expedition 445 (D/V JOIDES Resolution)

Selected recent publications
Complete list at: http://www.researcherid.com/rid/A-6205-2009

• Violay, M., Pezard, P. A., ildefonse, B., Célérier, B., & Deleau, A., **2012**. Structure of the hydrothermal root zone of the sheeted dikes in fats-spread oceanic crust: a core-log integration study of ODP Hole 1256D, Eastern Equatorial Pacific. Ofioliti, 37, 1-11. doi:10.4454/ofioliti.v37i1.402
• Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists, **2012**. Proc. IODP, 335: Tokyo (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.335.2012
• Koepke, J., France, L., Mueller, T., Faure, F., Goetze, N., Dziony, W., and Ildefonse, B., **2011**. Gabbros from IODP Site 1256 (Equatorial Pacific): Insight into axial magma chamber processes at fast-spreading ocean ridges, Geochem. Geophys. Geosyst., 12, Q09014, doi:10.1029/2011GC003655
• Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., and IODP 304-305 Science Party, **2011**. Drilling Constraints on Lithospheric Accretion and Evolution at Atlantis Massif, Mid-Atlantic Ridge 30°N. J Geoph. Res., 116, B07103, doi:10.1029/2010JB007931
• Lartaud, F., Little, C.T.S., de Rafelis, M., Bayon, G., Dyment, J., Ildefonse, B., Gressier, V., Fouquet, Y., Gaill, F., Le Bris, N., **2011**. Fossil evidence for serpentinization fluids fueling chemosynthetic assemblages. Proceedings of the National Academy of Sciences of the United States of America 108, 7698-7703. doi:10.1073/pnas.1009383108
• Teagle, D., and Ildefonse, B., **2011**. Journey to the Mantle of the Earth, Nature, 471, 437-439. doi:10.1038/471437a
• Drouin, M., B. Ildefonse, and M. Godard, **2010**. A microstructural imprint of melt impregnation in slow spreading lithosphere: Olivine-rich troctolites from the Atlantis Massif, Mid-Atlantic Ridge, 30°N, IODP Hole U1309D, Geochem. Geophys. Geosyst., 11, Q06003, doi:10.1029/2009GC002995.
• France L, Ildefonse B, Koepke J, Bech F, **2010**. A New Method to Estimate the Oxidation State of Basaltic Series from Microprobe Analyses. Journal of Volcanology and Geothermal Research.189, 340-346. doi:10.1016/j.jvolgeores.2009.11.023
• France, L., Koepke, J., Ildefonse, B., Cichy, S.B., and Deschamps, F., **2010**. Hydrous partial melting in the sheeted dike complex at fast spreading ridges: experimental and natural observations. Contrib. Mineral. Petrol., 160(5): 683-704. doi:10.1007/s00410-010-0502-6
• Ildefonse, B., Abe, N., Blackman, D.K., Canales, J.P., Isozaki, Y., Kodaira, S., Myers, G., Nakamura, K., Nedimovic, M., Skinner, A.C., Seama, N., Takazawa, E., Teagle, D.A.H., Tominaga, M., Umino, S., Wilson, D.S., and Yamao M., **2010**. The MoHole: A Crustal Journey and Mantle Quest, Workshop in Kanazawa, Japan, 3–5 June 2010. Scientific Drilling, 10, 56-62. doi:10.2204/iodp.sd.10.07.2010
• Violay, M., Pezard, P.A., Ildefonse, B., Belghoul, A., Laverne, C., **2010**. Petrophysical properties of the root zone of sheeted dikes in the ocean crust: A case study from Hole ODP/IODP 1256D, Eastern Equatorial Pacific. Tectonophysics, 493, 139–152. doi:10.1016/j.tecto.2010.07.013
• Beard J.S., Frost B.R., Fryer P., McCaig A., Searle R., Ildefonse B., Zinin P., and Sharma S.K., **2009**. Onset and progression of two-stage serpentinization and magnetite formation in olivine-rich troctolite from IODP Hole U1309D. J. Petrol. 50, 387-403. doi:10.1093/petrology/egp004
• Drouin, M., Godard, M., Ildefonse, B., Bruguier, O., and Garrido, C., **2009**. Geochemical and petrographic evidence for magmatic impregnation in the oceanic lithosphere at Atlantis Massif, Mid-Atlantic Ridge (IODP Hole U1309D, 30°N), Chemical Geology. doi:10.1016/j.chemgeo.2009.02.013
• France, L., Ildefonse, B., and Koepke, J., **2009**. Interactions between magma and hydrothermal system in Oman ophiolite and in IODP Hole 1256D: fossilization of a dynamic melt lens at fast spreading ridges. Geochem. Geophys. Geosyst. doi:10.1029/2009GC002652
• Mainprice, D., and Ildefonse, B., **2009**. Seismic anisotropy of subduction zone minerals : contribution of hydrous phases. In : Subduction Zone Geodynamics (S. Lallemand & F. Funiciello, eds), 'Frontiers in Earth Sciences' Springer-Verlag Berlin Heidelberg, p. 63-84. doi:10.1007/978-3-540-87974-9
• Ildefonse, B., Blackman, D.K., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and the Expedition 304/305 Scientists, **2007**. Oceanic Core Complexes and Crustal Accretion at Slow-Spreading Ridges. Geology, 35, 623-626. doi:10.1130/G23531A.1

CV Bjørn Jamtveit, Physics of Geological Processes (PGP), University of Oslo
Born 21.09.60 in Notodden, Norway.

a) Professional preparation

PostDoc (1991-1993) Dept of Geology, University of Bristol, UK
PhD, Geology (September 1990) Department of Geology, University of Oslo .
Master of Science, Geology (March 1986) Mineralogical-Geological Museum, University of Oslo. Grades: Thesis:1.2, Oral: 1.2 (top 1%)
Bachelor of Science University of Oslo (1982) Topics: Geology (33 credit points), Chemistry (35 credit points), Mathematics/Physics (20 credit points). Average grades: 1.4 (top 1%)
Military service: 08.07.86 - 07.07.87, Infantry at Terningmoen, Elverum and at the Norwegian Museum of Defence in Oslo.

b) Appointments

2006-:	Director of PGP, a Center of Excellence at the University of Oslo
2003-2006:	Co-director of PGP
2000-2001:	Group leader, Center for Advanced Studies, Norwegian Academy of Science
1993- :	Professor of Petrology, University of Oslo
1991-1993:	Odd Hassel research grant from the Norwegian Research Council to stay at the University of Bristol, UK (In 1991, two such grants were awarded within physical sciences in Norway).
1990-1991:	Post-Doc grant from the Norwegian Research Council, University of Oslo
1987-1990:	PhD grant from the Norwegian Research Council, University of Oslo
1985-1987:	Scientific Assistant, University of Oslo

c) Publications

i) 5 relevant publications

Jamtveit, B, Austrheim, H., and Malthe-Sørensen, A., 2000. Accelerated hydration of the Earth's deep crust induced by stress perturbations. *Nature,* 408, 75-79

Iyer, K., **Jamtveit, B**., Mathiesen, J., Malthe-Sørenssen, A., and Feder, J., 2008, Reaction assisted hierarchical fracturing during serpentinization. *Earth and Planetary Science Letters,* 267, 503-516.

Jamtveit, B., Malthe-Sørenssen, A., and Kostenko, O., 2008, Reaction enhanced permeability during retrogressive metamorphism. *Earth and Planetary Science Letters*, 267, 620-627.

Jamtveit, B., Kobchenko, M., Austrheim, H., Malthe-Sørenssen, A., Røyne, A., and Svensen, H., 2011, Porosity evolution and crystallization-driven fragmentation during weathering. *Journal of Geophysical Research,* B12204, doi:10.1029/2011JB008649

Plümper, O., Røyne, A., Sola, A.M., and **Jamtveit, B**., The interface-scale mechanism of reaction-induced fracturing during upper mantle serpentinization. *Geology* (in press)

ii) Significant publications

Svensen, H., Planke, S., Malthe-Sørenssen, A., **Jamtveit, B**., Myklebust, R., Rasmussen, T; and Rey, S., 2004, Explosive release of methane from volcanic basins. A triggering mechanism for global climate change. *Nature,* 429, 542-545

Hammer, Ø., Dysthe, D.K., **Jamtveit, B**., 2007, The dynamics of travertine dams. *Earth Planet Sci Letters,* 26, 258-263

Malthe-Sørenssen, A., **Jamtveit, B**., and Meakin, P., 2007, Fracture patterns generated by diffusion-controlled volume changing reactions. *Phys. Rev.Letters*, 96, art no. 245501

Røyne, A., **Jamtveit, B**., Mathiesen, J., Malthe-Sørenssen, A., 2009, Controls on weathering rates by reaction induced hierarchical fracturing. *Earth and Planetary Science Letters,* 275, 364-369

Meakin, P., and **Jamtveit, B.,** 2010, Geological pattern formation by growth and dissolution in aqueous systems. *Proceedings of the Royal Society A*, 466, 659-694

Jamtveit, B., and Hammer, Ø., Sculpting of rocks by reactive fluids. *Geochemical*

*Perspectives,*1, No.3, 340-480

d) Synergistic activities

i) Founder of the cross disciplinary research center 'Physics of geological processes' (PGP), a Norwegian Center of Excellence hosted by the University of Oslo. PGP comprises researchers with background from geology, physics, geophysics and applied matemathics. Ca 400 PGP papers have been published in ISI journals since the start in 2003 and currently receive ca 1200 citations/year. PGP also includes a cross-disciplinary Master program and a research school for PhD students. Ca 50 students have graduated from PGP. Ca 50% of these work for Academic institutions in Norway or abroad.

ii) Organizer of the annual Kongsberg seminar; A high quality cross-disciplinary international conference series run yearly since 1994.

iii) Convenor and co-convenor of numerous special sessions at international conferences, including the AGU Fall meeting and the Goldschmidt conferences. Also co-organizer of the 2004 Goldschmidt meeting in Copenhagen. Member of the Board, European Association of Geochemistry (2000-2004)

iv) Have also published on the dynamics of research organizations (cf. **Jamtveit, B**., Jettestuen, E., and Mathiesen, J., Scaling properties of European research units. *PNAS,* 106, 13160-13163 (doi: 10.1073/pnas.0903190106) and Mathiesen, J., **Jamtveit, B**., and Sneppen, K., Organizational structure and communication networks in a university environment. *Physical Review E, 82, 01610)* and has significant competence in the management of research units.

v) Extensive outreach activities, including participation in ca 30 radioprograms, and four Science/Art exhibits + numerous popular papers in Newspapers and magazines during the last 5 years.

e) Collaborators & Other Affiliations

i) Collaborators & Co-editors last 24 months. 20-25 people including:
Austrheim, Haakon, University of Oslo
Feder, Jens, University of Oslo, Norway
Iyer, Karthik, University of Kiel, Germany
Mathiesen, Joachim, Niels Bohr Institute, Copenhagen, Denmark
Meakin, Paul, Idaho National Lab
Putnis, Andrew, University of Münster, Germany
Renard Francois, University of Grenoble, France
Sneppen Kim, Niels Bohr Institute, Copenhagen, Denmark

ii) My own advisor and postdoc
PostDoc sponsor – personal grant from the Norwegian research Council.
Main scientific contact.
Prof. B.J.Wood, University of Bristol
PhD adviser – Prof Kurt Bucher (now Univ of Freiburg, Germany
Master adviser – Prof Willian L Griffin (now at Maquarie university)

iii) Students and postdocs
5 Master students
7 PhD students
15-20 Postdocs

CURRICULUM VITAE
FRIEDER KLEIN

Dept. of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, Phone: (508)-289-3355, E-mail: fklein@whoi.edu

Education:

2003	B.S. (distinction), Geosciences, University of Bremen
2005	Dipl. Geow. (distinction), Geosciences, University of Bremen
2009	Dr. rer. nat. (summa cum laude), Geosciences, University of Bremen

Professional Experience:

Since Oct. 2011	Assistant Scientist, WHOI
2010 – 2011	Visiting Research Associate, Laboratory for Atmospheric & Space Physics
2009 – 2011	Post-doctoral Scholar, WHOI
2009	Post-doctoral Fellow, Instituto Andaluz de Ciencias de la Tierra (IACT), Consejo Superior de Investigaciones Científicas (CSIC), Granada, Spain
2008	Research Fellow, Marum Center for Marine Environmental Sciences, University of Bremen
2005 – 2008	Research Assistant, Geosciences Department, University of Bremen
2002 – 2005	Student Assistant, Geosciences Department and Marum Center for Marine Environmental Sciences, University of Bremen

Professional Affiliations

Geochemical Society, American Geophysical Union, Mineralogical Society of America, European Association for Geochemistry, Deutsche Mineralogische Gesellschaft

Research Interests

Fluid-rock interactions in the Earth's lithosphere
Mineral replacement reactions
Geochemistry and petrology of metamorphic and metasomatic rocks
Applications of spectroscopic techniques, hydrothermal experiments and thermodynamics to study fluid-rock interactions

Cruise participation

R/V Atlantis/Jason II, Mid Cayman Rise, January 2012
R/V Maria S. Merian; North Pond, February 2009
R/V Maria S. Merian/ BGS Rockdrill II; Logatchev Hydrothermal field, November 2006
R/V Meteor; Shelf off NW Africa, June 2005

Relevant Publications:

Klein, F., Bach, W. McCollom, T. (in review) Compositional controls on hydrogen generation during serpentinization of ultramafic rocks.

Bach, W., Jöns, N., Klein, F. (2012) Metasomatic processes in the oceanic lithosphere. Invited book chapter, Lecture Notes in Earth Sciences, Springer.

Klein, F. and Garrido, C.J., (2011). Thermodynamic constraints on mineral carbonation of serpentinized peridotite, Lithos, 10.1016/j.lithos.2011.07.020.

Jöns, N., Bach, W., Klein, F. (2010) Magmatic influence on reaction paths and element transport during serpentinization. Chemical Geology v. 274, 196–211, doi:10.1016/j.chemgeo.2010.04.009.

Klein, F. and Bach, W., (2009) Fe-Ni-Co-O-S phase relations in peridotite-seawater interactions. Journal of Petrology, v. 50 (1), 37-59, doi:10.1093/petrology/egn071.

Bach, W. and Klein, F., (2009) The petrology of seafloor rodingites: Insights from geochemical reaction path modeling. Lithos, v. 112 (1-2), 103-117, doi:10.1016/j.lithos.2008.10.022.

Klein, F., Bach, W., Jöns, N., McCollom, T., Moskowitz, B. and Berquo, T. (2009) Iron partitioning and hydrogen generation during serpentinization of abyssal peridotites from 15°N on the Mid-Atlantic Ridge. Geochimica et Cosmochimica Acta, v. 73 (22), 6868-6893, doi:10.1016/j.gca.2009.08.021.

Nakamura, K., Morishita, T. Bach, W., Klein, F., Hara, K., Okino, K., Takai, H. and Kumagai, H. (2009) Serpentinized troctolites exposed near the Kairei Hydrothermal Field, Central Indian Ridge: Insights into the origin of the Kairei hydrothermal fluid supporting a unique microbial ecosystem. Earth and Planetary Science Letters, v. 280 (1-4), 128-136, doi:10.1016/j.epsl.2009.01.024.

