

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 Agrokippia 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/km³, 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 CO₂ result in permanent storage of carbon in form of carbonate minerals. Mantle peridotites have the potential to store gigatons of CO₂ 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 CO₂ injection into a basalt formation for studying the feasibility of permanent CO₂ storage via mineral carbonation. Basalt, similar to mantle peridotite reacts with CO₂ to form calcium carbonate. An injection of pure CO₂ (~170 tons) was accomplished in May 2012, followed by a continuous CO₂+H₂S 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 CO₂ with the basaltic host rocks.

A similar project, which involves the injection of 1,000 tons of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

References for Appendix 1

- Bednarz, U. and Schmincke, H.-U., (1989). Mass transfer during sub-seafloor alteration of the upper Troodos crust (Cyprus). *Contributions to Mineralogy and Petrology*. 102: 93-101.
- Bednarz, U. and Schmincke, H.-U., (1990). Chemical patterns of seawater and hydrothermal alteration in the northeastern Troodos extrusive series and sheeted dyke complex, Cyprus: in Malpas, J., Moores, E., Panayiotou, A. and Xenophontos, C., eds., *Proceedings of the Symposium on ophiolites and oceanic lithosphere - Troodos 87*. Nicosia, Cyprus Geological Survey Department: 639-654.
- Bickle, M.J. and Teagle, D.A.H., (1992) Strontium alteration in the Troodos ophiolite: implications for fluid fluxes and geochemical transport in mid-ocean ridge hydrothermal systems. *Earth Planet. Sci. Lett.* 113: 219-237.
- Brazelton, W., D. Cardace, G. Fruh-Green, S.Q. Lang, M.D. Lilley, P.L. Morrill, N. Szponar, K.I. Twing, M.O. Schrenk (2012) Biogeography of serpentinite-hosted microbial ecosystems [invited talk] Abstract B41F-07 presented at 2012 Fall Meeting, AGU, San Francisco, CA, 3-7 Dec.
- Browning, P., Roberts, S., and Alabaster, T., (1989). Fine scale modal layering and cyclic units in ultramafic cumulates from the CY-4 borehole, Troodos ophiolite, Cyprus. In Gibson, I.L., Malpas, J., Robinson, P.T. and Xenophontos, C., (eds.). *Cyprus Crustal Study Project: Initial Reports, Hole CY-4*. Geological Survey of Canada Paper . 88-9:193-220.
- Cardace, D., Schrenk, M., McCollom, T., Hoehler, T., 2011. Parameterizing Subsurface Habitat in the Serpentinizing Coast Range Ophiolite: a new integrative opportunity for the astrobiology community, NASA Astrobiology Institute Director's Discretionary Fund.
- Cardace, D., D. Carnevale, M.O. Schrenk, K.I. Twing, T.M. McCollom, T.M. Hoehler (2012) Mineral Controls on Microbial Niche Space in Subsurface Serpentinites of the Coast Range Ophiolite, Northern California. [poster] Abstract B43G-0511 presented at 2012 Fall Meeting, AGU, San Francisco, CA, 3-7 Dec.
- Gibson, I.L., Malpas, J., Robinson, P.T. and Xenophontos, C., (1989). *Cyprus Crustal Study Project: Initial Reports, Hole CY-4*. Geological Survey of Canada Paper. 88-9: 393p.
- Gibson, I.L., Malpas, J., Robinson, P.T. and Xenophontos, C., (1991). *Cyprus Crustal Study Project: Initial Report, Holes CY-1 and 1A*. Geological Survey of Canada Paper. 90-20: 283p.
- Gillis, K.M. and Robinson, P.T., (1988). Distribution of alteration zones in the upper oceanic crust. *Geology*. 16: 262-266.
- Gillis, K.M. and Robinson, P.T., (1990b). Patterns and processes of alteration in the lavas and dykes of the Troodos ophiolite, Cyprus. *Journal of Geophysical Research*. 95 (B13): 21 523-21 548.
- Gislason, S.R., Wolff-Boenisch, D., Stefansson, A., Oelkers, E.H., Gunnlaugsson, E., Sigurdardottir, H., Sigfusson, B., Broecker, W.S., Matter, J.M., Stute, M., Axelsson, G. and Fridriksson, T. (2010). Mineral sequestration of carbon dioxide in basalt: A pre-injection overview of the CarbFix project. *International Journal of Greenhouse Gas Control*, 4, 537-545
- IODP (2011) *Illuminating Earth's Past, Present, and Future, 2011. The International Ocean Discovery Program: Exploring the Earth under the sea: Science plan for 2013-2023: Integrated ocean Drilling Program Management International* (Washington DC), 92p. <http://www.iodp.org/Science-Plan-for-2013-2023/>
- Kelemen, P.B. and J. Matter, In situ mineral carbonation in peridotite for CO₂ storage, *Proc. National Acad. Sci.* 105, 17,295-17,300, 2008
- 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 CO₂ capture and storage, *Ann. Rev. Earth Planet. Sci.* 39, 545-76, 2011
- Muenow, D.W., Garcia, M.O., Aggrey, K.E., Bednarz, U. and Schmincke, H.U., (1990). Volatiles in submarine glasses as a discriminant of tectonic origin: application to the Troodos ophiolite. *Nature*. 343: 159-161.
- Rautenschlein, M., Jenner, G.A., Hertogen, J., Hofmann, A.W., Kerrich, R., Schmicke, H.-U. and White, W.M., (1985). Isotopic and trace element compositions of volcanic glasses from the Akaki Canyon, Cyprus: implications for the origin of the Troodos ophiolite. *Earth and Planetary Science Letters*. 75: 369-383.
- Richards, H.G., Cann, J.R. and Jensenius, J., (1989). Mineralogical zonation and metasomatism of the alteration pipes of Cyprus sulfide deposits. *Economic Geology*. 84: 91-115.
- Richardson, C.J., Cann, J.R., Richards, H.G. and Cowan, J.G., (1987). Metal-depleted root zones of the Troodos ore-forming hydrothermal systems, Cyprus. *Earth and Planetary Science Letters*. 84: 243-253.
- Robinson, P.T., Gibson, I.L. and Panayiotou, A., (1987). *Cyprus Crustal Studies Project: Initial Reports, Holes CY-2 and 2a*. Geological Survey of Canada Paper. 85-29: 381p.
- Schiffman, P. and Smith, B.M., (1988). Petrology and O-isotope geochemistry of a fossil hydrothermal system within the Solea graben, northern Troodos ophiolite, Cyprus. *Journal of Geophysical Research*. 93: 4612-4624.