Klügel, A. and Klein, F., 2006. Complex magma storage and ascent at embryonic submarine volcanoes from the Madeira Archipelago. Geology, v. 34 (5), 337-340. doi: 10.1130/G22077.1.

Students advised: Niya Grozeva (Ph.D. in progress), co-advisor for Gregory Horning (Ph.D. in progress), Tristan Kading (Ph.D. in progress), Adam Sarafian (guest student, U. Georgia)

Collaborators (last 48 months)

T. McCollom (U. Colorado), K. Edwards (USC), B. Toner (U. Minn), C. Garrido (U. Granada), A. Templeton (U. Colorado), D. Goldsby (Brown U.), W. Kahl (U. Kiel), J. Warren (U. Stanford), A. McCaig (U. Leeds), M. Hentscher (U. Bremen), N. Joens (U. Bremen), W. Bach (U. Bremen), M. Tominaga (WHOI), H. Marschall (WHOI), Sune Nielsen (WHOI), Weifu Guo (WHOI), J. Seewald (WHOI), J. Lin (WHOI), H. Dick (WHOI), S. Humphris (WHOI)

Graduate and Post-Doctoral Advisors

Post-Doc Advisors at WHOI	Jeff Seewald, Susan Humphris, Henry Dick
Post-Doc Advisor at the CSIC	Carlos Garrido
Ph.D. Advisor	Wolfgang Bach
Dipl. Geow. Advisor	Andreas Klügel
B.Sc. Advisor	Colin Devey

Synergistic Activities

Gave talks about the petrology seafloor serpentinization at WHOI Geology and Geophysics seminar class (graduate level students) and at the Bridgewater State College (undergraduate level students); wrote the screenplay and acted in the DFG (German Science Foundation) Science TV documentary 'Schwarze Raucher' (Black Smokers) about seafloor hydrothermal systems produced for high school- and undergraduate-level students (available online http://www.dfg-sciencetv. de/de/projekte/blaues-wunder/2008-05-27). Volunteer Falmouth Public High School. Session chair at the Goldschmidt 2011 conference. Session chair and student liaison the AGU Fall 2011 meeting.

Prof. Dr. Jürgen Koepke
Institut für Mineralogie
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Leibniz Universität Hannover

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Curriculum Vitae ***Hannover, November, 2012***

Personal

Institut für Mineralogie, Leibniz Universität Hannover, Callinstrasse 3, 30167, Germany
koepke@mineralogie.uni-hannover.de; 0049511 7624084 (phone); 0049511 7623045 (fax)
Born in Braunschweig, Germany, on Oct. 28, 1955
2 daughters; Jenny Koepke, born Dec. 29. 1983 & Nina Koepke, born Jan. 25, 1989
Private: Tonstrasse 3, 30449 Hannover, 0049511 9215153 (phone)

Education

M.Sc. (1981) Mineralogy, Technical University Braunschweig, Germany: "Petrology of the Upper Cretaceous crystalline complex of Leda (Uppermost unit, Asterousia Mountains, Crete)"
PhD (1986) Mineralogy, Technical University Braunschweig, Germany: "Ophiolites of the Southern Aegean Islands: Petrology and Geochronology"

Professional Experience

1982-1985: Scientific assistant, Inst. for Mineralogy, Technical University Braunschweig
1082-1985: Commercial mineral separation
1985-1994: Scientific assistant, Inst. for Physical Chemistry, Leibniz University of Hannover; head of the microanalytical lab
1994: Scientific assistant, Inst. for Mineralogy, Leibniz University of Hannover; head of the electron microprobe lab
2004: Postdoctoral lecture qualification (Habilitation), Inst. for Mineralogy, Leibniz University of Hannover: "Experimental investigations in hydrous basic systems: Differentiation of MORB, partial melting and trace element diffusion in melts"
2004: Appointment to "Privatdozent" at the Inst. for Mineralogy, Leibniz University of Hannover
2010: Appointment to "Professor" at the Inst. for Mineralogy, Leibniz University of Hannover

Research Interests

Petrology and geodynamics of ocean ridges; magmatic processes at the interface between igneous and hydrothermal processes; role of water during construction of the ocean crust
Experimental petrology of basalts and gabbros, especially the role of aH_2O and fO_2 on phase equilibria and the evolution of SiO_2-rich melts within basaltic systems
Development and application of microprobe techniques
Experimental geochemistry on properties of silicate melts and magmas

Important Funded Projects

Deutsche Forschungsgemeinschaft (DFG), Project Leader: 15 projects (see http://gepris.dfg.de)
Deutsche Forschungsgemeinschaft (DFG), Co-Project Leader: 10 projects (see http://gepris.dfg.de)
Person in charge of a Joint Research Project with Russian Federation funded by DFG (co-operation partner: Sergei Silantyev, Vernadsky Institute, Moscow)

Person in charge of a DAAD PROCOPE Exchange Program with the University of Montpellier, France (co-operation partner: B. Ildefonse)

Person in charge of a DAAD PROCOPE Exchange Program with the University of Montpellier, France (co-operation partner: F. Boudier, A. Nicolas)

Person in charge of 7 projects on the development of synchrotron microprobe techniques and application to silicate melt properties at HASYLAB, Deutsches Elektronen-Synchrotron DESY, Hamburg

German supervisor in two joint doctorate funded by the “Cotutuelle” Program within the Deutsch-Französische Hochschule; based on an agreement between the Universities of Hannover and Montpellier, France (co-operation partner: B. Ildefonse)

German supervisor in a joint doctorate funded by the “Cotutuelle” program; based on an agreement between the Universities of Hannover and Toulouse, France (co-operation partner: G. Ceuleneer)

Co-Proponent for the IODP Mission Proposal “Mission Moho”, submitted in 2007

Co-Proponent for the IODP Drilling Proposal "Superfast-Spreading Crust IV" (522-Full4), submitted in 2006

Co-Proponent for the IODP MDP Proposal “MoHole to Mantle (M2M)”, submitted in 2012

Co-Proponent for the IODP Proposal “Nature of the Lower Crust and Moho at Slower-spreading Ridges" submitted in 2012

Supervisor Activity

MSc and BSc supervisor for: A. Tegge-Schüring, S.T. Feig, S. Graßmann, A. Schimroscyk, M. Johannson, T. Attia, V. Petrov, S. Schönborn, J. Stichnothe, K. Ziaja, J. Blume, D. Penner, W. Dziony, A. Matthias, M. Pump, T. Stampehl, E. Wolff, M. Albrecht, D. Kosanke, P. Nasemann, N. Götze, K. Voges, J. Wiencke, T. Müller, L. Fischer

MSc and BSc co-supervisor for: M. Freise, K. Klimm, M. Haack, O. Beermann, S. Cichy, F. Rohlfs, A. Stechern, J. Probst, L. Kuschel, C. Bonnecke, A. Fiege, C. Kirchner, J. Probst, M. Oeser (Münster), M. Tiedke, M. Singer, S. Wilke, C. Klahn, R. Brodehl, N. Strube, K. Streuff (Kiel),

PhD supervisor for: J. Berndt, S.T. Feig, W. Dziony, C. Kirchner, E. Wolff, M. Erdmann, T. Müller

PhD co-supervisor for: A. Tegge-Schüring; M. Hahn, R. Almeev, L. France (in the framework of a joint doctorate with the University of Montpellier, France), B. Abily (in the framework of a joint doctorate with the University of Toulouse, France)

Post-doctoral co-supervisor for: R. Botcharnikov; R. Almeev; C. Zhang

Long-term responsibilities in the Administration of the Leibniz University Hannover

Program coordinator BSc, MSc "Earth Sciences" at Leibniz University of Hannover

Member of the audit committee "Earth Sciences" at Leibniz University of Hannover

International program coordinator "Earth Sciences" within the Natural Science Faculty

Member of the selection committee for MSc "Earth Sciences" at Leibniz University of Hannover

5 selected Publications

Koepke, J., France, L., Müller, T., Faure, F., Goetze, N., Dziony, W., Ildefonse, B. (2011): Gabbros from IODP Site 1256 (Equatorial Pacific): Insight into axial magma chamber processes at fast-spreading ocean ridges. Geochem Geophys Geosyst 12: doi:10.1029/2011GC003655.

Koepke, J., Berndt, J., Feig, S.T., Holtz, F. (2007): The formation of SiO_2-rich melts within the deep oceanic crust by hydrous partial melting of gabbros. Contrib. Mineral. Petrol. 153, 67–84.

Koepke, J., Feig, S.T., Snow, J. (2005): Late-stage magmatic evolution of oceanic gabbros as a result of hydrous partial melting: Evidence from the ODP Leg 153 drilling at the Mid-Atlantic Ridge. Geochem. Geophys. Geosyst. 6, 2004GC000805, pp. 1-27.

Koepke, J., Feig, S.T., Snow, J., Freise, M. (2004): Petrogenesis of oceanic plagiogranites by partial melting of gabbros: An experimental study. Contrib. Mineral. Petrol. 146, 414-432.

Koepke, J., Behrens, H. (2001): Trace element diffusion in andesitic melts: An application of synchrotron X-ray fluorescence analysis. Geochim. Cosmochim. Acta 65, 1481-1498.

CURRICULUM VITAE

CHARLES H. LANGMUIR
Department of Earth and Planetary Sciences
20 Oxford Street
Harvard University
Cambridge, MA 02138
Langmuir@eps.harvard.edu

EDUCATION:

1973	:	B.A. with honors - Harvard University - History of Science and Geology
1980	:	Ph.D. - SUNY, Stony Brook

FELLOWSHIPS AND AWARDS:

1973 - 1974	:	Henry Russell Shaw traveling fellowship from Harvard University
1980 - 1981	:	Post-doctoral fellowship from Lamont-Doherty
1983 - 1985	:	Alfred Sloan Research Fellow
1993	:	Fellow, American Geophysical Union
1996	:	N. L. Bowen Award, American Geophysical Union
1997	:	Fellow, American Academy of Arts and Sciences
1998	:	Daly Lecturer, American Geophysical Union
1998		Fellow, Geochemical Society and European Geochem. Soc.
2003	:	Arthur Holmes Medal, European Union of Geosciences
2006	:	National Academy of Sciences
2010	:	Urey Medal, European Association of Geochemistry
2010	:	Leverhulme Fellowship, Oxford University
2011	:	Christensen Fellow, Oxford University

PROFESSIONAL ACTIVITIES:

1998 - 2000	:	Co-founder, *Geochemistry, Geophysics, Geosystems*
1999-		PI for PetDB, the Petrological Database of the Ocean Floor
2007-2010	:	AAAS Program Committee
2002 - 2006	:	Ridge 2000 Steering Committee
2006 -	:	Adjunct Scientist, Woods Hole Oceanographic Institution
2006 -	:	Director of the Mineralogical and Geological Museum, Harvard University

EMPLOYMENT:

1981 - 1986	:	Assistant Professor, Lamont-Doherty Earth Obs., of Columbia University, Palisades, New York 10964
1986 - 1988	:	Associate Professor, Lamont-Doherty Earth Obs.
1988 - 2002	:	Professor, Lamont-Doherty Geol. Obs.
1989 - 2002	:	Arthur D. Storke Memorial Professor, Lamont-Doherty
1989 - 1990	:	Visiting Scientist, Institut de Physique du Globe, Paris
2002 - 2003	:	Visiting Scientist, Institut de Physique du Globe, Paris
2002 - 2006	:	Professor of Geochemistry, Harvard University
2006 -	:	Higgins Professor of Geochemistry, Harvard University
2010 -2011	:	Visiting Professor, Oxford University

SEAGOING EXPERIENCE: 15 cruise, 8 as Chief Scientist

Recent cruises:

2001	USCGC Healy	Gakkel Ridge, Arctic Ocean, Co-chief scientist
2004	R/V Kilo Moana	Lau Basin, South Pacific, Chief Scientist
2012	R/V Knorr	Mid-Atlantic Ridge, Chief Scientist

PUBLICATION LIST

Book: Charles Langmuir and Wallace Broecker, *How to Build a Habitable Planet*, 2nd ed. Princeton University Press, 2012.

Selected papers:

Langmuir, C., Bender, J., Batiza, R. (1986). Petrologic and tectonic segmentation of the East Pacific Rise from 6˚-14˚N. *Nature,* 332, 422-429.

Klein, E. and Langmuir, C. (1987). Global correlations of ocean ridge basalt chemistry, axial depth, crustal thickness. *J. Geophys. Res.* 92*,* 8089-8115.

Langmuir, C. (1989). Geochemical Consequences of *In Situ* Crystallization. *Nature,* 340, 199-205.

Langmuir, C., Klein, E., Plank, T. (1992). Petrological systematics of mid-ocean ridge basalts: Constraints on melt generation beneath ocean ridges. *AGU Monograph,* 71, 183-280.

Lehnert, K., Su, Y., Langmuir, C. (1999). A global geochemical database structure for rocks. *Geochem. Geophys. Geosyst. 1,* Paper # 1999GC000026.

Michael, P., Langmuir, C., Dick, H., Snow, J., Goldstein, S., Graham, D., Lehnert, K., Kurras, G., Jokat, W., Mühe, R., Edmonds, H. (2003). Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean. *Nature,* 423, 956-961.

Langmuir, C., Bezos, A., Escrig, S., Parman, S. (2006). Chemical systematics and hydrous melting of the mantle in back-arc basins. *AGU Geophysical Monograph Series* 166, 87-146.

Escartin, J., Smith, D., Cann, J., Schouten, H., Langmuir, C., and Escrig, S. (2008). Central role of detachment faults in accretion of slow-spreading oceanic lithosphere. *Nature*, 455, 790-794, doi:10.1038/nature07333.

Bézos, A., S. Escrig, C. H. Langmuir, P. J. Michael, and P. D. Asimow (2009). Origins of chemical diversity of back-arc basin basalts: A segment-scale study of the Eastern Lau Spreading Center, *J. Geophys. Res.,* 114, B06212, doi:10.1029/2008JB005924.

Escrig, S., A. Bézos, S. L. Goldstein, C. H. Langmuir, and P. J. Michael (2009). Mantle source variations beneath the Eastern Lau Spreading Center and the nature of subduction components in the Lau basin–Tonga arc system. *Geochem. Geophys. Geosyst.* 10, Q04014, doi:10.1029/2008GC002281.

Curriculum vitae – Christopher John MacLeod

School of Earth & Ocean Sciences, Cardiff University, Cardiff CF10 3AT, Wales, UK

Tel: *+44 29 20874332;* ***Fax****: +44 29 20874326;* ***E-mail:*** *macleod@cardiff.ac.uk*

Nationality: *British* ***Date of birth:*** *8th August 1964*

Employment history:

2009	Professor, School of Earth & Ocean Sciences, Cardiff University
2002-2009	Senior Lecturer in Marine Geology, Cardiff University
2005-2007	Chair, ESSAC (Science Support & Advisory Committee of the European Consortium for Ocean Research Drilling), and Director of the ESSAC Office
1995-2002	Lecturer in Marine Geology, Cardiff University
1993-1995	NERC Fellow, Inst. Oceanographic Sciences/University of Leicester: *'Application of borehole imaging techniques to structural geological studies with the Ocean Drilling Program: structure of the lower oceanic crust in Hess Deep'*
1991-1993	NERC PDRA, Inst. Oceanographic Sciences: *'Tectonic evolution of the Lau Basin, SW Pacific, from structural studies of ODP core and geophysical well logs'*
1990-1991	Open University Research Fellow *'Geological evolution of the Southern Troodos Transform Fault Zone, Cyprus'*
1988-1989	Royal Society European Exchange Fellow, Université de Montpellier 2, France *'Oceanic spreading axis segmentation in the Oman ophiolite'*

Qualifications:

Ph.D. (Open University, 1988): *'Tectonic Evolution of the Eastern Limassol Forest Complex Troodos Ophiolite, Cyprus'* (supervisor: Professor I.G. Gass, F.R.S., now deceased)

B.Sc. (Hons.) Geology, Upper Second Class (University of Durham, 1984)

Relevant research cruise/field experience:

- Semail ophiolite, Sultanate of Oman/UAE 9 months field experience 1989-2012
- Troodos ophiolite, Cyprus ~24 months field experience since 1985
- Chief Scientist, RRS James Cook cruise JC021, Hess Deep (2008)
- Co-Chief Scientist, RRS James Cook cruise JC007, Mid-Atlantic Ridge 13°N (2007)
- Chief Scientist, RRS James Clark Ross cruise JR63, Mid-Atlantic Ridge 15°45'N (2001)
- Co-Chief Scientist, RRS James Clark Ross cruise JR31, Atlantis Bank (1998)
- ODP Leg 147, Hess Deep (1992-93) *Structural geologist + JOIDES logging scientist*
- ODP Leg 135, Lau Basin (1990-91) *Structural geologist + JOIDES logging scientist*
- participant in four further research cruises in Atlantic, Indian & Pacific oceans (1992-2010)

Professional appointments and memberships:

- Chair, ESSAC (ECORD Science Support & Advisory Committee), 2005-2007
- Vice-Chair, ESSAC, 2003-2005, 2007-2008; UK representative ESSAC, 2003-2008
- ECORD Representative, IODP Science Planning Committee (SPC), 2003-2007
- IODP INVEST Session Chair 'Variability in ocean crust composition and structure', Sept 2009
- IODP Thematic Review Committee 'Oceanic Crustal Structure and Formation', 2008-2009
- IODP Science Advisory Structure Executive Committee Permanent Alternate, 2007-09
- InterRidge Deep Earth Sampling Working Group member, 2004-2009
- NERC UK ODP & IODP Strategy Group and Grants Committee member, 1995-2008
- UK representative, ODP (JOIDES) Science Committee (SCICOM), 2001-2003
- UK representative, ODP Scientific Measurements Panel, 1997-1999
- ODP Curatorial Advisory Board member, 1997-2000
- UK representative, ODP Information Handling Panel, 1995-1997

Selected research grants

- NERC grant NE/J021741/1 (2014-2017, £103,941) *'Role and extent of detachment faulting at slow-spreading mid-ocean ridges'* (with T. Reston & C. Peirce)
- *NERC grant IP1193-1110 (2011-2013; £33,000) *'Geodynamics of the Oman/UAE ophiolite: spatial and temporal variability in lithospheric accretion at the onset of intraoceanic subduction'*
- *NERC grant NE/C509023/1 (2008-2011; £332,992) *'Accretion of the lower oceanic crust at fast-spreading ridges: a rock drill and near-bottom seafloor survey at Hess Deep'*
- *NERC grant NE/B500058/1 (2007-2010; £147,575) '*Geological and Geophysical Studies of the Mid-Atlantic Ridge, 12º30'N to 14º30'N'*
- NERC grant NE/E003079/1 (2007-2009; £18,446) *'Spatial and temporal scales of crustal accretion in slow-spreading rate oceanic crust (IODP Site U1309)*
- *NERC + ECORD Managing Agency (2005-2007, £295,240) *Management of the ESSAC Office and ECORD education & outreach activities*
- *NERC grant GR3/11767 (1999-2004, £155,234) *'A low-angle detachment fault on the MAR'*
- *NERC grants GR3/10791+ GST/02/2293 (1997-2001, £169,699) *'Plutonic foundation of the oceanic crust: portable rock drilling on the SW Indian Ridge'*
- NERC grant GST/02/1166 (1996-1998, £56,549) *'Sea trials of the oriented hard-rock corer'*
- NERC grant GST/02/996 (1995-1996, £82,265) *'A seafloor drill for oriented rock cores'*

[= first-named Principal Investigator];* + in-kind contributions (shiptime, ROV hire, NERC facilities use): £2,799,540*;* + 10 further grants from miscellaneous other sources: £882, 721

Selected relevant publications:

MacLeod CJ, Lissenberg, CJ, & Bibby, LE, 2013. 'Moist MORB' axial magmatism in the Oman ophiolite: the evidence against a mid-ocean ridge origin. *Geology*, **41**, doi:10.1130/G33904.1, *in press.*

MacLeod CJ, et al., 2009. Life cycle of oceanic core complexes. *Earth Planet. Sci. Lett.*, **287**, 333-344.

MacLeod CJ, Escartín J, et al., 2002. Direct geological evidence for oceanic detachment faulting: the Mid-Atlantic Ridge, 15°45'N. *Geology*, **30**, 879–882.

Coogan LA, Thompson G & **MacLeod CJ**, 2002. A textural and geochemical investigation of high level gabbros from the Oman ophiolite. *Lithos*, **63**, 67-82.

MacLeod CJ & Yaouancq G, 2000. A fossil melt lens in the Oman ophiolite: implications for magma chamber processes at fast-spreading ridges. *Earth Planet. Sci. Lett.*, **176**, 357-373.

Manning CE, **MacLeod CJ** & Weston PE, 2000. Lower-crustal cracking front at fast-spreading ridges: evidence from the East Pacific Rise and the Oman ophiolite. *Geol. Soc. Am. Spec. Pap.*, **349**, 261-272.

Yaouancq G. & **MacLeod CJ**, 2000. The use of the anisotropy of magnetic susceptibility in petrofabric investigation of gabbros from the Oman ophiolite. *Mar. Geophys. Res.*, **21**, 289-305.

MacLeod CJ, et al., 1995. Further techniques for core reorientation by core-log integration: application to structural studies of lower oceanic crust in Hess Deep, Eastern Pacific. *Scientific Drilling*, **5**, 77-86.

Gass IG, **MacLeod CJ**, et al., 1994. *The Geological Evolution of the Southern Troodos Transform Fault Zone*. Cyprus Geological Survey Memoir, **9**, Geol. Surv. Dept., Nicosia, Cyprus, 218pp.

MacLeod CJ & Rothery DA, 1992. Ridge axial segmentation in the Oman ophiolite: evidence from along-strike variations in the sheeted dyke complex. *Spec. Publ. Geol. Soc. London,* **60**, 39-63.

MacLeod CJ, Allerton S, Gass IG & Xenophontos C, 1990. Structure of a fossil ridge-transform intersection in the Troodos ophiolite. *Nature*, **348**, 717-720.

MacLeod CJ, et al., 1992. Identification of tectonic rotations in boreholes by the integration of core information with Formation MicroScanner and Borehole Televiewer images. *Spec. Publ. Geol. Soc. London* **65**, 235-246.

Biographical Sketch – Craig E. Manning

Professional Preparation

University of Vermont	Geology	BA, 1982
Stanford University	Geology	MS, 1986
Stanford University	Geology	Ph.D, 1989
U.S. Geological Survey	Geochemistry	Postdoctoral Scientist, 1989-90

Appointments

2010-	Affiliate Member, UCLA Insitute of the Environment
2008-2012	Chairman, Dept. of Earth and Space Sciences, UCLA
2002-2008	Vice-Chairman, Dept. of Earth and Space Sciences, UCLA
2008-	Humboldt Fellow, Bayerisches Geoinstitut, Bayreuth, Germany
2007,2008	Visiting Scientist, École Normale Supérieur de Lyon, France
2006	Visiting Scientist, GeoForschungsZentrum, Potsdam, Germany
2002-	Professor of Geology and Geochemistry, UCLA
2000	Visiting Professor, Swiss Federal Institute of Technology (ETH Zürich)
1996-2002	Associate Professor of Geology and Geochemistry, UCLA
1990-1996	Assistant Professor of Geology and Geochemistry, UCLA
1989-1990	Postdoctoral Scientist, U.S. Geological Survey, Menlo Park, Ca.
1983	Geological Field Assistant, U.S. Geological Survey, Menlo Park, Ca.
1981-1982	Field Geologist, Wagner, Heindel and Noyes, Consulting Hydrologists, Burlington, Vt.

Relevant Publications

Dolejs D., and Manning, C. E., 2010, Thermodynamic model for mineral solubility in aqueous fluids: theory, calibration, and application to model fluid-flow systems. Geofluids, v. 10, p. 20-40.

Manning, C. E., Antignano, A., Lin, H. A., 2010, Premelting polymerization of crustal and mantle fluids, as indicated by solubility of albite + paragonite + quartz in H_2O at 1 GPa and 350-620°C. Earth and Planetary Science Letters, v. 292, p. 325-336.

Ingebritsen, S. E., and Manning, C. E., 2010, Permeability of the continental crust: Dynamic variations inferred from seismicity and metamorphism. Geofluids, v. 10, p. 193-205.

Manning, C. E., MacLeod, C., and Weston, P. E., 2000, Lower-crustal cracking front at fast-spreading ridges: evidence from the East Pacific Rise and the Oman ophiolite. In Dilek, Y., Moores, E., Elthon, D., and Nicolas, A., eds., Ophiolites and Ocean Crust: New Insights From Field Studies and Ocean Drilling Program, Geological Society of America Special Paper 349, p. 261-272.

Manning, C. E., Weston, P. E., and Mahon, K. I., 1996, Rapid high-temperature metamorphism of East Pacific Rise gabbros from Hess Deep: Earth and Planetary Science Letters, v. 144, p. 123-132.

Five Other Publications

Manning, C. E., and Ingebritsen, S. E., 1999, Permeability of the continental crust: constraints from heat flow models and metamorphic systems. Reviews in Geophysics, v. 37, p. 127-150.

Manning, C. E., 1997, Coupled reaction and flow in subductions zones: Si metasomatism in the mantle wedge. In: Jamtveit, B., and Yardley, B. W. D., eds., Fluid Flow and Transport in Rocks, Chapman Hall, p. 139-148.

Manning, C. E., 1994, The solubility of quartz in H_2O in the lower crust and upper mantle. Geochimica et Cosmochimica Acta, v. 58, p. 4831-4839.

Newton, R. C., and Manning, C. E., 2002, Solubility of silica in equilibrium with enstatite, forsterite, and H_2O at deep crust/upper mantle pressures and temperatures and an activity-concentration model for polymerization of aqueous silica. Geochimica et Cosmochimica Acta, v. 66, p. 4165-4176.

Manning, C. E., and MacLeod, C. J., 1996, Fracture-controlled metamorphism of Hess Deep Gabbros, Site 894: Constraints on the root zones of mid-ocean ridge hydrothermal systems at fast spreading centers. In: Mével, C., Gillis, K. M., Allan, J. F., and Meyer, P. S., eds., Proceedings of the Ocean Drilling Program, Scientific Results, v. 147, College Station, TX (Ocean Drilling Program), p. 189-209.

Five Synergistic Activities

2012-13	GeoPRISMS Distinguished Lecturer
2011-	Co-Chair, Physics and Chemistry of Carbon Direcotrate, Deep Carbon Observatory

2006-08 Secretary, American Geophysical Union VGP section
2001-03 Councilor, Mineralogical Society of America
1997-2000 Panelist, Ocean Drilling Program Scientific Steering and Evaluation Panel

Collaborators and Other Affiliations

Collaborators (last 4 years)

J. Boyce (UCLA)
E. Cowgill (UC Davis)
I. Daniel (ENS Lyon, France)
D. Dolejs (U Bayreuth, Germany)
J. Hanchar (Memorial U)
M. Harrison (UCLA)
D. Hirsch (Western Washington U)
S. Ingebritsen (USGS Menlo Park)
E. Johnson (James Madison U)
P. Kapp (U Arizona)
A. Kavner (UCLA)
H. Keppler (U Bayreuth, Germany)
J. Mavrogenes (ANU Canberra, Australia)
T. McCollum (U Colorado)
S. Mojzsis (U Colorado)
R. Newton (UCLA)
T. Plank (Columbia U)
E. Schauble (UCLA)
C. Schmidt (GeoForschungsZentrum, Potstdam, Germany)
D. Sverjensky (Johns Hopkins U)
A. Thompson (ETH Zürich)
P. Tropper (U Innsbruck)
M. Wilke (GeoForschungsZentrum, Potstdam, Germany)
A. Yin (UCLA)
E. Young (UCLA)

Graduate and Postdoctoral Advisors

D. Bird (Stanford U)
S. Bohlen (Joint Oceanographic Inst.)
R. Coleman (Stanford U)
J. Liou (Stanford U)

PhD students[§], MS students[||] and Postdoctoral Scientists[†] mentored in last 5 years

A. Antignano[§] (Exxon Research)
S. Briggs[§] (William Lettis & Associates)
C. Colasanti[||] (PhD cand., U Munich)
M. Cruz[||] (PhD cand., Stanford U)
L. Hayden[†] (Researcher, USGS)
Michael Huh[||*]
J. Hunt[§](Postdoc, Lawrence Livermore)
C. Lazar[§] (Postdoc, Geophysical Lab)
C. Macris[§*]
A. Mahkluf[§*]
C. Menold[§] (Asst Prof, Albion College)
A. Shahar[§] (Staff Scientist, Geophysical Lab)
R. Thomas[||*]
A. Wohlers[†] (Researcher, GFZ Potsdam)
J. Wykes[||§#] (PhD cand., ANU Canberra)

[*]Current graduate student or postdoctoral scientist at UCLA
[#]Australian National U student who did experimental part of MS work at UCLA; in residence at UCLA in 2010-11 as a Fulbright Fellow
Total students = 13; total postdoctoral scientists = 2

Katsuyoshi MICHIBAYASHI

Contact Information

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Shizuoka, 422-8529, JAPAN

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Fax: +81-54-238-0491
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Education

Shizuoka University, Japan	Geology	B.Sc	**1988**
Shizuoka University, Japan	Structural Geology	M.Sc	**1990**
James Cook University of North Queensland, Australia	Structural Geology	Ph.D	**1994**

Work Experience

April/12-	Professor at Shizuoka University, Japan
April/02-March/12	Associate Professor at Shizuoka University, Japan
Aug/97-Aug/99	JSPS Postdoctoral Fellow at Université Montpellier II, France
Oct/94-March/02	Assistant Professor at Shizuoka University, Japan
April/94-April/94	JSPS Postdoctoral Fellow at the University of Tokyo, Japan

Shipboard Experience

8/Oct/11-28/Oct/11	JAMSTEC R/V Yokosuka YK11-08
17/Sept/10-1/Oct/19	JAMSTEC R/V Yokosuka YK10-12
3/May/09-22/May/09	JAMSTEC R/V Yokosuka YK09-05
8/July/08-22/July/08	JAMSTEC R/V Yokosuka YK08-08
27/Aug/06-5/Sept/06	JAMSTEC R/V Yokosuka YK06-12
11/Jan/05-3/March/05	IODP Exp305

Professional & Synergistic Activities

IODP SSEP 2010-2011; PEP 2011-present
J-DESC IODP Steering Committee 2010-present
Geological Society of Japan Representative Member 2010-present

Selected Publications

Michibayashi, K., Kusafuka, Y., Satsukawa, T. and S. Nasir, 2012. Seismic properties of peridotite xenoliths as a clue to imaging the lithospheric mantle beneath NE Tasmania, Australia. *Tectonophysics*, 522-523, 218-223.