- Schiffman, P., Smith, B.M., Varga, R.J. and Moores, E.M., (1987). Geometry, conditions and timing of off-axis hydrothermal metamorphism and ore-deposition in the Solea graben. *Nature*. 325: 423-425.
- Schmincke, H.-U., Rautenschlein, M., Robinson, P.T. and Mehegan, J.M., (1983). Troodos extrusive series of Cyprus: a comparison with oceanic crust. *Geology*. 11: 405-409.
- Schrenk, M.O., C. George, K.I. Twing, W.J. Brazelton (2012) Alkaliphilic Clostridia and the Serpentinite-Hosted Deep Biosphere. [poster] Abstract B51A-474 presented at 2012 Fall Meeting, AGU, San Francisco, CA, 3-7 Dec.
- Teagle, D.A.H., Ildefonse, B., Blackman, D.K., Edwards, K., Bach, W., Abe, N., Coggon, R., and Dick, H., 2009. Melting, Magma, Fluids and Life; Challenges for the next generation of scientific ocean drilling into the oceanic lithosphere. Workshop Report. Southampton, July 2009, <http://www.interridge.org/WG/DeepEarthSampling/workshop2009>
- Twing, K.I., W.J. Brazelton, A. Kloysuntia, D. Cardace, T.M. Hoehler, T.M. McCollom, M.O. Schrenk (2012) Identity and Metabolic Potential of the Serpentinite Subsurface Microbiome [poster] Abstract B51A-480 presented at 2012 Fall Meeting, AGU, San Francisco, CA, 3-7 Dec.
- Varga, R.J. and Moores, E.M., (1985). Spreading structure of the Troodos ophiolite, Cyprus. *Geology*. 13: 846-850.

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.

Oman Drilling Workshop Steering Committee

Ali Al Rajhi (Assistant Director General of Minerals, Ministry of Commerce & Industry, Oman)
Marguerite Godard (Chargée de Recherche, Université de Montpellier II, France)
Benoit Ildefonse (Directeur de Recherche, Université de Montpellier II, France)
Peter Kelemen (Vice Chair, Dept. of Earth & Environmental Sciences, Columbia University, USA)
Jürgen Koepke (Professor, Leibniz Universitaet, Germany)
Chris MacLeod (Professor, Cardiff University, UK)
Craig Manning (Chair, Dept. of Earth & Space Sciences, UCLA, USA)
Katsu Michibayashi (Professor, Shizuoka University, Japan)
Sobhi Nasir (Head, Dept. of Earth Sciences, Sultan Qaboos University, Oman)
Everett Shock (Professor, Arizona State University, USA)
Eiichi Takazawa (Professor, Niigata University, Japan)
Damon Teagle (Professor, University of Southampton, UK)

Oman Drilling Workshop Speakers

Muriel Andreani	Laboratoire de Géologie de Lyon, France	muriel.andreani@univ-lyon1.fr
Wolfgang Bach	University of Bremen, Germany	wbach@uni-bremen.de
Keir Becker	RSMAS, University of Miami, USA	kbecker@rsmas.miami.edu
Georges Ceuleneer	CNRS, Univ. Paul Sabatier, France	georges.ceuleneer@get.obs-mip.fr
PhilippeGouze	CNRS, Univ. Montpellier, II France	philippe.gouze@um2.fr
Benoit Ildefonse	CNRS, Univ. Montpellier II, France	ildefonse@um2.fr
Peter Kelemen	LDEO, Columbia University, USA	peterk@ldeo.columbia.edu
Juergen Koepke	Leibniz Universitaet, Germany	koepke@mineralogie.uni-hannover.de
Jun Korenaga	Yale University, USA	jun.korenaga@yale.edu
Kerstin Lehnert	LDEO, Columbia University, USA	lehnert@ldeo.columbia.edu
Christopher MacLeod	Cardiff University, UK	macleod@cardiff.ac.uk
Craig Manning	UCLA, USA	manning@ess.ucla.edu
Jürg Matter	LDEO, Columbia University, USA	jmatter@ldeo.columbia.edu
Katsuyoshi Michibayashi	Shizuoka University, Japan	sekmich@ipc.shizuoka.ac.jp
Jay Miller	IODP, Texas A&M University, USA	miller@iodp.tamu.edu
Sobhi Nasir	Sultan Qaboos University, Oman	sobhi@squ.edu.om
Matt Schrenk	East Carolina University, USA	schrenkm@ecu.edu
Everett Shock	Arizona State University, USA	eshock@asu.edu
Rob Sohn	WHOI, USA	rsohn@whoi.edu
Marc Spiegelman	LDEO, Columbia University, USA	mspieg@ldeo.columbia.edu
Eiichi Takazawa	Niigata University, Japan	takazawa@geo.sc.niigata-u.ac.jp
Damon Teagle	University of Southampton, UK	Damon.Teagle@southampton.ac.uk
Alexis Templeton	University of Colorado, USA	alexis.templeton@colorado.edu
Jill VanTongeren	Yale University, USA	jvantong@ldeo.columbia.edu

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				

Oman Drilling Workshop Participants

Ali Al Rajhi	Ministry of Commerce & Industry, Oman	aalrajhi@business.gov.om
Adnan Al Ansari	GCC Ambassador to the UN	dra797@hotmail.com
Jesse Ausubel	DCO, Sloan Foundation, USA	ausubel@mail.rockefeller.edu
Jim Beard	National Science Foundation, USA	jbeard@nsf.gov
Valérie Beaumont	IFPEN Energies Nouvelles, France	valerie.beaumont@ifpen.fr
Harry Becker	Freie Universitaet Berlin, Germany	hbecker@zedat.fu-berlin.de
Donna Blackman Scripps	Institution of Oceanography, USA	dblackman@ucsd.edu
Mathilde Cannat	CNRS, Institut de Physique du Globe de Paris	cannat@ipgp.fr
Dawn Cardace	University of Rhode Island, USA	cardace@uri.edu

Laura Crispini	DIPTERIS, University of Genova, Italy	crispini@dipteris.unige.it
Jake Eichenbaum-Pikser	LDEO, Columbia University, USA	jpikser@gmail.com
Aida Farough	Virginia Tech, USA	afarough@vt.edu
Emanuele Fontana	Università degli Studi di Milano, Italy	emanuele.fontana@unimi.it
Marguerite Godard	CNRS, Univ. Montpellier II, France	mgodard@univ-montp2.fr
David Goldberg	LDEO, Columbia University, USA	goldberg@ldeo.columbia.edu
Steve Goldstein	LDEO, Columbia University, USA	steveg@ldeo.columbia.edu
George Harlow	American Museum of Natural History, USA	gharlow@amnh.org
Greg Hirth	Brown University, USA	greg_hirth@brown.edu
Bjorn Jamtveit	PGP, University of Oslo, Norway	bjorn.jamtveit@geo.uio.no
Kevin Johnson	University of Hawaii, USA	kjohnso2@hawaii.edu
Andreas Kronenberg	Texas A&M University, USA	kronenberg@geo.tamu.edu
Yuki Kusano	Kanazawa University, Japan	ykusano@staff.kanazawa-u.ac.jp
Art Lerner-Lam	LDEO, Columbia University, USA	lerner@ldeo.columbia.edu
Yongsheng Liu	University of Geosciences (Wuhan), China	yshliu@hotmail.com
Robert Lowell	Virginia Tech, USA	rlowell@vt.edu
Kate Maher	Stanford University, USA	kmaher@stanford.edu
Isabelle Martinez	Institut de Physique du Globe de Paris	martinez@ipgp.fr
Lisa Mayhew	University of Colorado – Boulder, USA	lisa.mayhew@colorado.edu
Andrew McCaig	University of Leeds, UK	a.m.mccaig@leeds.ac.uk
Diane Moore	U. S. Geological Survey, Menlo Park, USA	dmoore@usgs.gov
Tomo-aki Morishita	Kanazawa University, Japan	moripta@staff.kanazawa-u.ac.jp
Penny Morrill	Memorial University of Newfoundland, CA	pmorrill@mun.ca
Antony Morris	University of Plymouth, UK	amorris@plymouth.ac.uk
H. Richard Naslund	SUNY Binghamton, USA	Naslund@binghamton.edu
Amelia Paukert	LDEO, Columbia University, USA	apaukert@ldeo.columbia.edu
Oliver Pluemper	PGP, University of Oslo, Norway	oliver.pluemper@fys.uio.no
Mike Purdy	Columbia University, USA	mpurdy@ldeo.columbia.edu
Matthew Rioux	UC Santa Barbara, USA	riouxm@mit.edu
Vincent Salters	NHMFL, Florida State University, USA	salters@magnet.fsu.edu
Cara Santelli	Smithsonian Institution, USA	santellic@si.edu
Tsutomu Sato	Hokkaido University, Japan	tomsato@eng.hokudai.ac.jp
Tim Schroeder	Bennington College, USA	tschroeder@bennington.edu
Esther Schwarzenbach	Virginia Tech, USA	esther11@vt.edu
Sean Solomon	LDEO, Columbia University, USA	scs@dtm.ciw.edu
Harald Strauss	Universität Münster, Germany	hstrauss@uni-muenster.de
Lisa Streit	LDEO, Columbia University, USA	estreit@ldeo.columbia.edu
Martin Stute	LDEO/Barnard College, USA	martins@ldeo.columbia.edu
Michael Styles	British Geological Survey, UK	mts@bgs.ac.uk
Paola Tartarotti	Università di Milano, Italy	paola.tartarotti@unimi.it
Igor Tiago	Universidade de Coimbra, Portugal	itiago@ci.uc.pt
Maya Tolstoy	LDEO, Columbia University, USA	tolstoy@ldeo.columbia.edu
Masako Tominaga	Michigan State University, USA	masako.tominaga@gmail.com
Benjamin Tutolo	University of Minnesota, USA	tuto1001@umn.edu
Jessica Warren	Stanford University, USA	warrenj@stanford.edu

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 CO₂ 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 CO₂ capture and transport, a method for mitigating distributed emissions from vehicles and agriculture, and a route to achieve “negative emissions” should atmospheric CO₂ 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 CO₂-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 CO₂ 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 CO₂ 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 CO₂-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 CO₂ 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 CO₂ 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 CO₂ capture and storage from the point of view of chemical engineering, keynote lectures were on natural and enhanced geological storage of CO₂ in mafic and ultramafic rocks, experimentally determined rates of CO₂ 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 CO₂ storage at sea and on land, use of ultramafic mine tailings for mineral carbonation, ongoing projects involving CO₂ 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 CO₂ storage sites, geophysical rock properties necessary for CO₂ 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 of 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 CO₂, 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 CO₂

Elevated temperature, up to ~ 120 to 250°C of olivine, enhances mineral carbonation kinetics, as does elevated partial pressure of CO₂. 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 CO₂ 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 CO₂ per 250 km at rates of 40 to 5 megatons per year, respectively, for the mature CO₂ 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 CO₂ 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 CO₂ transport to near-shore, submarine sites.

cross-section A-A'

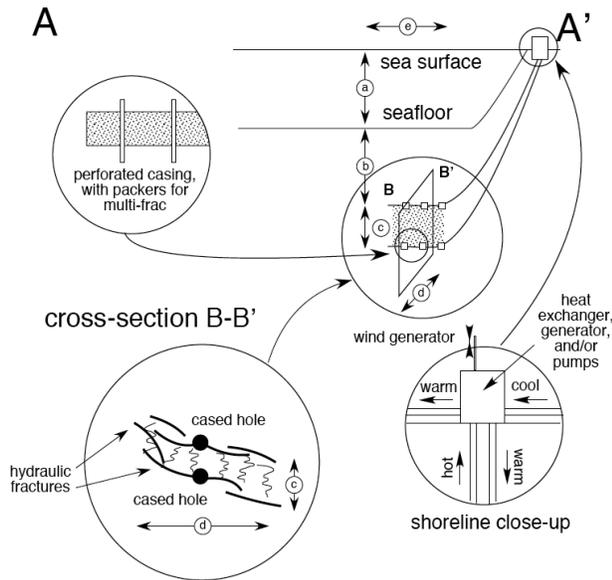


Figure A3-1: Notional design of shoreline installation for capture and storage of CO₂ from thermal convection of seawater through sub-seafloor peridotite via thermal convection, with low-grade geothermal power as a by-product.

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, CO₂-rich (or methane-rich!) fluids. Where storage sites are deep and cold, as in ancient, near-seafloor lavas, CO₂-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 CO₂ storage projects in mafic and ultramafic rock formations. Only field-scale tests will allow evaluation of the different methods envisaged for delivering and storing CO₂. While injection of CO₂-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 CO₂ production sites, have a sufficient permeability to allow large of CO₂ 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 CO₂ 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 CO₂ storage reservoirs. To limit costs, sites should preferentially be close to land with drilling from the shoreline if possible;
- (vi) Where storage of CO₂-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, CO₂ 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 CO₂ 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 aforementioned, 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.beauxsongs.fr/IMG/jpg/H0H7YH1W1111111.jpg>.

General site selection criteria for geological capture and storage of CO₂

Geologic capture of CO₂ by reaction of surface waters with ultramafic rocks may be an effective alternative to industrial capture of CO₂ followed by geologic storage. Site selection for this approach differs significantly from selection of a site for injection of fluids with high CO₂ concentrations. For example, a low permeability caprock may be unnecessary. Furthermore, because of the low concentration of CO₂ 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 CO₂ 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 CO₂, whereas in most places fresh water is relatively scarce and in high demand. However, extraction of CO₂ from, e.g., oceanic bottom water will have no impact on atmospheric greenhouse gas concentrations, so it is necessary to return CO₂-depleted fluid to the sea-surface, where it will draw down CO₂ from the air. Furthermore, because fluid will be heated during reaction with sub-surface rocks, it is desirable to extract heat from the produced, CO₂-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.

List of participants

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..

Muriel Andreani	**	ENS-Université de Lyon, France	muriel.andreani@univ-lyon1.fr
Caitlin Augustin	*	School of Marine and Atmospheric Science University of Miami, USA	c.augustin@umiami.edu
Hafidh Khlafan Al Ghanami		Ministry of Commerce, Sultanate of Oman	-
Abdulrahman Al Harthi		Department of Earth Science, Sultan Qaboos University, Sultanate of Oman	-
Mohamed Issa Al Harthi		Ministry of Commerce, Sultanate of Oman	-
Talal Al Hosni		Sultan Qaboos University, Sultanate of Oman	hosni@squ.edu.om
Zhair Al Suleimani		Public Authority for Electricity and Water, Sultanate of Oman	-
Saleh Al-Anboori		Ministry of Oil & Gas, Sultanate of Oman	-
Abdelmajeed Abdullah Al-Ansari		Ministry of Commerce , Sultanate of Oman	-
Yahya Al-Wahaibi		Sultan Qaboos University, Sultanate of Oman	yym@squ.edu.om
Ibrahim Ashour		Department of Petroleum and Chemical Engineering, Sultan Qaboos University, Sultanate of Oman	ashour@squ.edu.om
Roy Baria	†	MIL-TECH UK Ltd	roybaria@onetel.com
Keir Becker	†	University of Miami - RSMAS, USA	kbecker@rsmas.miami.edu
Claire Bendersky	*	Lamont Doherty Earth Observatory, USA	claireb@ldeo.columbia.edu
Pascale Benezeth		Laboratoire des Mécanismes et Transferts en Géologie (LMTG-CNRS)-Toulouse, France	benezeth@lmtg.obs-mip.fr
Dominique Bernard		ICMCB-CNRS, France	bernard@icmcb-bordeaux.cnrs.fr
Eleanor Berryman	*	McGill University, Canada	eleanor.berryman@mail.mcgill.ca
Márton Berta	*	ELTE University, Budapest, Hungary	marci87@chello.hu
Chiara Boschi		Institute of Geosciences and Earth Resources-	c.boschi@igg.cnr.it