Ohara, Y., Reagan, M., Fujikura, K., Watanabe, H., Michibayashi, K., Ishii, T., Stern, R. J., Pujana, I., Martinez, F., Girard, G., Ribeiro, J., Brounce, M., Komori, N. and Kino, M., 2012. A serpentine-hosted ecosystem in the Southern Mariana Forearc. *Proceeding of the National Academy of Science*, 109, 2831-2835.

Satsukawa, T., Michibayashi, K., Anthony, E. Y., Stern, R. J., Gao, S. S. and Liu, K. H., 2011. Seismic anisotropy of the uppermost mantle beneath the Rio Grande rift: Evidence from Kilbourne Hole peridotite xenoliths, New Mexico. *Earth and Planetary Science Letters*, 311, 172-181.

Harigane, Y., Michibayashi, K. and Ohara, Y., 2011b. Deformation and hydrothermal metamorphism of gabbroic rocks within the Godzilla Megamullion, Parece Vela Basin, Philippine Sea. *Lithos*, 124, 185-199.

Harigane, Y., Michibayashi, K. and Ohara, Y., 2011a. Relicts of deformed lithospheric mantle within serpentinites and weathered peridotites from the Godzilla Megamullion, Parece Vela Back-Arc Basin, Philippine Sea. *Island Arc*, 20, 174-187.

Muramoto, M., Michibayashi, K., Ando, J. and Kagi, H., 2011. Rheological contrast between garnet and clinopyroxene in the mantle wedge: an example from Higashi-akaishi peridotite mass, SW Japan. *Physics of* *the Earth and Planetary Interiors*, 84, 14-33.

Satsukawa, T., Michibayashi, K., Raye, U., Anthony, E. Y., Pulliam, J. and Stern, R. J., 2010. Uppermost mantle anisotropy beneath the southern Laurentian margin: Evidence from Knippa peridotite xenoliths, Texas. *Geophysical Research Letters*, 37, L20312, 5pp.

Hirauchi, K., Michibayashi, K., Ueda, H and Katayama, I., 2010. Spatial variations in antigorite fabric across a serpentine subduction channel: Insight from the Ohmachi Seamount, Izu-Bonin frontal arc. *Earth and Planetary Science Letters*, 299, 196-206.

Harigane, Y., Michibayashi, K. and Ohara, Y., 2010. Amphibolitization within the lower crust in the termination area of the Godzilla Megamullion, an oceanic core complex in the Parece Vela Basin, *Island Arc*, 19, 718-730.

Kamei, A., Obata, M., Michibayashi, K., Hirajima, T. and Svojtka, M., 2010. Two contrasting fabric patterns of olivine observed in garnet- and spinel-peridotite from a mantle-derived ultramafic mass enclosed in felsic granulite, the Moldanubian Zone, Czech Republic. *Journal of Petrology*, 51, 101-123.

Ohuchi, T., Nakamura, M. and Michibayashi, K., 2010. Effect of grain growth on cation exchange between dunite and fluid: implications for chemical homogenization in the upper mantle. *Contribution to Mineralogy and Petrology*, 160, 339-357.

Katayama, I., Michibayashi, K., Terao, R., Ando, J. and Komiya, T., 2010. Water content of the mantle xenoliths from Kimberley and implications for explaining textural variations in cratonic roots. *Geological Journal*, 46, 173-182.

Katayama, I., Hirauchi, K. Michibayashi, K. and Ando, J., 2009. Trench-parallel anisotropy produced by serpentine deformation in the hydrated mantle wedge. *Nature*, 461, 1114-1117.

Michibayashi, K., Oohara, Y., Satsukawa, T., Ishimaru, S., Arai, S. and Okrugin, V. M., 2009. Rock seismic anisotropy of the low velocity zone beneath the volcanic front in the mantle wedge. *Geophysical Research Letters*, 36, L12305, doi:10.1029/2009GL038527.

Michibayashi, K., Ohara, Y., Stern, R.J., Fryer, P., Kimura, J.-I., Tasaka, M., Harigane, Y. and Ishii, T., 2009. Peridotites from a ductile shear zone within backarc lithospheric mantle, southern Mariana Trench: results of a Shinkai6500 dive. *Geochemistry Geophysics Geosystems*, doi:10.1029/2008GC002197.

Michibayashi, K., Hirose, T., Nozaka, T., Harigane, Y., Escartin, J., Delius, H., Linek, M. and Ohara, Y., 2008. Hydration due to high-T brittle failure within in situ oceanic crust, 30°N Mid-Atlantic Ridge. *Earth and Planetary Science Letters*, 275, 348-354.

Harigane, Y., Michibayashi, K. and Ohara, Y., 2008. Shearing within lower crust during progressive retrogression: structural analyses of gabbroic rocks from the Godzilla Mullion, an oceanic core complex in the Parece Vela backarc basin. *Tectonophysics*, 457, 183-196.

Tasaka, M., Michibayashi, K. and Mainprice, D., 2008. B-type olivine fabrics developed in the fore-arc side of the mantle wedge along a subducting slab. *Earth and Planetary Science Letters*, 272, 747-757.

Michibayashi, K., Tasaka, M., Ohara, Y., Ishii, T., Okamoto, A. and Fryer, P., 2007. Variable microstructure of peridotite samples from the southern Mariana Trench: evidence of a complex tectonic evolution. *Tectonophysics*, 444, 111-118.

Michibayashi, K., Ina, T. and Kanagawa, K., 2006. The effect of dynamic recrystallization on olivine fabric and seismic anisotropy: Insights from a ductile shear zone in the Oman ophiolite. *Earth and Planetary Science Letters*, 244, 695-708.

Michibayashi, K., Abe, N., Okamoto, A., Satsukawa, T., Michikura, K., 2006. Seismic anisotropy in the uppermost mantle, back-arc region of the northeast Japan arc: petrophysical analyses of Ichinomegata peridotite xenoliths. *Geophysical Research Letters*, 33, L10312.

Michibayashi, K. and Mainprice, D., 2004. The role of pre-existing mechanical anisotropy on shear zone development within oceanic mantle lithosphere: an example from the Oman ophiolite. *Journal of Petrology*, 45, 405-414.

Michibayashi, K., Gerbert-Gaillard, L. and Nicolas, A., 2000. Shear sense inversion in the Hilti mantle section (Oman ophiolite) and active mantle uprise. *Marine Geophysical Researches*, 21, 259-268.

D. JAY MILLER

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Texas A&M University — Phone: (979) 845-5740
1000 Discovery Drive — FAX: (979) 845-0856
College Station, TX 77845 — email: miller@iodp.tamu.edu

Professional History

2009-present	Manager**,** Technical and Analytical Services Department Integrated Ocean Drilling Program, Texas A&M University
2008-2009	Project Manager, Scientific Ocean Drilling Vessel Refit Integrated Ocean Drilling Program. Texas A&M University
2003-2008	Expedition Project Manager Integrated Ocean Drilling Program. Texas A&M University
1993-2003	Staff Scientist Ocean Drilling Program, Texas A&M University

Education

PhD, Geochemistry-Ore Petrology Program	Purdue University, 1992
M.Sc., Geology	University of Texas, Arlington 1988
B.S., Geology	University of Texas, Arlington 1985

Professional and Synergistic Activities

Project Management Institute certified Project Management Professional
Project Manager Scientific Ocean Drilling Vessel (SODV) conversion
Project Manager/Science Coordinator for nine expeditions of the Ocean Drilling Program and two expeditions of the Integrated Ocean Drilling Program
Contributing scientist for eleven ODP expeditions, two IODP expeditions and two Alvin dive programs
Fulbright Fellow, Nordic Volcanological Institute
Penrose Conference on Ophiolites Invited Presenter and Closing Session Panelist
National Science Foundation Distinguished Lecturer

Five publications relevant to proposed research

Carlson, R. L., and Miller, D.J., 2003. Mantle wedge water contents estimated from seismic velocities in partially serpentinized peridotites, *Geophys. Res. Lett.,* 30(5), 1250.

Carlson, R. L., and Miller, D. J., 2004. Influence of pressure and mineralogy on seismic velocities in oceanic gabbros: Implications for the composition and state of the lower oceanic crust. *J. Geophys. Res.,* Vol. 109, No. B9, B09205
10.1029/2003JB002699

Kelemen, P.B., Kikawa, E., and Miller, D.J., 2007. Processes in a 20-km-Thick Conductive Boundary Layer beneath the Mid-Atlantic Ridge, 14°–16°N. *In* Kelemen, P.B., Kikawa, E., and Miller, D.J., (Eds.), *Proc. ODP, Sci. Results,* 209 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/209_SR/.

Ildefonse, B., Blackman, D.K., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and Shipboard Scientific Party, 2007. Oceanic core complexes and crustal accretion at slow spreading ridges. *Geology.* 35, 623-626.

Carlson, R. L., Miller, D.J., and Newman, J., 2009. Olivine enigma: Why alteration controls the seismic properties of oceanic gabbros, Geochem. Geophys. Geosyst., 10, Q03O16, doi:10.1029/2008GC002263.

Five other recent publications (student co-authors*)

D'Hondt, S., Jørgensen, B.B., Miller, D.J., et al., 2004. Distributions of microbial activities in deep subseafloor sediments, *Science.* 306:2216-2221.

Carlson, R.L., and Miller, D.J., 2005. Unraveling the structure and composition of the ocean crust. *Sea Technology*, 46:10:10-13.

Miller, D.J., Vanko, D.A., and Paulick, H., 2006. Petrology and geochemistry of fresh, recent dacite lavas at Pual Ridge, Papua New Guinea, from an active, felsic-hosted seafloor hydrothermal system. *In* Barriga, F.J.A.S., Binns, R.A., Miller, D.J., and Herzig, P.M. (Eds.), *Proc. ODP, Sci. Results,* 193 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/193_SR/208/208.htm>.

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Other activitiy:

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Publications (last 10 years):

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Nasir, S., Salah Al-Khirbash, Hugh Rollinson Abdulrahman Al-Harthy Abdulrazak Al-Sayigh, Ali Al-Lazki, ., T. Theye, H.J. Massone E. Belousova F **(2011).** Petrogenesis of ultramafic lamprophyres and carbonatites from the Batain Nappes, eastern Oman continental margin **Contribution to Mineralogy and Petrology, 161, 47-74.**
Nasir , S. J. . Everard, J., McClenaghan, MP., Bombardieri , D., M. A. Worthing, MA. (2010). The petrology of high pressure xenoliths and associated Cenozoic basalts from Northeastern Tasmania. **Lithos** 118, 35-49
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Nasir, S , Theye T.and Hans-Joachim Massonne **(2009)** REE-rich aeschynite minerals in Tertiary apatite-dolomite carbonatite, eastern Oman Mountains **Open Journal of Mineralogy 3,17-27**
Al-Safarjalani, A., **Nasir, S**., Fockenberg, T., Massonne, H.J., **(2009)** Chemical composition of an intermediate part of the lower crust beneath southwestern Syria. **(Chemie der Erde) 69:359-375**
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Al-Rawas, A., **Nasir, S**., Gismelseed, A., **(2008)** ^{57}Fe Mössbauer spectroscopy study of phlogopite megacrysts from an evolved carbonatitic kimberlite in the northeastern Oman Mountains. **Hyperfine Interaction 186, 147-151**
Worthing, M.**, Nasir, S**. **(2008)**: Cambro-Ordovician potassic (alkaline) magmatism in central Oman: Petrological and geochemical constraints on petrogenesis**. Lithos 106, 25-38**
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Al-Sayigh, A., **Nasir, S**. Steven N., Schulpe A**. (2008)**: The first record of Arsinoitherium from Oman: Paleogeographic implication. **Palaeoworld 17,** 41-46**.**
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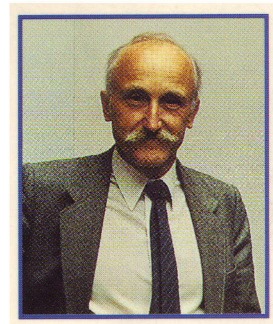

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SELECTED BIBLIOGRAPHY SINCE 1997

NICOLAS, A. ET ILDEFONSE, B., 1996. Flow mechanism and viscosity in basaltic magma chambers. Geophys. Res. Lett., 23: 2013-2016.

NICOLAS, A., BOUDIER, F. ET ILDEFONSE, B., 1996. Variable crustal thickness in the Oman ophiolite-Implication for oceanic ridges. J. Geophys. Res., 101: 17941-17950.

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CHENEVEZ, J., MACHETEL, P. ET NICOLAS, A., 1998. Numerical models of magma chamber in the Oman ophiolite. J. Geophysical Research, 103: 15,443-15,455.

DELOUIS, B., NICOLAS, A., ILDEFONSE, B. ET PHILIP, H., 1998. Earthquake focal mechanism and oceanic thrust in easter microplate. Analogy with Oman ophiolite. Geophys. Res. Lett., 25: 1443-1446.

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NICOLAS, A., BOUDIER, F. ET MESHI, A., 1999. Slow spreading accretion and mantle denudation in the Mirdita ophiolite (Albania). J. Geophys. Res., 104: 15,155-15,167

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NICOLAS, A.,. MAINPRICE, D, and BOUDIER,F., 2003. High temperature seawater circulation throughout crust of oceanic ridges : A model derived from the Oman ophiolite, J. Geophys. Res., 108 : 2371, on line.

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Nicolas A., and Boudier F**.** (2008) Large shear zones with no relative displacement. Terra Nova 3, 200-205, doi:10.1111/j.1365-3121.2008.00806.x

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Nicolas, A. & Boudier, F. (2011) Structure and dynamics of ridge axial melt lenses in the Oman ophiolite. J. Geophys. Res., 116, B03 103, doi:10.1029/2010JB007934

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2. Brazelton, W.J., B. Nelson, **M.O. Schrenk.** 2012. Metagenomic evidence of H_2 oxidation and H_2 production by serpentinite-hosted subsurface microbial communities. *Frontiers in Microbiology* 2:268. doi: 10.3389/fmicb.2011.00268
3. Szponar, N., W.J. Brazelton, **M.O. Schrenk,** D.M. Bower, A. Steele, P. Morrill. 2012. Biogeochemistry of a continental site of serpentinization in the Tablelands ophiolite, Gros Morne National Park: A Mars Analogue. *Icarus.* In press.
4. **M.O. Schrenk,** J.A. Huber, K.J. Edwards. 2010. Microbial Provinces in the Subseafloor. *Annual Review of Marine Science.* 2:279-304.
5. W.J. Brazelton, **M.O. Schrenk**, D.S. Kelley, J.A. Baross. 2006. Methane and sulfur metabolizing microbial communities dominate in the Lost City Hydrothermal Field ecosystem. *Appl. Environ. Microbiol.* 72(9):6257-6270.

FIVE OTHER SIGNIFICANT PUBLICATIONS:

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2. **Schrenk, M.O.,** J.F. Holden, J.A. Baross. 2008. Magma-to-Microbe Networks in Seafloor Sulfide Deposits. *In* Magma to Microbe at Mid Ocean Ridges. AGU Monograph. R. Lowell, A. Metaxas, M. Perfit (Eds.). 233-258.