		CNR, Italy	
Françoise Boudier		Université Montpellier 2, France	Francoise.Boudier@gm.univ-montp2.fr
Andrew Bungler	†	CSIRO Earth Science and Resource Engineering, Australia	andrew.bungler@csiro.au
Richard Darton	†	University of Oxford, UK	richard.darton@eng.ox.ac.uk
Henry Dick		Woods Hole Oceanographic Institution, USA	hdick@whoi.edu
Andrea Dini		Institute of Geosciences and Earth Resources-CNR, Italy	a.dini@igg.cnr.it
Gregory M. Dipple	†	University of British Columbia, Canada	gdipple@eos.ubc.ca
Steve Ehreinberg		Shell Chair, Sultan Qaboos University, Sultanate of Oman	sne@squ.edu.om
Issa El-Hussain		Sultan Qaboos University, Sultanate of Oman	elhussain@squ.edu.om
Katy Evans		Curtin University, Australia	k.evans@curtin.edu.au
Gretchen Früh-Green		ETH Zurich, Switzerland	frueh-green@erdw.ethz.ch
Eric Gaidos		Department of Geology and Geophysics, University of Hawaii, USA	gaidos@hawaii.edu
Pablo Garcia Del Real	*	Stanford University, USA	gdelreal@stanford.edu
Sigurdur Gislason		Institute of Earth Sciences, University of Iceland	sigrg@raunvis.hi.is
Marguerite Godard	†	CNRS-Géosciences Montpellier, France	Marguerite.Godard@um2.fr
David S. Goldberg		Lamont-Doherty Earth Observatory, USA	goldberg@ldeo.columbia.edu
Philippe Gouze	†	CNRS-Géosciences Montpellier, France	Philippe.Gouze@um2.fr
Marc Hesse	**	University of Texas at Austin, USA	mhesse@jsg.utexas.edu
Astrid Holzheid		Universität Kiel, Germany	holzheid@min.uni-kiel.de
Richard Hunwick		Integrated Carbon Sequestration Pty Ltd (ICS), Australia	richard@hunwickconsultants.com.au
Benoît Ildefonse		CNRS - Géosciences Montpellier, France	benoit.ildefonse@um2.fr
Karthik Iyer	**	The Future Ocean, IfM-GEOMAR, Germany	kiyer@ifm-geomar.de
Bjorn Jamveit		PGP, University of Oslo, Norway	bjorn.jamtveit@geo.uio.no
Junfeng Ji		School of Earth Sciences and Engineering, Nanjing University, P. R. China	jjunfeng@nju.edu.cn
Kevin Johnson		University of Hawaii, USA	kjohnso2@hawaii.edu
Natalie Johnson	*	Stanford University, USA	nataliej@stanford.edu
Jens Kallmeyer		University of Potsdam, Institute of Earth and Environmental Sciences, Germany	kallm@geo.uni-potsdam.de
Peter Kelemen	†	Columbia University, USA	peterk@LDEO.columbia.edu
Juergen Koepke		Leibniz University Hannover, Germany	koepke@mineralogie.uni-hannover.de
Marvin Lilley		School of Oceanography, University of Washington, USA	lilley@u.washington.edu
Harrison Lisabeth	**	Columbia University, USA	hlisabeth@gmail.com
Kristin Ludwig		Consortium for Ocean Leadership, USA	kludwig@oceanleadership.org
Sarah Mackintosh	**	The University of Nottingham, UK	Sarah.Mackintosh@nottingham.ac.uk
Jagan Mahadevan	**	The University of Tulsa, USA	jmahadevan@utulsa.edu
David Manning		University of Newcastle, UK	David.Manning@newcastle.ac.uk
Juerg Matter	†	Lamont-Doherty Earth Observatory of Columbia University, USA	jmatter@ldeo.columbia.edu

B. Peter McGrail	†	Pacific Northwest National Laboratory, USA	pete.mcgrail@pnl.gov
Travis L. McLing		Idaho National Laboratory, Center for Advanced Energy Studies, USA	travis.mcling@inl.gov
Bénédicte Menez		CNRS - Institut de Physique du Globe de Paris, France	menez@ipgp.fr
Peter Michael		The University of Tulsa, USA	pjm@utulsa.edu
Katsuyoshi Michibayashi		Shizuoka University, Japan	sekmich@ipc.shizuoka.ac.jp
Jay Miller		Integrated Ocean Drilling Program	miller@iodp.tamu.edu
Christophe Monnin		CNRS- Université Paul Sabatier, France	monnin@lmtg.obs-mip.fr
Sobhi Nasir		Sultan Qaboos University, Sultanate of Oman	sobhi@squ.edu.om
Eric Oelkers	†	CNRS- Université Paul Sabatier, France	oelkers@lmtg.obs-mip.fr
Jonas Olsson	*	Nordic Volcanological Institute, Institute of Earth Sciences, University of Iceland	jolsson@hi.is
Mike Oristaglio		Yale University, USA	michael.oristaglio@yale.edu
Jason Ornstein	*	New York University, USA	jmo326@nyu.edu
Amelia Paukert	*	Columbia University, USA	anp2119@columbia.edu
D. Graham Pearson		University of Alberta, Canada	gdpearso@ualberta.ca
Robert Podgorney		Idaho National Laboratory and Center for Advanced Energy Studies, USA	robert.podgorney@inl.gov
Herbert Poellmann		University of Halle, Germany	herbert.poellmann@geo.uni-halle.de
Bernhard Pracejus		Sultan Qaboos University, Sultanate of Oman	pracejus@squ.edu.om
Valentina Prigobbe	**	University of Texas at Austin, USA	valentina.prigobbe@mail.utexas.edu
Barbara Ransom		National Science Foundation, USA	bransom@nsf.gov
Lars Ruepke		The Future Ocean - IFM-GEOMAR; Germany	lruepke@ifm-geomar.de
Olaf Schuiling		Institute of Geosciences, Utrecht University, The Netherlands	schuiling@geo.uu.nl
Nina S.C. Simon	**	Environmental technology, Norway	nina.simon@ife.no
Sven Sindern		RWTH Aachen University, Germany	sindern@rwth-aachen.de
Michael Styles		British Geological Survey, UK	mts@bgs.ac.uk
Narasimman Sundararajan		Sultan Qaboos University, Sultanate of Oman	visvid12@squ.edu.om
Yutaro Takaya	*	Department of Systems Innovation, Graduate School of Engineering, University of Tokyo, Japan	tt097074@mail.ecc.u-tokyo.ac.jp
Damon Teagle	†	University of Southampton, UK	dat@noc.soton.ac.uk
H. Henry Teng		Nanjing University/George Washington University, USA	hteng@gwu.edu
Masako Tominaga	**	Dept. of Geology and Geophysics - WHOI, USA	mtominaga@whoi.edu
Reinier Van Noort	**	HPT-Laboratory, Utrecht University, The Netherlands	vannoort@geo.uu.nl
A. Joshua West	**	University of Southern California Earth Sciences, USA	joshwest@usc.edu
Anthony Williams-Jones		McGill University, Canada	anthony.williams-jones@mcgill.ca
Liang Zhao		School of Earth Sciences and Engineering, Nanjing University, P. R. China	zhaoliang@nju.edu.cn

Notes: *PhD student, **Post-doc and young scientist, † Keynote speaker

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

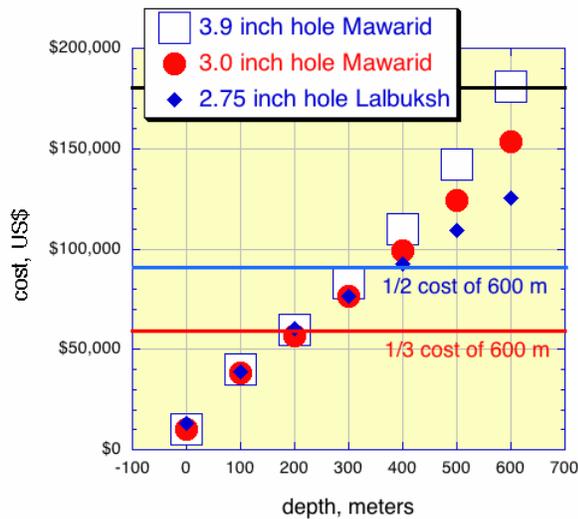


Figure A4-1: Drilling cost estimates from Mawarid Mining and Lalbuksh Irrigation and Drilling Company LLC, both Oman based wireline diamond drilling contractors.

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 specific drill sites

1. Igneous and metamorphic processes at oceanic spreading centers

A5.1.1 Crust-mantle transition zone, mantle flow, and melt transport features

Site MD-1 (22.992°N, 57.967°E) is on the periphery of the steep lineation zone at the center of the “Maqsad diapir”, the best mapped and studied part of the ophiolite, close to the south end of cross-section B in Jousselin et al. [1998], (their Figure 7, reproduced here as Figure A5-1). Drilling at this Site will collect core from the lowermost crust, through the crust mantle transition zone, and into the underlying residual mantle peridotites. Three holes will be drilled at the site: One central 600 m diamond cored hole (MD-1A), flanked by two 250 m diamond cored holes, situated 200 to 500 meters to north (MD-1B) and south (MD-1C) of MD-1A will allow us to evaluate lateral variation in deformation structures and mineral composition.

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 is a late feature, a “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 have been interpreted to support this hypothesis, but the data are noisy, with many exceptions. Continuous observations 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., *Braun and Kelemen*, 2002; *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 GT5). 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 and at Site GT1.

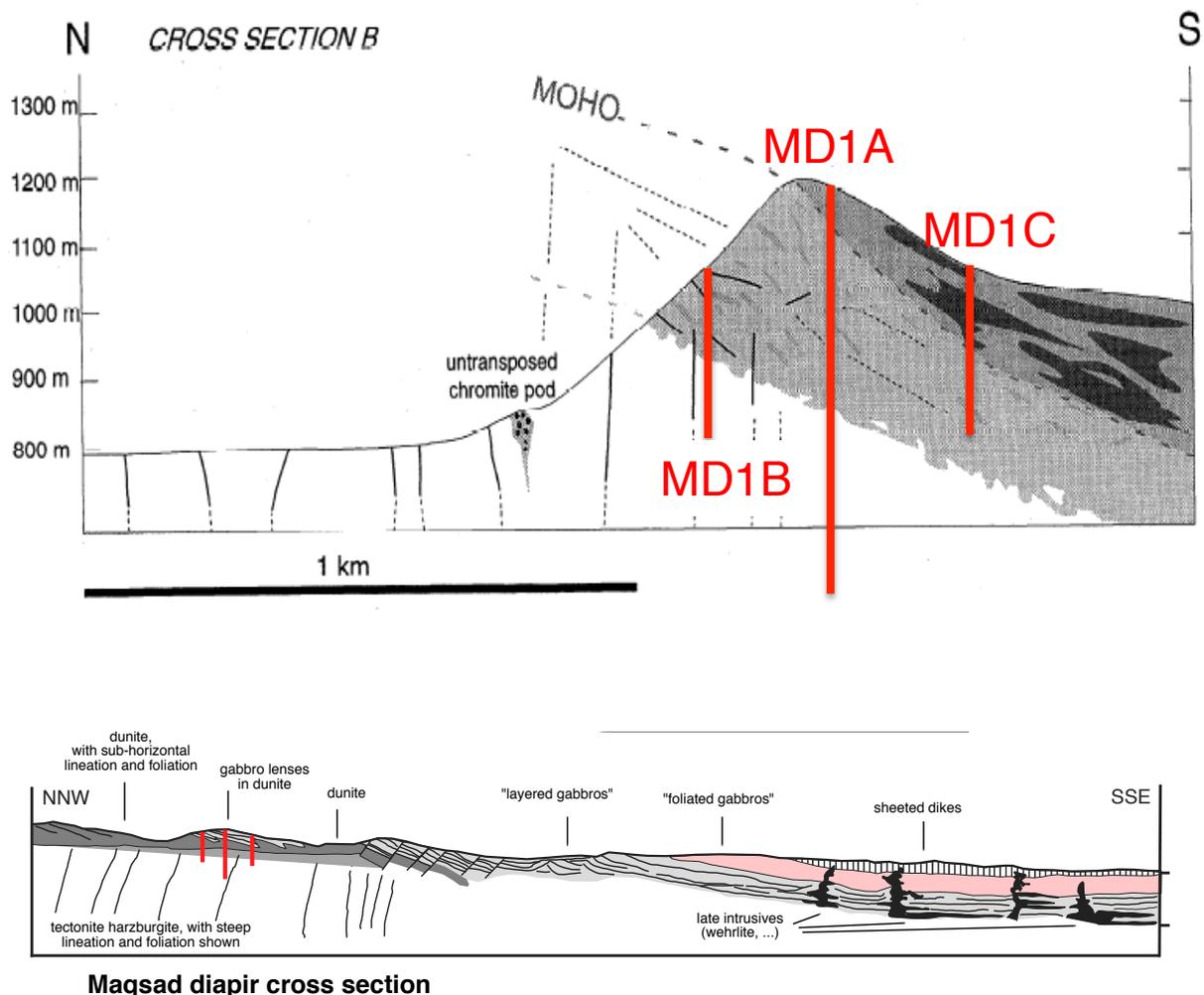


Figure A5-1: Top: Cross section B from Ildefonse et al. [1995] at the periphery of the “Maqsad diapir”, a region with steep solid-state flow trajectories in the shallow mantle, extending into the crust-mantle transition zone, with proposed drill sites marked. Bottom: regional section along Wadi Kurah (Boudier, pers. comm. 1998), showing the geological 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). The Site MD1 drill holes are marked. The lower section is about 21.5 km wide, with no vertical exaggeration (tick marks on right are 1 km apart).