3. Baross, J.A., J.A. Huber, and **M.O. Schrenk**. 2006. Limits of Carbon Life on Earth and Elsewhere. In *Planets and Life: The Emerging Science of Astrobiology*. J.A. Baross and W.T. Sullivan (Eds). Cambridge University Press. 275-291.
4. **Schrenk, M.O.,** S.A. Bolton, D.S. Kelley, and J.A. Baross. 2004. Low archaeal diversity linked to subseafloor geochemical processes at the Lost City Field, Mid Atlantic Ridge. *Environ. Microbiol.* 6(10):1086-1095.
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- Science Steering Committee- Center for Dark Energy Biosphere Investigations.
- Coordinating Committee- North Carolina Space Grant at ECU
- Primary Faculty Member- North Carolina Center for Biodiversity

STUDENTS SUPERVISED: Postdoctoral- W. Brazelton, M. Crespo-Medina, D. Morgan-Smith. Graduate- K. Twing (ECU- Ph.D., IDPBS), J. Blackburn, H. Blumenfeld, C. George, A. Kloysuntia, Q. Woodruff (ECU- M.Sc.)

COLLABORATORS WITHIN THE PAST 48 MONTHS:
J. Amend (USC), J. Banfield (UC-Berkeley), J. Baross (UW), D. Cardace (URI), G. Cody (CIW), K. Edwards (USC), G. Früh-Green (ETH-Zurich), P. Girguis (Harvard), J. Holden (UMass), J. Huber (MBL), D. Kelley (UW), D. Meyer-Dombard (UIC), S. Mitra (ECU), P. Morrill (Memorial U.), S. Seager (MIT)

GRADUATE ADVISORS AND POSTDOCTORAL SPONSORS:

Dr. John A. Baross	Ph.D. Advisor	U. of Washington
Dr. George D. Cody	Post-doctoral advisor	Carnegie Institution
Dr. Sara Seager	Post-doctoral advisor	MIT

BARBARA SHERWOOD LOLLAR, F.R.S.C.

Dept. of Earth Sciences, University of Toronto, Toronto, ON M5S 3B1
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1. Professional Preparation

B.A. Geological Sciences, Harvard University, 1985.
Ph.D. Earth Sciences, University of Waterloo, 1990.

2. Appointments

NSERC Postdoctoral Fellow, University of Cambridge	1990-92
Professor, Dept. of Earth Sciences and Director, Stable Isotope Laboratory	1992-present
Canada Research Chair (Isotope Geochemistry)	2007-2014

Awards and Fellowships

Eni Award for Protection of the Environment	2012
Geological Society of America Geobiology and Geomicrobiology Award	2012
Distinguished University Professor, University of Toronto	2010
Canada Council Killam Research Fellowship, University of Toronto	2004-2006
TIME Magazine – profiled as one of "Leaders for 21st Century"	2000
Darcy Lecturer (U.S. National Ground Water Association)	1998

3. Publications, 5 most relevant

1. Gilfillan, S.M.V., Sherwood Lollar, B., Holland, G., Blagburn, D., Stevens, S., Schoell, M., Cassidy, M., Ding, Z. Lacrampe-Couloume, G., Zhou, Z. and Ballentine, C.J. (2009) Solublity trapping in formation water as dominant CO_2 sink in natural gas fields. **Nature** 458:614-618. **Cover story**
2. Sherwood Lollar, B. and McCollom, T.M. (2006) Biosignatures and abiotic constraints on early life. (2006) **Nature** 444:E18. Dec. 14, 2006.
3. Lin, L.-H., Wang, P.-L., Rumble, D., Lippmann-Pipke, J., Boice, E., Pratt, L., Sherwood Lollar, B., Brodie, E. Hazen, T., Andersen, G., Moser, D.P., Kershaw, D. and Onstott, T.C. (2006) Long-term sustainability of a high energy, low diversity crustal biotome. **Science** 314:479-482.
4. Sherwood Lollar, B., Lacrampe-Couloume, G., Slater, G.F., Ward, J., Moser, D.P., Gihring, T.M., Lin, L.-H. and T.C. Onstott. (2006) Unravelling abiogenic and biogenic sources of methane in the Earth's deep subsurface. **Chemical Geology** Vol. 226:328-339. **One of top 10 most highly cited 2005-2010 in Chemical Geology.**
5. Sherwood Lollar, B., Westgate, T., Ward, J., Slater, G.F., and Lacrampe-Couloume, G. (2002) Abiogenic formation of alkanes in the Earth's crust as a minor source for global hydrocarbon reservoirs. **Nature** Vol. 416:522-524.

4. Publications, 5 other significant

1. Sherwood Lollar, B., Voglesonger, K., Lin, L.-H., Lacrampe-Couloume, G., Telling, J., Abrajano, T.A., Onstott, T.C. and Pratt, L.M. (2007) Hydrogeologic controls on episodic H_2 release from Precambrian fractured rocks - Energy for deep subsurface life on Earth and Mars. **Astrobiology** 7:971-986.
2. McCollom, T.M., Sherwood Lollar, B., *Lacrampe-Couloume, G.* and Seewald, J.S. (2010) The influence of carbon source on abiotic organic synthesis and carbon isotope fractionation under hydrothermal conditions. **Geochimica et Cosmochimica Acta** 74:2717-2740. **One of the "Top-25 most cited articles" Geochimica et Cosmochimica Acta for 2010.**
3. Allen, M., Sherwood Lollar, B., Runnegar, B., Oehler, D.Z., Lyons, J.R., Manning, C.E., Summers, M.E. (2006) Is Mars Alive? **EOS Transactions,** American Geophysical Union. 87 (41): 433, 439.

4. Lin, L.-H., Slater, G.F., Sherwood Lollar, B., Lacrampe-Couloume, G., and T .C. Onstott. (2005) The yield and isotopic composition of radiolytic H_2, a potential energy source for the deep subsurface biosphere. **Geochimica Cosmochimica Acta** Vol. 69(4):893-903.

5. Ballentine, C.J., Marty, B., Sherwood Lollar, B. and Cassidy, M. (2005) The Ne isotopic ratio of the convecting mantle and the origin of volatiles in the Earth. **Nature** Vol. 433:33-38.

Plus >100 additional papers

5. Synergistic Activities (up to 5 examples)

1. Member of National Research Council National Academies of Sciences Committee on Astrobiology and Planetary Science (2011-2014). Executive Committee member of the Sloan Foundation Deep Carbon Observatory and co-investigator of Deep Energy Directorate.
2. Member of MEPAG sub-committee developing the White paper on design of the Mid-Range Rover mission for Mars. NASA Mid-Range Rover Science Analysis Group member (MRR-SAG 2009). Co-author of the 2007 Astrobiology Strategy for the Exploration of Mars (ISBN 978-0-309-10851-5).
3. International collaborator with the NAI Indiana-Princeton-Tennessee team (co-PIs Pratt and Onstott) (2003-2008) and while on that team participated in the NAI Distributed Workshop "Methane on Mars' hosted by the NASA Goddard Space Flight Center. With Mark Allen of JPL co-authored "Is Mars Alive?" EOS Transactions AGU 87(41):433-439.
4. Vice-President of the Geochemical Society (2012-2014) and President-elect for 2014-2016. Executive Program Committee Co-Chair, Goldschmidt 2008; Organizing Committee, AbSciCon 2010.
5. Co-PI on $1.6 million NSERC Canadian Astrobiology Training grant to McGill-Toronto-Western Ontario-McMaster to fund international student and postdoctoral fellow research in astrobiology. International partners include NASA Ames (McKay; Stoker, Rothschild), JPL (Mielke), Cornell (Bell), SETI (Anderson), the OU (Cockell) and Princeton (Onstott).

6. Thesis advisor and post-graduate scholar sponsor, last 5 years

Penny Morrill (now Ass. Prof. Memorial University), Sarah Hirschorn (NWMO), Silvia Mancini (Golder Associates), Jennifer Gray McKelvie (NWMO), Michelle Chartrand (University of Ottawa), Martin Elsner (Helmholtz Zentrum Munich), Jon Telling (University of Bristol), Ken Voglesonger (Northeastern Illinois University), L. Li (now Ass. Prof. Univ. of Alberta). Current are L. Douglas (PhD), T. Brisco (MSc), B. Esen (MSc); S.Mundle (PDF), K. Wilkie (PDF), E. Passeport (PDF).
Total number of graduate students advised is 25. Total number of postdoctoral scholars sponsored is12.

7. Collaborators

E. Edwards (University of Toronto), B. Sleep (University of Toronto), G. Slater (McMaster University), M. Simpson (University of Toronto), S. Mabury (University of Toronto), J. Brenan (University of Toronto), D. Muir (CCIW), N. Roulet (McGill University), L. Whyte (McGill University), C. McKay (NASA Ames), M. Allen (NASA JPL), T.C. Onstott (Princeton), J. Gossett (Cornell University), J. Spain (Georgia Tech), K.K. Lehmann (University of Virginia), P. Mahaffy (NASA Goddard), L. Pratt (Indiana University), S. Pfiffner (University of Tennessee), T. Phelps (ORNL), F. Brockman (PNNL), T. Kieft (NMIMT), T. Hazen (LBNL), S. Clifford (LPI), W. Pollard (McGill University), N. Perreault (McGill University), D. Anderson (SETI), J.K. Fredrickson (PNNL), K. Pederson (Goteborg University), C.J. Ballentine (University of Manchester), G. Southam (University of Western Ontario), G. R. Osinski (University of Western Ontario), N. Banerjee (University of Western Ontario), D. Moser (DRI), T. McCollom (LASP), J. Seewald (WHOI).

8. Consultation / advising to government bodies, etc.

NASA Mid-Range Rover Science Analysis Group member (MRR-SAG 2009)
NASA E2E SAG Advisory member (Sept. 2010- June 2011)
National Academies of Sciences Space Studies Board COEL committee (2005-11) and CAPS (2011-41)
Executive Committee Carnegie Institution of Washington Deep Carbon Observatory (2010-2013)
In Canada serve on Council (Advisory Board) for our national research funding organization (NSERC).

Biographical Sketch for Everett L. Shock
School of Earth & Space Exploration,
and Dept. of Chemistry & Biochemistry
Arizona State University, Tempe, AZ, 85287

Professional Preparation

Undergraduate: Univ. of California, Santa Cruz	Earth Sciences	B.S. 1978
Graduate: Univ. of California, Berkeley	Geology	Ph.D. 1987

Appointments

Professor, School of Earth & Space Exploration and Department of Chemistry & Biochemistry, Arizona State University (since July 2002).

Director, W.M. Keck Foundation Laboratory for Environmental Biogeochemistry, Arizona State University (since July 2002).

Director, Environmental Studies Program, Washington University, St. Louis, MO, USA (1993-2001).

Professor, Associate Professor, and Assistant Professor, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO, USA: (1987-2002).

Research Assistant, U.C. Berkeley: theoretical research in high-pressure/temperature inorganic and organic aqueous solution chemistry, chemical interaction of minerals and organic compounds with aqueous solutions in geochemical processes (six years).

Teaching Assistant, U.C. Berkeley: structural geology, introductory geology, theoretical geochemistry (one year).

Five Recent Publications Most Closely Related

Dick, J.M. and Shock, E.L. (2011) Calculation of the relative chemical stabilities of proteins as a function of temperature and redox chemistry in a hot spring. *PLoS ONE* 6(8), e22782. doi:10.1371/journal.pone.0022782

Manning, C.E., Shock E. L. and Sverjensky, D.A. (2013) The chemistry of carbon in aqueous fluids at crustal and upper-mantle conditions: experimental and theoretical constraints. *Reviews in Mineralogy & Geochemistry* (in press).

Paukert, A.P., Matter, J.M., Kelemen, P.B., Shock, E.L. and Havig, J.R. (2012) Reactive transport modeling of enhanced *in situ* CO_2 mineralization in the peridotite of the Samail ophiolite aquifer, Sultanate of Oman. *Chemical Geology* **330-331**, 86-100.

Shock, E.L. and Canovas P.C. (2010) The potential for abiotic organic synthesis and biosynthesis at seafloor hydrothermal systems. *Geofluids* **10**, 161-192.

Shock E.L., Holland, M.E., Meyer-Dombard, D.R., Amend, J.P., Osburn, G.R., and Fischer, T. (2010) Quantifying inorganic sources of geochemical energy in hydrothermal ecosystems, Yellowstone National Park, USA. *Geochim. Cosmochim. Acta* **74**, 4005-4043.

Five Additional Publications of Relevance to this Proposal

Cox, A. Shock, E. and Havig, J. (2011) The transition to microbial photosynthesis in hot spring ecosystems. *Chemical Geology* **280**, 344-351.

Havig, J.R., Raymond, J., Meyer-Dombard, D., Zolotova, N., and Shock, E.L. (2011) Merging isotopes and community genomics in a siliceous sinter-depositing hot spring. *Journal of Geophysical Research* **116**, G01005, doi:10.1029/2010JG001415.

Meyer-Dombard, D.R., Shock, E.L. and Amend, J.P. (2012) Effects of elevated trace element concentrations on culturing thermophiles. *Extremophiles* doi:10.1007/s00792- 012-0432-5.

Swingley, W.D., Meyer-Dombard, D.R., Alsop, E.B., Falenski, H.D., Havig, J.R., Shock, E.L. and Raymond, J. (2012) Coordinating environmental genomics and geochemistry reveals metabolic transitions in a hot spring ecosystem. *PLoS ONE* 7(6): e38108. doi:10.1371 /journal.pone.0038108.

Yang, Z., Gould, I.R., Williams, L., Hartnett, H., and Shock, E.L. (2012) The central role of ketones in reversible and irreversible hydrothermal organic functional group transformations. *Geochim.*

Cosmochim. Acta **98**, 48-65.

Synergistic Activities

- Development of thermodynamic databases for aqueous organic and inorganic species that are freely distributed over the internet, and used around the world.
- Application of High-Resolution Inductively-Coupled Plasma Mass Spectrometry to trace element studies of natural and human-impacted water resources, hydrothermal fluids, petroleum, and soils.
- Director of field research on hydrothermal ecosystems at Yellowstone National Park involving scientists from Arizona State University, Washington University, University of New Mexico, Yale, Stanford, MIT, University of Colorado, Carleton College, University of Waikato, McMaster University, Lawrence Livermore National Lab, Woods Hole Oceanographic Institution, University of North Carolina, University of Nevada-Las Vegas, NASA-Ames, University of Illinois-Chicago, Montana State University, University of Oslo, Universidad Nacional Autónoma de México, and China University of Geosciences - Wuhan.

Collaborators & Other Affiliations

Jan Amend (USC) Ariel Anbar (ASU), Eric Boyd (MSU), Steve Desch (ASU), Jeremy Dodsworth (UNLV), Tobias Fischer (U. New Mexico), Ian Gould (ASU), Hilairy Hartnett (ASU), Brian Hedlund (UNLV), Melanie Holland (Geotek), D'Arcy Meyer-Dombard (U. Ill. Chicago), John Peters (MSU), Sandra Pizzarello (ASU), Panjai Prapaipong (ASU), Jason Raymond (ASU), Matthew Stott (GNS-New Zealand), Paul Westerhoff (ASU), Lynda Williams (ASU), Hongyu Yu (ASU), Natalya Zolotova (ASU).