A5.1.2 Residual mantle at the base of the Wadi Gideah crustal transect

Site GT-1 will be near the head of Wadi Gideah, just north of the watershed separating the Wadi Gideah drainage to the south from the Wadi Dima drainage to the north. It will be at 22.947°N, 58.514°E if accessible to drill rigs, or 22.921°N, 58.512°E if accessible, or 22.958°N, 58.470°E which is accessible by road. Mantle core and geophysical logs from this site will serve as a reference for the detailed characterization of residual upper mantle structures and geochemistry, far from mapped mantle diapirs and also from zones rich in dunite [e.g. Braun and Kelemen, 2002], for comparison with zones rich in melt transport features, peridotite in the crust-mantle

transition zone, and mineral chemistry in the nearby sites (GT-2, 3, 4) proposed for study of a crustal transect. In addition to a diamond-drill hole for core, a rotary hole will allow sampling of fluids, for comparison with more detailed studies of peridotite alteration at Site BA1. The peridotites at Site GT1 are less serpentinized than those at BA1, so this is an important reference site.

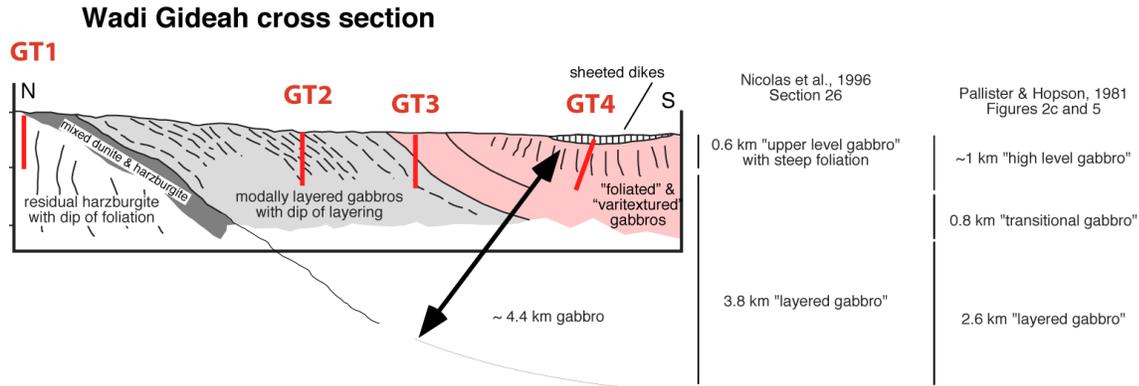


Figure A5-2: Cross section along Wadi Gideah, drawn based on published maps and cross-sections [Nicolas et al., 1996; Pallister and Hopson, 1981] and on data from Koepke et al. (pers. comm.) is about 12 km wide, with no vertical exaggeration; tick marks on left side are 1 km apart.

A5.1.3 Lower crustal section in Wadi Gideah

Site GT2 (22.890°N, 58.520°E), Two holes: one 600 m, cored hole and an adjacent 600 m rotary hole for logging and fluid sampling

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 GT2 (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 [Coogan et al., 2006].

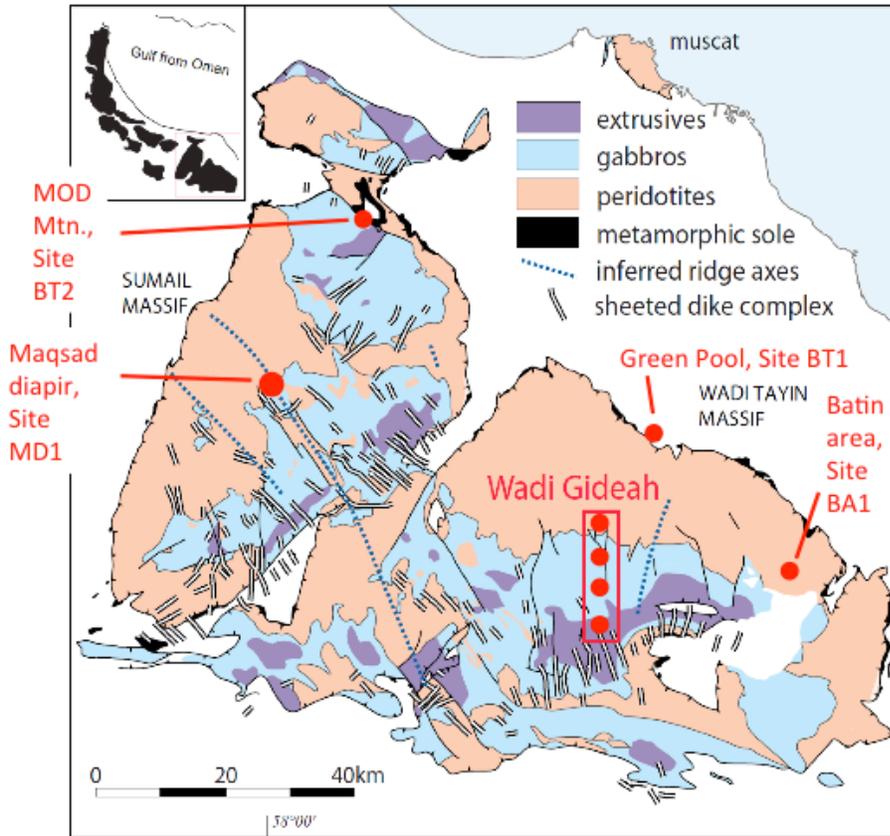
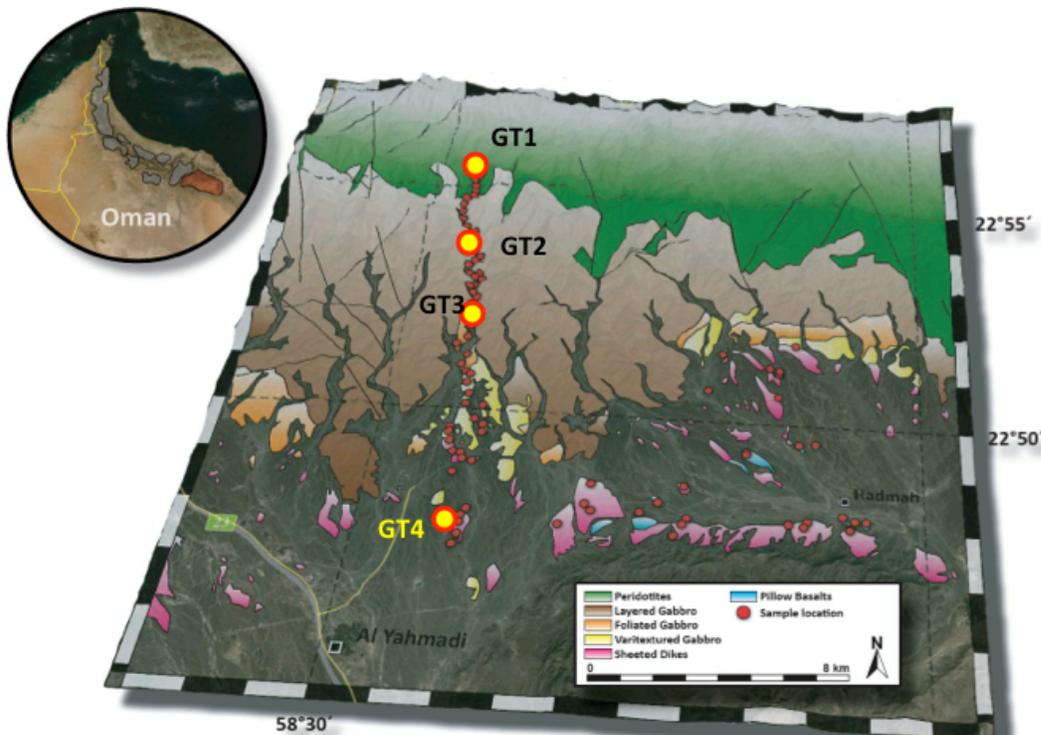
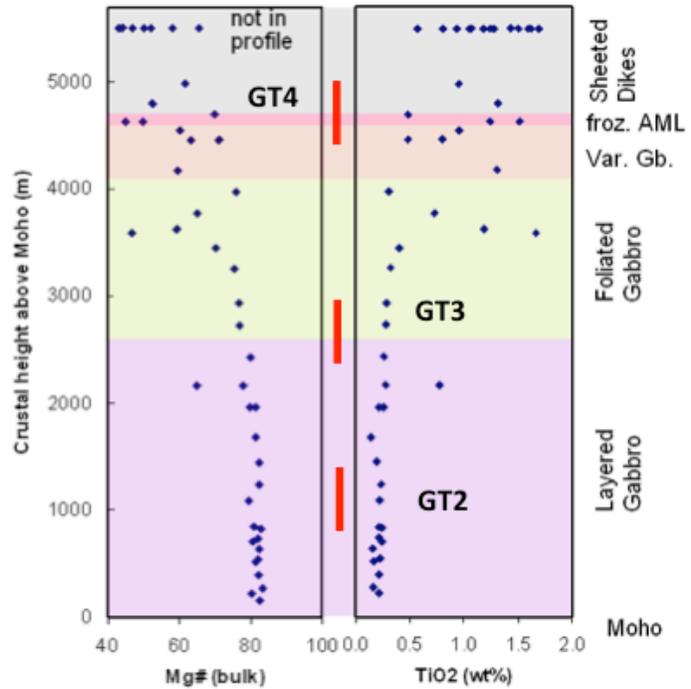