PhD Advisor: Harold C. Helgeson (UC Berkeley; deceased) *Postdoctoral Advisor:* none

Graduate Advisees: David Sassani (PhD, 1992, Golder Associates); Marc Willis (MS, 1993, Fullerton College); Tom McCollom (PhD, 1996, U. Colorado); Laura Wetzel (PhD, 1997, Eckerd College); Mitch Schulte (PhD, 1997, NASA HQ); Laura Griffith (PhD, 1998, Charleston Collegiate School); Panjai Prapaipong (PhD, 2001; ASU); Samantha Fernandes (MS, 2002; consulting); D'Arcy Meyer-Dombard (PhD, 2004, U. Ill. Chicago); Jennifer Smith (MS, 2006, Dugway Data Services Team); Brandon McLean (MS, 2007, HydroSystems, Inc.); Jeff Havig (PhD, 2009, Penn State); Todd Windman (PhD, 2010, ASU); Tracy Lund (MS, 2010, Dept. of Health, Minnesota); Xiaoding Zhuo (PhD, 2010, Germinian Capital, Boston); Ziming Yang (MS, 2011, PhD, current, C&B); Chris Glein (PhD, 2012, Geophysical Lab, Carnegie Institution, Washington, DC); Peter Canovas (PhD, current, SESE); Kris Fecteau (PhD, current, C&B); Brian St. Clair (PhD, current, ELS); Grayson Boyer (PhD, current, C&B); Kirt Robinson (PhD, current, C&B); Kristin Johnson (PhD, current, C&B); Apar Prasad (PhD, current, C&B); Peter Marsala (PhD, current, SESE); Alta Howells (PhD, current, Microbiology).
Post-doctoral Advisees: David Sassani (Golder Associates), Johnson Haas (U. Western Michigan), Jan Amend (Washington University), Mikhail Zolotov (ASU), Andrey Plyasunov, Melanie Holland (Geotek), Natalya Plyasunova, Jenny Cox (U. Guelph), Florian Schwandner (Earth Observatory of Singapore), Jeffrey Dick (Curtin University), Jeff Havig (Penn State), Jordan Okie (ASU).

Totals: Masters: 6; PhD: 21; Post-docs: 12.

Satish Singh

Laboratoire de Geosciences Marine
Institut de Physique du Globe de Paris
1 rue Jussieu, 75238 Paris, France
singh@ipgp.fr

EDUCATION

1987 Ph.D., Theoretical Seismology, University of Toronto, Canada 1980 Master of Science, Exploration Geophysics, Banaras Hindu University, India

PROFESSIONAL EXPERIENCE

2012 to-date Professor Class Exceptional, IPG Paris, France 1999 to 2012 Professor First Class, IPG Paris, France 1999 to-date Principal Research Fellow, University of Cambridge, U.K. 1997-1999 Senior Research Fellow, University of Cambridge, U.K. 1990-1997 Senior Assistant in Research, University of Cambridge, U.K. 1989-1990 Research Scientist, Elf Research Centre, Pau, France 1988-1989 Post-doctoral Fellow, Institut de Physique du Globe de Paris, France

AWARDS/SCHOLARSHIPS

2012 Prime d'Excellence Scientifique by the French Ministry of Education 2012 Laureate of the Agence Nationale de Recherche, Chaire Industrielle 2011 Grand Prix, French Academy of Sciences 2010 Elected AGU Fellow 2009 Distinguished Lecturer for European Association of Geoscientists and Engineers 2009 2009 Laureate of the French Ministry of Research in Scientific Innovation and Ecole des Mines de Paris and industry partners

Creation 2009 Cecil Green Scholar, Scripps Institution of Oceanography, California 2008 Cecil Green Scholar, Scripps Institution of Oceanography, California 2007 Visiting Scientist, Scripps Institution of Oceanography, California 2004 Visiting Scientist, Woods Hole Oceanographic Institution 1999 NERC Senior Research Fellowship 1996 Cecil Green Scholar, Scripps Institution of Oceanography, California 1983-1987 University of Toronto Open Fellowship. 1980 Gold Medal, Banaras Hindu University, India

ACADEMIC ACHIEVEMENTS

Publications: Author of more than 120 articles in international peer reviewed journals, and 10 in *Nature*, *Science*, *Nature Geoscience* Ph.D.: Supervised 27 Ph.D. students Present Ph.D.: Supervise (Co-) 15 Ph. D. Students in Paris and one in Cambridge Post-docs: Supervised 25 post-doctoral fellows LITHOS: Founder of LITHOS consortium of oil and service companies Marine Geosciences: Founder of Marine Geosciences Department at the IPG Paris French Ocean Bottom Seismometer Pool: Founder of the French OBS Pool SAGER: Creator of Sumatra Andaman Great Earthquake Research Initiative Master of Research: Creator of Master of Research in Exploration Geophysics in partnership with

SCIENTIFIC RESPONSIBILITIES

Director of Paris Exploration Geophysics (GPX) Group, 2012-2016 Member of the Scientific Council of Institut Francais du Pétrole Energies Nouvelles, 2012-2014 Director of Marine Geosciences Department, IPG Paris, 2001-2008

Project Leader, SAGER Project, 2005-2009 Director of LITHOS, 1998-2012, consortium of oil and service companies Director of the French OBS Pool, 2001-2010 Member of the Scientific Council of Institut de Physique du Globe de Paris, 2012-2014 Coordinator of NERIES broadband OBS (European Broadband Seismometer Network): 2006-2010 NSF Review Panel 2008-2011 NSF R/V Markus Langseth Panel, invited guest 2009-2010

RESEARCH EXPEDITIONS

Co-Chief Scientist, RHUM-RUM, 2012, R/V Marion Dufresne, Indian Ocean Chief Scientist, Pre-Tsunami Survey, 2009, S/V Geowave Champion (CGGVeritas), Sumatra Chief Scientist, PreTI-Gap cruise, 2008, R/V Baruna Jaya (Indonesia), Sumatra Chief Scientist, Sumatra-OBS, 2006, R/V Marion Dufresne (France), Sumatra Chief Scientist, Sumatra-Deep, 2006, WesternGeco Geco Searcher (Schlumberger), Sumatra Chief Scientist, SISMOMAR, 2005, N/O L'Atalante (France), Mid-Atlantic Ridge Chief Scientist, Test-OBS, 2004, N/O Suroît (France), Offshore Toulon Chief Scientist, SHALIMAR, 2003, N/O Suroît (France), Offshore Lebanon Chief Scientist, SEISMARMARA, 2001, N/O Le Nadir (France), Marmara Sea Chief Scientist, FIRST, 1998, R/V Pacific Horizon (Spectrum), 2D MCS, Falkland Co-Chief Scientist, ARAD, 1997, R/V Ewing (USA), 3D MCS and OBS, EPR Chief Scientist, SWABS, 1992, R/V Shatsky (Geco-Prakla), two vessels MCS and OBS, North Sea

IMPORTANT PUBLICATIONS **Singh**, S.C. et al. (2011). Aseismic zone and earthquake segmentation associated with a deep subducted seamount in Sumatra, *Nature Geoscience*, 4, 308-311. **Singh**, S.C. & Macdonald, K. (2009). Mantle skewness and ridge segmentation, *Nature*, 458, E11-12, doi: 10.1038/nature07887. **Singh**, S.C., Carton, H., Tapponnier, P. et al. (2008). Seismic evidence of broken crust in the 2004 Sumatra earthquake epicentral region, *Nature Geosciences,* 1, 777-781.

Singh, S.C., Crawford, W., Carton, H., Seher, T., Combier, V., Cannat, M., Canales, J., Dusunur, D., Escartin, J., Miranda, M. (2006a). Discovery of magma chamber and faults beneath a hydrothermal field at the Mid-Atlantic Ridge, *Nature*, 442, 1029-1033.
Singh, S.C., Harding, A., Kent, G., Sinha, M.C., Combier, V., Hobbs, R., Barton, P., White, R., Tong, V., Pye, J., Orcutt, J. (2006b). Seismic reflection images of Moho underlying melt sills at the East Pacific Rise, *Nature*, 442, 287-290.
Singh, S.C., Taylor, M. and Montagner, J.P. (2000). On the presence of liquid in Earth's inner core, *Science* 287, 2471-2474.
Kent, G.M, **Singh**, S.C, Harding, A.J., Sinha, M.C., Tong, V., Barton, P.J., Hobbs, R., White, R., Bazin, S., and Pye, J. (2000). Evidence from three-dimensional seismic reflectivity images for enhanced melt supply beneath mid-ocean-ridge discontinuities, *Nature*, 406, 614-618.
Singh, S.C. and Montagner, J.P. (1999). Anisotropy of iron in the inner core, *Nature*, 400, 629.
Singh, S.C., Kent, G., Collier, J., Harding A. and Orcutt J. (1998). Melt to Mush variations in the crustal magma properties beneath the Southern East Pacific Rise, *Nature*, 394, 874-878.
Singh, S.C., Minshull, T.A. and Spence, G.D. (1993). Velocity structure of a gas hydrate reflector, *Science*, 260, 204-20

ROBERT A. SOHN
Associate Scientist
Woods Hole Oceanographic Institution, Woods Hole, MA 02543

Born:
3 August, 1965; Indianapolis, Indiana U.S. citizen

Education:
Ph.D. 1996, Scripps Institution of Oceanography, Oceanography
B.S. 1987, Purdue University, Mechanical Engineering

Professional Appointments:

2003-present	Associate Scientist, Woods Hole Oceanographic Institution
1999-2003	Assistant Scientist, Woods Hole Oceanographic Institution
1998-1999	Assistant Project Scientist, Scripps Institution of Oceanography
1996-1998	Post-graduate researcher, Scripps Institution of Oceanography
1991-1996	Graduate Research Assistant, Scripps Institution of Oceanography
1987-1991	Project Engineer, McDonnell Douglas Inc., Long Beach, CA

Publications: Five Publications Relevant to the Proposed Project

Sohn, R. A., R. E. Thomson, A. B. Rabinovich, and S. F. Mihaly, Bottom pressure signals at the TAG deep-sea hydrothermal field: Evidence for short-period, flow-induced ground deformation, *Geophys. Res. Lett*., 36, L19301, doi:1029/2009GL040006, 2009.

Sohn, R. A., Stochastic analysis of exit-fluid temperature records from the active TAG hydrothermal mound (Mid-Atlantic Ridge, 26°N), 1. Modes of variability and implications for sub-surface flow, *J. Geophys. Res*., *112*, B07101, doi:10.1029/2006JB004435, 2007.

deMartin, B. J., R. A. Sohn, J. P. Canales, S. E. Humphris, Kinematics and geometry of active detachment faulting beneath the TAG hydrothermal field on the Mid-Atlatntic Ridge, *Geology*, 35(8), 711-714, doi: 10.1130/G23718A.1, 2007.

Sohn, R. A., A. H. Barclay, and S. C. Webb, Microearthquake patterns following the 1998 eruption of Axial Volcano, Juan de Fuca Ridge: Mechanical relaxation and thermal strain, *J. Geophys. Res*., *109*, B01101, doi:10.1029/2003JB002499, 2004.

Sohn, R. A., J. A. Hildebrand, and S. C. Webb, A microearthquake survey of the high-temperature vent fields on the volcanically active East Pacific Rise, *J. Geophys. Res*., *104(11)*, 25,367-25,378, 1999.

Five Other Publications

Karlstrom, L., S. Hurwitz, R. Sohn, J. Vandemeulebrouck, F. Murphy, M. R. Rudolph, M. Johnston, M. Manga, R. B. McCleskey, Eruptions at Lone Star Geyser, Yellowstone National Park, USA, Part 1: Energetics and Eruption Dynamics, *J. Geophys. Res*., submitted.

Pontbriand, C. W., S. A. Soule, R. A. Sohn, S. E. Humphris, C. Kunz, H. Singh, K. Nakamura, M. Jakobsson, T. Shank, Effusive and explosive volcanism on the ultraslow-spreading Gakkel Ridge, 85°E, *Geochem, Geophys. Geosyst*, *13(10)*, Q10005, doi:10.1029/2012GC004187, 2012.

Zhao, M., J. P. Canales, R. A. Sohn, Three-dimensional seismic structure of a Mid-Atlantic Ridge segment characterized by active detachment faulting (Trans-Atlantic Geotraverse, 25°55'N-26°20'N), *Geochem, Geophys. Geosyst*, *13(1)*, Q0AG13, doi:10.1029/2012GC004454, 2012.

Barreyre, T., S. Adam Soule, Robert A. Sohn, Dispersal of volcaniclasts during deep-sea eruptions: Settling velocities and entrainment in buoyant seawater plumes, *J. Volc. Geotherm. Res.*, 205, 84-93, doi:10.1016/j.jvolgeores.2011.05.006, 2011.

Sohn, R. A., and the *AGAVE* science team, Explosive volcanism on the ultraslow-spreading Gakkel ridge, Arctic Ocean, *Nature*, *453*, doi:10.1038/nature07075, 2008.

Synergistic Activities

Teaching: Active Source Marine Seismology (2006), Introduction to Marine Geology and Geophysics (2002-2005), Computational Data Analysis (2001), Geodynamics Seminar – Plume/Ridge Interactions (2001).

Professional Panels, Committees, and Societies: WHOI Marine Operations Committee (2006-2012), NSF R2K Distinguished Lecturer (2009), NSF R2K Steering Committee (2004-2007), ECOR Specialist Panel on Under-Ice AUV Operations (2006-2007), iODP Site Survey Panel (2001-2004), NSF Innovation in Graduate Education and Research Training Panel (2000), American Geophysical Union (member 1993-present).

Outreach: Research featured in NPR WNYC Radiolab (Season 5, Episode 5), "*Yellow Fluff and Other Curious Encounters*", and The Field Museum of Chicago exhibit, "*Exploring the Arctic Seafloor*".

Collaborators and Other Affiliations

Ph.D. advisors: Spahr Webb (LDEO), John Hildebrand (SIO)

Collaborators: Shaul Hurwitz (USGS, Menlo Park), Susan Humphris (WHOI), Rick Thomson (PGC – Canada), Jean Vandemuelebrouck, (IS Terre, France), Dan Fornari (WHOI), Ken Sims (U. Wyoming), Uri ten Brink (USGS), Pablo Canales (WHOI), Hedy Edmonds (UT), Tim Shank (WHOI), Hanu Singh (WHOI), Dana Yoerger (WHOI), Louis Whitcomb (Johns Hopkins), Militza Stojakovic (MIT), Dave Akin (U. Maryland), Robert Dunn (U. Hawaii), Timothy Crone (LDEO), Leif Karlstrom (Stanford), Malcolm Johnston (USGS, Menlo Park).

Students advised**:** Gregory Horning (Ph.D., exp. 2017), Thibaut Barryere (Ph.D. exp. 2013 – IPGP France), Claire Pontbriand (Ph.D, exp. 2012), Andrea Llenos (Ph.D., 2010), Bhaskar Deo (summer intern, 2010), Brian deMartin (Ph.D., 2007), Sacha Wichers (M.Sc., 2005), Juliana Gay (summer intern, 2006), Don Pfitsch (summer intern, 2000), Shawn Sorenson (summer intern, 1998).