Figure A5-3: Two geologic maps showing locations of proposed drill sites in the Samail and Wadi Tayin massifs. Top, map from Nicolas et al. [2000]. Bottom, map based on recent work by Koepke and co-workers (personal communications) showing their sample locations and the proposed drill sites of the Wadi 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 Sites BA1 and SA1.

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).



A5.1.4 Mid-crustal section in Wadi Gideah

Site GT3 (22.852°N, 58.520°E) is sited 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. One 600 meter cored hole will be drilled at this site.

A5.1.5 Dike-gabbro transition in Wadi Gideah

Site GT4 (22.796°N, 58.533°E) is sited 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 600 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 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.

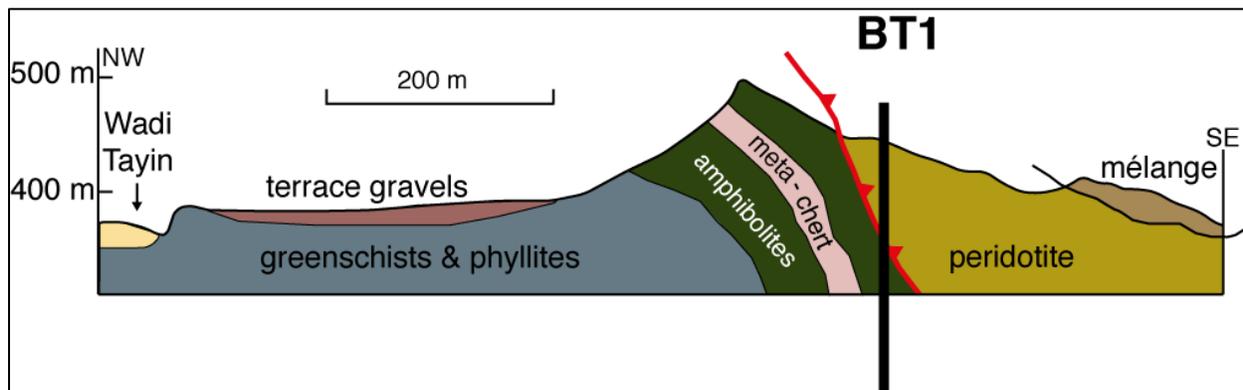
2. Mass transfer into the shallow mantle above subduction zones

A5.2.1 Basal thrust between Samail mantle and metamorphic sole at the Green Pool

Site BT1 (23.057°N, 58.596°E) at the “Green Pool”, is the best-studied outcrop of the basal thrust of the ophiolite, in a site that has been little affected by later tectonic reactivation of faults. Tectonite mantle peridotite with a metamorphic fabric overlies amphibolite facies metamorphic rocks (mostly metasediments, including quartzites) that in turn overlie low grade metasediments interpreted as belonging to the allochthonous Hawasina group [Ghent and Stout, 1981]. ⁴⁰Ar/³⁹Ar geochronology and metamorphic studies [Hacker and Gnos, 1997; Hacker et al., 1996] of this area have yielded ages of 90-95 Ma, and peak metamorphic pressure and temperature estimates of ~800°C and 0.5 to 1 GPa for this locality. However, the underlying metasediments have not been heated over ~ 300°C, and the steep, implied temperature gradient (~ 3°C/m) is probably an artifact of tectonic juxtaposition of blocks with unrelated metamorphic histories during oceanic thrusting and emplacement of the ophiolite onto the Arabian continental margin.

A 250 m short, cored hole at this site will allow systematic characterization of mass transfer from the underlying metasediments into the hanging wall peridotites, and provide a reference site for comparison with the zone of extensive peridotite carbonation at Site BT2.

Figure A5-5: Cross section of the Green Pool outcrop, modified from Ghent and Stout [1981].



A5.2.2 Basal thrust between Samail mantle with listwanite bands and metamorphic sole

Site BT2 (23.366°N, 58.184°E) is in an outcrop area we call MOD Mountain in reference to a nearby Ministry of Defense compound. 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 SiO₂ 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 (2σ), indicating that the listvenites formed by metasomatic introduction of CO₂-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 CO₂ in carbonate minerals formed by interaction between subduction zone fluids at the “leading edge of the mantle wedge” [Kelemen & co-workers, unpublished data, and *Kelemen et al.*, 2011]. 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.

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 or the Hawasina Group.

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

45.3.1 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. It 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 H₂ 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 ~12 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 allays 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 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.