Biographical Sketch

Martin Stute
Lamont-Doherty Earth Observatory of Columbia University
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& Barnard College
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A. Professional Preparation

University of Muenster and Heidelberg	Physics BS, MS 1985 (Diplompruefung)
University of Heidelberg	Physics PhD 1989 (Promotionspruefung)
Columbia University	Post-Doc, Earth&Environmental Science 1989-91

B. Appointments

2007-present	Ann Whitney Olin Professor of Environmental Science, Barnard College, CU
2006-present	Prof. & Co Chair, Environmental Science Dep., Barnard College, CU
2004-present	Senior staff member, Lamont-Doherty Earth Observatory
2001-2002	Visiting Professor at Biosphere 2 Center (Oracle, AZ), and the University of Arizona (Tucson, AZ)
2000-2006	Associate Professor of Environmental Science at Barnard College, CU
1999-present	Adjunct Research Scientist at the Lamont-Doherty Earth Observatory, CU
1996-present	Voting member of the Department of Earth and Environmental Science, CU
1995-2000	Assistant Professor of Environmental Science at Barnard College, CU
1995-1999	Adjunct Associate Research Scientist at the Lamont-Doherty Earth Observatory of CU
1991-1995	Associate Research Scientist at the Lamont-Doherty Earth Observatory, CU
1989-1991	Adjunct Associate Research Scientist at the Lamont-Doherty Earth Observatory, CU, supported by a fellowship of the Alexander v. Humboldt Foundation (Feodor Lynen program)
1989-1992	Research Assistant, Inst. for Environmental Physics, Univ. Heidelberg

C. Publications

i. Five Publications Most Relevant

1. Stute, M., J. Deak, K. Revesz, J.K. Boehlke, E. Deseo, R. Weppernig, and P. Schlosser (1997) Tritium/^{3}He dating of river infiltration: An example from the Danube in the Szigetkoez area, Hungary. *Ground Water*, 35, 905-911.
2. Stute, M., Y. Zheng, P. Schlosser, A. Horneman, R. K. Dhar, M. A. Hoque, A. A. Seddique, M. Shamsudduha, K. M. Ahmed, and A. van Geen. (2007). Increase in arsenic concentrations with groundwater age in shallow Bangladesh aquifers. *Water Res. Res* 43, 9.
3. Stute, M., C. Sonntag, J. Deak, and P. Schlosser (1992) Helium in deep circulating groundwater in the Great Hungarian Plain: Flow dynamics and crustal and mantle He fluxes. *Geochimica et Cosmochimica Acta*, 56, 2051-2067.
4. Lippmann J., Stute M., Torgersen T., Moser, D.P., Hall, J. Lin, L., Borcsik, M., Bellamy, R.E.S., and Onstott, T.C. (2003) Dating ultra-deep mine waters with noble gases and Cl-36, Witwatersrand Basin, South Africa *Geochmica et Cosmochimica Acta,* 67(23): 4597-4619.
5. Matter, J. M., D. S. Goldberg, R. H. Morin, and M. Stute (2006) Contact zone permeability at intrusion boundaries: new results from hydraulic testing and geophysical logging in the Newark Rift basin. *Hydrogeology Journal* , 14, 689-699.

ii. Five Other Significant Publications

1. Stute, M., M. Forster, H. Frischkorn, A. Serejo, J.F. Clark, P. Schlosser, W.S. Broecker, and G. Bonani (1995) Cooling of tropical Brazil (5°C) during the last glacial maximum. *Science*, 269, 379-383.
2. Stute, M. and P. Schlosser (1999) Atmospheric noble gases. In: *Environmental tracers in subsurface hydrology*, Cook, P.G., and Herczeg, A.L. (ed.), Kluwer, Boston, 349-377.
3. Stute, M., P. Schlosser, J.F. Clark, and W.S. Broecker (1992) Paleotemperatures in the southwestern United States derived from noble gas measurements in groundwater. *Science,* 256, 1000 -1003.
4. Castro, M.C., M. Stute, and P. Schlosser (2000) Comparison of ^{4}He ages and ^{14}C ages in simple aquifer systems: implications for groundwater flow and chronologies. *Applied Geochemistry,* 15, 1137-1167.
5. Marcantonio, F., R.F. Anderson, M. Stute, N. Kumar, P. Schlosser, and A. Mix (1996) Extraterrestrial He-3 as a constant-flux tracer for paleoceanographic studies. *Nature*, 383, 705-707.

D. Synergistic Activities

Undergraduate Research and Senior Seminar coordinator, Env. Sci. Dep., Barnard College (since 1997)
Advisory Committee, REU Lamont-Doherty Earth Observatory (since 2003)
Project Kaleidoscope F21 (Faculty for the 21st century) member (since 2001)

E. Collaborators and other Affiliations

(i) Collaborators, other than persons at home institution during last 48 months:

J.F. Clark (UC Santa Barbara), A.L. Herczeg (CSIRO, Australia)., F. Marcantonio (Tulane), T.C. Onstott (Princeton), F.M. Phillips (New Mexico Tech), N. Plummer (USGS, VA), S. Szabo (USGS, NJ), T. Torgersen (Univ. of Connecticut).

(ii) Graduate and postdoctoral advisors:

K.O. Münnich and T. Kirsten (University of Heidelberg); W.S. Broecker and P. Schlosser (LDEO, CU)

(iii) Thesis Advisor and Postgraduate-Scholar Sponsor

A. Caniano (LDEO), J.F. Clark (UC Santa Barbara), S. Higgins (LDEO), A. Horneman (Portland, ME), A. Keimowitz (LDEO), J. Nichols (LDEO), K. Radloff (LDEO), N. Santella (Mahwah, NJ), M. Tobin (Atlanta, GA), K. Wovkulich (LDEO), I. Mihajlov (LDEO), A. Pauckert (LDEO), D. Fernandez de la Reguera (LDEO), Shahla Ali (LDEO) **PostGraduate-Scholar Sponsor:** W. Aeschbach (Univ. Heidelberg), M.C. Castro (Univ. Michigan), J. Lippmann (Leipzig, Germany), F. Marcantonio (Texas A&M), M. Seidl (PEW Charitable Trust), G. Winckler (LDEO)

Eiichi TAKAZAWA

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Personal Born February 9, 1963, Saitama, Japan

Education **Massachusetts Institute of Technology** Cambridge, MADoctor of Philosophy in Geochemistry, September 1996. Thesis under Professor F. A. Frey and Dr. N. Shimizu on "Geodynamic Evolution of the Horoman Peridotite, Japan: Geochemical Study of Asthenospheric and Lithospheric Processes". Investigation of melt-mantle interaction based on trace element abundances and radiogenic isotope ratios of peridotites derived from the upper mantle.

Hokkaido University Sapporo, Japan
M.S. degree in Geology, March, 1989. Thesis under Professor K. Niida on "Petrological Study of the Horoman Ultramafic Complex, Japan".Investigation of melting process in the upper mantle based on major element compositions of the Horoman ultramafic rocks.

Hokkaido University Sapporo, Japan
B.S. degree in Geology, March, 1986. Thesis under Professor K. Niida on "Stratification of the Horoman Ultramafic Complex, Japan". Geologic mapping and petrographic investigation of the Horoman ultramafic rocks.

Professional
Experience **Japanese Society for the Promotion of ScienceResearch Fellow -DC** Kumamoto UniversityApril - August 1990

Research Assistant Massachusetts Institute of TechnologySept 1990 - Jan 1994; June 1994 - June 1996

Teaching Assistant Massachusetts Institute of TechnologyFeb - May 1994 (Analysis of Geological Material)

COE Fellow National Institute for Research in Inorganic MaterialsAugust 1996 -September 1997

Lecturer Niigata UniversityOctober 1997 - June 1999

Associate Professor Niigata UniversityJuly 1999 - present

Professional
Societies American Geophysical UnionGeochemical SocietyGeological Society of JapanGeochemical Society of JapanJapan Association of Mineralogical SciencesVolcanological Society of Japan

Research
Field Petrology and geochemistry of orogenic peridotites, abyssal peridotites and ophiolite mantle section

ODP&IODP
Experience ODP Leg 209 to Mid-Atlantic Ridge 15°20' Fracture Zone as igneous scientist May to July 2003

Organization of 2nd Post-cruse meeting for ODP Leg 209, Samani, Hokkaido, Japan (June 23 -25, 2005)

SSEP member from April 2007 to March 2010

J-DESC IODP section executive committee member from April 2007 to March 2011

PEP member from December 2011 to present

Publications

Agashev, A.M., Pokhilenko, N.P., Takazawa, E., McDonald, J.A., Vavilov, M.A., Watanabe, T., Sobolev, N.V. (2008) Primary melting sequence of a deep (> 250 km) lithospheric mantle as recorded in the geochemistry of kimberlite–carbonatite assemblages, Snap Lake dyke system, Canada. *Chemical Geology*, **255**, 3-4, 317-328.

Takazawa, E., Abe, N., Seyler, M. and Meurer, W. P. (2007) Hybridization of Dunite and Gabbroic Materials in Hole 1271B from Mid-Atlantic Ridge 15°N: Implications for Melt Flow and Reaction in the Upper Mantle. In Kelemen, P.B., Kikawa, E., and Miller, D.J. (Eds.), *Proceedings of Ocean Drilling Program, Science Results*, **209**, 1–23, doi:10.2973/odp.proc.sr.209.005.2007.

Morishita, T., Takazawa, E. et al. (2006) Corundum-bearing mafic granulites in the Horoman (Japan) and Ronda (Spain) Peridotite Massifs: Possible remnants of recycled crustal materials in the mantle. Island Arc, 15, 2-3.

Shuto, K., Ishimoto, H., Hirahara, Y., Sato, M., Matsui, K., Fujibayashi, N., Takazawa, E., Yabuki, K., Sekine, M., Kato, M., and Rezanov, A. I. (2006) Geochemical secular variation of magma source during Early to Middle Miocene time in the Niigata area, NE Japan: Asthenospheric mantle upwelling during back-arc basin opening. Lithos, 86, 1-33.

Obata, M. and Takazawa, E. (2004) Compositional continuity and discontinuity in the Horoman peridotite, Japan, and its implication for melt extraction processes in partially molten upper mantle. *J. Petrol*., **45**, 223-234.

Takazawa, E., Okayasu, T. and Satoh, K. (2003) Geochemistry and origin of the basal lherzolites from the northern Oman ophiolite (northern Fizh block). *Geochem. Geophys. Geosyst.,* 4(2), 1021, doi:10.1029/2001GC000232.

Toramaru, A., Takazawa, E., Morishita, T. and Matsukage, K. (2001) Model of layering formation in a mantle peridotite (Horoman, Hokkaido, Japan). *Earth and Planetary Science Letters*, vol. 185, pp. 299-313.

Saal, A.E., Takazawa, E., Frey, F.A., Shimizu, N. and Hart, S.R. (2001) Re-Os isotopes in the Horoman Peridotite: evidence for refertilization? *Journal of Petrology*, vol. 42, pp. 25-37

Dr. Alexis S. Templeton
Department of Geological Sciences, University of Colorado, Boulder CO 80309-0399

EDUCATION

2002	Ph.D. in Aqueous and Environmental Geochemistry, Stanford University
1996	M.S. in Geochemistry, Dartmouth College
1993	A.B. with high honors in Earth Sciences, Dartmouth College

APPOINTMENTS

20012-Present	***Associate Professor*** Department of Geological Sciences, University of Colorado at Boulder
2005-2001	***Assistant Professor*** Department of Geological Sciences, University of Colorado at Boulder
2002-2005	***NSF Postdoctoral Fellow,*** Microbial Biology Scripps Institution of Oceanography, Marine Biology Research Division
1997-2002	***Graduate Research Assistant*** Geological & Environmental Sciences, Stanford University
1995-1997	***Senior Research Associate***, Center for Isotope Geochemistry, Earth Sciences Division, Lawrence Berkeley National Laboratory
1993-1995	***Graduate Research Assistant*** Department of Earth Sciences, Dartmouth College

AWARDS AND HONORS

2012	Geobiology & Geomicrobiology Division Award, GSA
2011	Department of Energy Early Career Award
2006	David and Lucille Packard Foundation Fellowship
2006	F.W. Clarke Medal, Geochemical Society
2005	Popular Science 4th Annual Brilliant 10
2004	Rosalind Franklin Young Investigator Award, Advanced Photon Source
2002-2004	NSF Microbial Biology Postdoctoral Fellowship
1999	Wolf Vishniac Award, ISEB

RELEVANT EXPERIENCE

Field experience in subsurface fluid-flow, subsurface biosphere and water-rock interactions in terrestrial and submarine environments in New Zealand, Colorado, Canadian High Arctic, Hawaii and Samoa. Specific expertise in microbe-mineral interactions & life detection, including the development of synchrotron-based X-ray spectroscopic techniques, cultivation of chemo-lithoautotrophic bacteria, and application of electron microscopy & isotope geochemistry.

SELECTED SYNERGISTIC ACTIVITIES

Advisory Member: NSF-RCN Seamount Biogeosciences Network, 2005-Present

Recent Participant, ICDP-Sloan sponsored "Oman Drilling workshop" and DOE-ERSP Strategic Planning Workshop in "Subsurface Complex System Science".

Panelist: NASA Exobiology and Evolutionary Biology Panel; National Science Foundation Low-Temperature Geochemistry & Geobiology

Editorial Board: *Geobiology Journal*; Review Editor: *Frontiers in Microbiological Chemistry.*

TEN RECENT PUBLICATIONS MOST RELEVANT TO PROPOSAL

Gleeson, D.F., Pappalardo, R.T., Anderson, M.S., Grasby, S.E., Wright, K.E., **Templeton, A.S.**, 2012, Life detection at an Arctic analog to Europa. *Astrobiology Journal* v. 12, 135-150.

Swanner, E.D., **Templeton, A.S.**, 2011 Potential for nitrogen fixation and nitrification in the granite subsurface at Henderson Mine, CO. *Frontiers in Extreme Microbiology* 2:254.

Mayhew, L.E., Webb, S.M., and **Templeton, A.S.**, 2011, Microscale imaging and identification of Fe speciation and distribution during fluid-mineral interactions under highly reducing conditions. *Environmental Science and Technology*. doi:10.1021/es104292n.

Swanner, E.D., Nell, R., and **Templeton, A.S.**, 2011, *Ralstonia* species mediate Fe-oxidation in circumneutral, metal-rich subsurface fluids of Henderson Mine, CO. *Chemical Geology,* v. 284, p. 339-350.

Gleeson, D.F., Williamson C.H.D., Grasby S.E., Spear J.R., Pappalardo R.T., **Templeton A.S.**, 2011, Low temperature S^0 biomineralization at a supraglacial spring system in the Canadian High Arctic, *Geobiology Journal* v. 9, p. 360-375.

Templeton, A.S., Knowles, E.J., Eldridge, D.L., Arey, B.W., Dohnalkova, A., Webb, S.M., Bailey, B.E., Tebo, B.M., Staudigel, H.S., 2009, A seafloor microbial biome hosted within incipient ferromanganese crusts. *Nature Geoscience* v. 2, p. 872-876.

Templeton, A., and Knowles, E., 2009, Microbial transformations of minerals and metals: recent advances in Geomicrobiology derived from synchrotron-based x-ray spectroscopy and x-ray microscopy. *Annual Reviews in Earth and Planetary Sciences*, v.37, p. 245-260.

Templeton, A.S., Conrad, M.E., Chu, K.H., Alvarez-Cohen, L., 2006, Metabolic controls on the carbon isotope fractionations expressed by methane-oxidizing bacteria. *Geochimica et Cosmochimica Acta* v. 70, p.1739-1752.

Templeton, A.S., Staudigel, H., Tebo, B.M., 2005, Diverse Mn(II)-oxidizing bacteria isolated from submarine basalts at Loihi Seamount *Geomicrobiology Journal*, v. 22, 129-137.

ADVISORS

Dr. Gordon Brown (Stanford University), Dr. Page Chamberlain (Stanford University), Dr. Bradley Tebo (Oregeon Health Sciences University).

GRADUATE STUDENTS ADVISED

Dr. Damhnait Gleeson (Center for Astrobiology, Spain), Dr. Elizabeth Swanner (University of Tubingen, Germany), Dr. Lisa Mayhew (University of Colorado), Dr. Emily Knowles (Jet Propulsion Laboratory), Dr. Katherine Wright (University of Bristol), Graham Lau (current), Hannah Miller, Current.

RECENT COLLABORATORS

Thomas McCollom (University of Colorado), Spear, John (Colorado School of Mines), Thomas Trainor (University of Alaska), Peter Eng (University of Chicago), Sam Webb (SSRL), Robert Pappalardo (JPL), Steven Grasby (Canadian GS), Staudigel, Hubert (UCSD), Tebo, Bradley (OHSU), Butler, Alison (University of California, SB), Connell, Laurie (University of Maine), Dohnalkova, Alice (PNNL), Arey, Bruce (PNNL), Harald Furnes (University of Bergen), Nicola McLoughlin (University of Bergen), Conrad, Mark (LBNL), Kieft, Tom (New Mexico Tech), Smith, Dick (US Geological Survey), Wanger, Greg (Craig Ventner Institute), Gorby, Yuri (Craig Ventner Institute), Brandy Toner (University of Minnesota), Katrina Edwards (USC), Richard Wirth (Helmholtz Center, Potsdam), Daniel Fliegel (University of Berge

Susumu UMINO

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Ishikawa 920-1192, Japan

Phone: +81-76-264-6522
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Citizenship: Japan

Education:
B.S., Petrology & Geology, University of Tokyo, 1981
M.S., Petrology & Geology, University of Tokyo, 1983
PhD, Petrology & Geology, University of Tokyo, 1987

Professional Experience:
Research fellow of JSPS, 1987-1988
Assistant Professor, Institute of Geosciences, Faculty of Science, Shizuoka University, 1988-1992
Lecturer, Department of Biology and Geosciences, Faculty of Science, Shizuoka University, 1992-1993
Associate Professor, Department of Biology and Geosciences, Faculty of Science, Shizuoka University, 1993- 2004
Professor, Department of Geosciences, Faculty of Science, Shizuoka University, 2004- 2007
Professor, Department of Earth Sciences, Kanazawa University, 2008-Present

Selected seagoing experience:
1991 JOIDES Resolution, DOP Leg 140, Costa Rica Rift, site 504B
1998 YOKOSUKA-KAIKO, Off Hawaii Islands
2002 YOKOSUKA-SHINKAI 6500, Off Hawaii Islands
2002- 2003 JOIDES Resolution, ODP Leg 206, Cocos plate off Nicaragua, site 1256
2004 YOKOSUKA-SHINKAI 6500, southern East Pacific Rise14S (Chief Scientist)
2005 JOIDES Resolution, IODP EXP 309, Cocos plate off Nicaragua, site 1256 (D. Teagle, S. Umino, co-chiefs)
2008 YOKOSUKA-SHINKAI 6500, Mariana Trough (Chief: Fujiwra, T.)
2009 YOKOSUKA-SHINKAI 6500, Bonin Ridge (Chief: Ishizuka, O.)
Selected international workshop on scientific drilling experience:
1997 CONference on Cooperative Ocean Riser Drilling, Tokyo
2006 Mission Moho Workshop, Portland
2009 Melting, Magma, Fluids and Life, NOC Southampton
2009 IODP New Ventures in Exploring Scientific Targets (INVEST), Bremen
2010 The MoHole, Kanazawa

Synergistic activities:
Guest editor of Geophysics, Geochemistry, Geosystems, AGU, 2001-2004
Member, Earth Interior Panel, Japan Drillin Earth Science Consortium, 2003-2006
Member, Science Steering and Evaluation Panel, Integrated Ocean Drilling Program, 2003-2006
Member, Science Planning committee, Integrated Ocean Drilling Program, 2009-2011
Editor-in-Chief, Island Arc, Geological Society of Japan, 2012-

Selected Publications

Kanayama, K., Umino, S., and Ishizuka, O., 2012. Eocene volcanism during the incipient stage of Izu–Ogasawara Arc: Geology and petrology of the Mukojima Island Group, the Ogasawara Islands. Island Arc, 21, 288 – 316, DOI: 10.1111/iar.12000.
Umino, S., 2012. Emplacement mechanism of off-axis large submarine lava field from the Oman Ophiolite. J. Geophys. Res., 117, B11210, doi:10.1029/2012JB009198.
Kusano, Y., Adachi, Y., Miyashita, S. and Umino, S., 2012. Lava accretion system around mid-ocean-ridges: Volcanic stratigraphy in the Wadi Fizh area, northern Oman ophiolite, Geochem. Geophys. Geosyst. , 13, Q05012, doi:10.1029/2011GC004006.
Asada, M., Fujiwara, T. and Umino, S., 2012. Implications of volcanic activity in the central Mariana Trough median valley, based on the deep-towed side-scan sonar imagery and manned submersible observations (in Japanese with English abstract). Bull. Volcanol. Soc. Japan, 57, 1 - 18.
Ishizuka, O., Tani, K., Reagan, M.K., Kanayama, K., Umino, S., Harigane, Y., Sakamoto, I., Miyajima, Y., Yuasa, M. and Dunkley, D.J., 2011. The timescales of subduction initiation and subsequent evolution of an oceanic island arc. Earth Planet. Sci. Lett., 306, 229 - 240.
Tominaga, M. and Umino, S., 2010. Lava deposition history in ODP Hole 1256D: Insights from log-based volcanostratigraphy. Geochem. Geophys. Geosyst., Q05003, doi: 10.1029/2009GC002933.
Umino, S., Crispini, L., Tartarotti, P., Teagle, D.A.H., Alt, J.C., Miyashita, S. and Banerjee, N.R., 2008. The origin of the sheeted dike complex at superfast spread East Pacific Rise revealed by deep ocean crust drilling at ODP Hole 1256D. Geochem. Geophys. Geosyst., Q06O08, doi: 10.1029/2007GC001760.
Geshi, N., Umino, S., Kumagai, H., Sinton, J.M., White, S.M., Kishimoto, K. and Hilde, T.W., 2007. Discrete plumbing systems and heterogeneous magma sources of a 24 km3 off-axis lava field on the western flank of East Pacific Rise, 14°S. Earth Planet. Sci. Lett., 258, 61 - 72.
White, S.M., Umino, S. and Kumagai, H., 2006. Transition from seamount chain to intraplate volcanic ridge at the East Pacific Rise. Geology, 34, 293 - 296.
Umino, S., Nonaka, M. and Kauahikaua, J., 2006. Emplacement of subaerial pahoehoe lava sheet flows into water: 1990 Kūpaianaha flow of Kilauea Volcano at Kaimū Bay, Hawai`i. Bull. Volcanology, 69, 125-139. DOI 10.1007/s00445-006-0059-4.
Umino, S., Miyashita, S., Hotta, F. and Acachi, Y., 2003. Along-Strike Variation of the Sheeted Dike Complex in the Oman Ophiolite — Insights into Subaxial Ridge Segment Structures and Magma Plumbing System. Geochem. Geophys. Geosyst., 8618, doi:10.1029/2001GC000233.
Umino, S., Obata, S., Lipman, P., Smith, J.R., Shibata, T., Naka, J. and Trusdell, F., 2002. Emplacement and Inflation Structures of Submarine and Subaerial Pahoehoe Lavas From Hawaii. In Takahashi, E. et al., (eds.), Hawaiian Volcanoes: Deep Underwater Perspectives, AGU Monograph, 128, 85-101.
Umino, S., Lipman, P.W. and Obata, S., 2000. Subaqueous lava flow lobes, observed on ROV KAIKO dives off Hawaii. Geology , 28, 502 - 506.

Biographical Sketch - Jessica M. Warren

Education

University of Cambridge	B.A., Natural Sciences, 1999
University of Cambridge	M.Sci., Earth Sciences, 2000
University of Cambridge	M.A., Natural Sciences, 2003
MIT/WHOI Joint Program	Ph.D., Geochemistry & Geophysics, 2007
Carnegie Institution of Washington	Postdoctoral Fellow, Geochemistry, 2008-2010

Academic Appointments

2010-present	*Assistant Professor*, Stanford University
2008-present	*Guest Investigator*, Woods Hole Oceanographic Institution
2008-2010	*Postdoctoral Fellow*, Carnegie Institution of Washington
2007	*Postdoctoral Investigator*, Woods Hole Oceanographic Institution
2005-2006	*COE-21 Collaborative Researcher*, Okayama University at Misasa
2001-2007	*Graduate Research Assistant*, MIT/WHOI Joint Program

Five Publications Related to Proposed Research:

Warren, J.M. and S.B. Shirey (2012). Pb and Os isotopic constraints on the oceanic mantle from single abyssal peridotite sulfides, *Earth and Planetary Science Letters*, 359-360, 279-293.

Skemer, P., J.M. Warren, P.B. Kelemen, and G. Hirth (2010). Microstructural and rheological evolution of a mantle shear zone, *J. Petrology*, 51(1-2), 43-53.

Warren, J.M., N. Shimizu, C. Sakaguchi, H.J.B. Dick, and E. Nakamura (2009). An assessment of upper mantle heterogeneity based on abyssal peridotite isotopic compositions, Journal of Geophysical Research, *J. Geophys. Res.*, 114, B12203, doi:10.1029/2008JB006186.

Warren, J.M., G. Hirth and P.B. Kelemen (2008). Evolution of olivine lattice preferred orientation during simple shear in the mantle, *Earth and Planetary Science Letters*, 272, 501-512.

Warren, J.M. and G. Hirth (2006). Grain Size Sensitive Deformation Mechanisms in Naturally Deformed Peridotites, *Earth and Planetary Science Letters*, 248, 423-435.

Five Additional Publications

Recanati A., M.D. Kurz, J.M. Warren, J. Curtice, 2012. Helium distribution in a mantle shear zone from the Josephine Peridotite, *Earth and Planetary Science Letters*, 359-360, 161-172.

Skemer, P., J.M. Warren and G. Hirth, 2012. Interpreting mantle seismic anisotropy in complex kinematic settings, *G-Cubed*, 13, Q03006, doi:10.1029/2011GC003988.

Warren, J.M. and N. Shimizu (2010). Cryptic Variations in Abyssal Peridotite Composition: Evidence for Recent Melt-Rock Reaction at the Ridge, *J. Petrology*, 51(1-2), 395-423.

Dick, H.J.B., C.J. Lissenberg and J.M. Warren (2010). Mantle Melting, Melt Transport, and Delivery Beneath a Slow-Spreading Ridge: The Paleo-MAR from 23°15'N to 23°N, *J. Petrolog*y, 51(1-2), 425-467.

Kurz, M.D., J.M. Warren and J. Curtice (2009). Mantle deformation and noble gases: helium and neon in oceanic mylonites, *Chemical Geology*, 266, 10-18.

Synergistic Activities:

(i) Educational Activities:

Stanford, 2012-2013: GES190 *Ultramafics of California and Oregon (2 week field class)*; GES 315 *Literature of Structural Geology*; GES340 *Oxidation State of the Earth's Interior*
Stanford, 2011-2012: GES209 *Microstructures*; GES382 *Mantle Geochemistry*; GES104 *Introduction to Petrology*;
Stanford, 2010-2011: GES340 *Volatiles in the Mantle*; GES104 *Introduction to Petrology*.

(ii) Service:
Steering committee, 2011-present: Physical Properties of Earth Materials, AGU focus group;
Council member, 2009: Geological Society of Washington.

(iii) Reviewer:
Proposal reviewer, 2008-present: NSF, DOE, InterRidge; FONDECYT.
Manuscript reviewer, 2002-present: *Nature, Nature Geoscience, G-Cubed, Contributions to Mineralogy and Petrology*, *Earth and Planetary Science Letters*, *Journal of Petrology*.

(iv) Conference Sessions:
Co-convener, 2011 AGU Fall Meeting: *Volatiles in the Earth's Mantle*;
Co-convener, 2011 AGU Fall Meeting: *Integrated Study of Oceanic Spreading Centers: From Mid-Ocean Ridges to Back-Arc Basins*;
Co-convener, 2009 AGU Fall Meeting: *Using Small-Scale Observations to Answer Big Questions in Earth Sciences: Advances From 30 Years of Ion Microprobe Analysis*;
Co-convener, 2007 AGU Fall Meeting: *Origin and Evolution of Continents: Lithospheric and Asthenospheric Perspectives*.

(v) Workshop Participation:
2012 – Workshop on Scientific Drilling in the Samail Ophiolite, Sultanate of Oman; 2012 – Workshop on Advancing Experimental Rock Deformation Research; 2012 – IODP Building U.S. Strategies for 2013-2023 Scientific Ocean Drilling; 2011 – EarthScope Institute on the Lithosphere-Asthenosphere Boundary; 2010 – DCO Workshop on Reaching the Mantle Frontier; 2009 – MARGINS Theoretical and Experimental Institute: Volatiles in the Subduction Factory; 2009 – CIDER Community Workshop; 2009 – Marine Geoscience Leadership Symposium; 2006 – 2nd Cooperative Inst. for Deep Earth Research.

Collaborators & Other Affiliations

Collaborators: J. Blusztajn (WHOI); E. Cottrell (Smithsonian); P. Craddock (Schlumberger); J. Curtice (WHOI); N. Dauphas (U Chicago); J. Day (Scripps); H. Dick (WHOI); M. Godard (U Montepllier II); J. Harvey (U Leeds); E. Hauri (CIW); G. Hirth (Brown U); B. Ildefonse (U Montepllier II); C. Johnson (PSI); P. Kelemen (LDEO); M. Kurz (WHOI); K. Lawrence (PSI); J. Lissenberg (Cardiff U); E. Nakamura (ISEI); A. Recanati (ENSG, France); S. Roeske (UC Davis); C. Sakaguchi (ISEI); A. Shahar (CIW); N. Shimizu (WHOI); S. Shirey (CIW); P. Skemer (Washington U in St Louis); C. Teyssier (U Minnesota); R. Walker (U Maryland); M. Zimmerman (U Minnesota).

Graduate Advisors and Postdoctoral Sponsors: Graduate: Henry J.B. Dick (WHOI), Greg Hirth (Brown U), Nobumichi Shimizu (WHOI); Postdoctoral: S.B. Shirey (CIW).

Thesis Advisor: Megan D'Errico (current); Nik Deems (current); Suzanne Birner (current); Katie Kumamoto (current).
Postgraduate-Scholar Sponsor: Lars Hansen (2012-present).