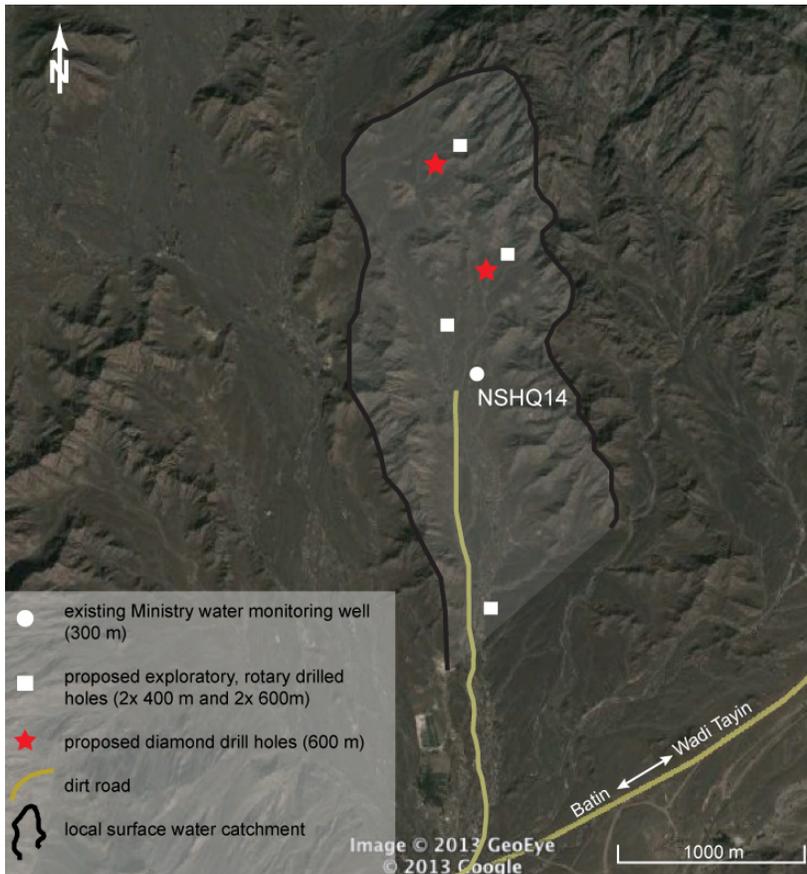


Figure A5-6. Map of proposed drilling site BA1 near the village of Batin. The site is located in partially altered mantle peridotite and includes an existing water monitoring well from the Omani Ministry of Regional Municipalities and Water Resources. Four proposed 400-m deep rotary drilled exploratory 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 the rotary holes, and the adjacent rotary holes will be deepened to 600-m

The drilling strategy for this site will be different from all other sites. As noted in Section 2.3, we believe that the reaction zone, where pH 8 to 9, Mg-HCO₃ 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 first, and sampled as described in the section on water sampling strategy below, in order to locate reaction zone(s) or reaction front(s). Once these are located, two 600 m cored holes will be drilled to sample these zones, and adjacent rotary holes will be deepened to 600 m for water sampling, hydrological measurements, and possible future downhole experiments. Pre-filtered, ozonated, drinking water will be used as a lubricant to drill at least one of these cored holes, to minimize contamination of formation waters with drilling fluid. A schematic illustration of this strategy is shown in Figure A5-6. However, note that the exact sites of the rotary and cored holes will depend on information gathered during the drilling program.

Boreholes in the Batin area (Site BA1) will be drilled along a transect aligned with the general groundwater flow path from the recharge area to the "reaction zone" and to the discharge zone of the Ca-OH-rich hyperalkaline end-member fluids. Two of these holes will be drilled with diamond core drilling to a total depth of 600 m to retrieve cores. The other four holes will be drilled with rotary drilling to depths of 400 and 600 m. 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 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.

A5.3.2 Tertiary (and ongoing?) low temperature alteration in peridotite

Site SA-1 (22.916 °N, 59.217°E) is along the coast of the Gulf of Oman, where Eocene-Miocene limestones unconformably overlie altered mantle peridotite. Our objective here is to drill through the limestones into peridotite beneath the seafloor, in an inclined hole from a site on the coast.

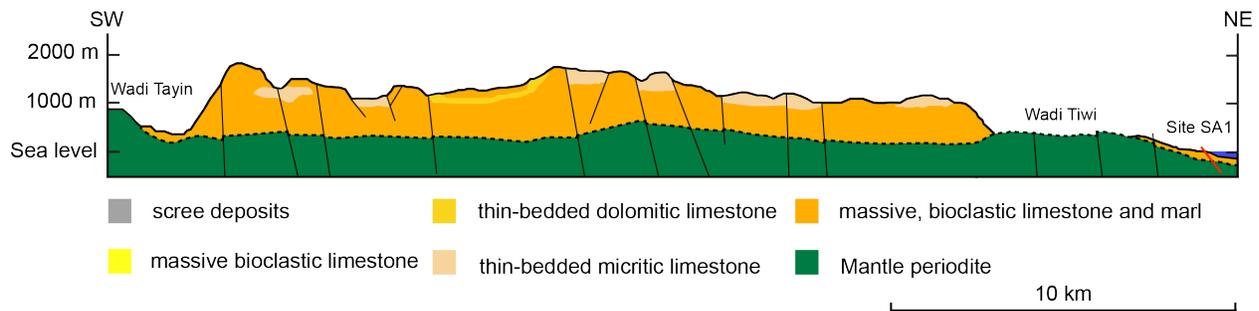
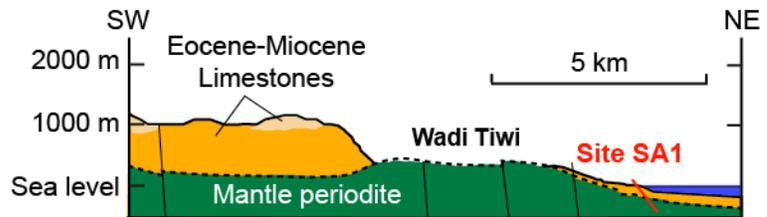


Figure A5-7: *Geologic cross-sections based on mapping by the Geological Survey of Oman and the French Bureau de Recherche Geologique et Mineralogique. Top section shows how the Wadi Tayin massif mantle section extends beneath Tertiary limestones across the coastal mountains, and outcrops locally within steep canyons near the shore of the Gulf of Oman. Bottom section shows the proposed drill site in more detail.*



After a period of subaerial weathering and erosion, which exposed and weathered mantle peridotites to form laterites in some places, a Late Cretaceous to Early Miocene marine transgression deposited shallow water carbonates unconformably over the Samail ophiolite. This unconformity is best exposed at the eastern margin of the Wadi Tayin massif, disappears beneath a ridge of Tertiary carbonates to the east, and outcrops again in a few windows in the deepest canyons along the coast surrounding the Omani villages of Fins and Tiwi. Beneath the unconformity, peridotites are heavily weathered and – in places – contain abundant, wide carbonate veins that are probably Tertiary in age.



Figure A5-7: Carbonate veins in serpentinized peridotite just below the unconformity with overlying Tertiary limestones in Wadi Fins, about 6 km from the coast near the village of Fins, which in turn is north of the regionally important village of Tiwi. The age of the vein formation is unknown, but is probably Late Cretaceous to Eocene, during a period of subaerial weathering prior to a marine transgression and deposition of overlying, shallow marine limestones.

One cored 600 meter hole and an adjacent 600 meter rotary hole at Site SA-1 will be drilled through the unconformity into carbonate vein-rich peridotite, from the shoreline near Wadi Fins. Preliminary mapping indicates that the unconformity – which dips 2° to 10° ESE – lies ~20 to 200 m below sealevel at the coast in this region. Systematic study of the weathered peridotite below the unconformity will provide essential data on the difference between Tertiary seafloor weathering and ongoing, subaerial weathering. It may reveal ongoing alteration of the peridotite via interaction with seawater, and provide fascinating information on the hydrology of the groundwater-seawater interface in coastal Oman. By characterizing the extent of alteration, permeability, and fracture spacing it will lay the groundwork for potential, future experiments on engineered carbon capture and solid storage via carbonation of peridotite, which can be achieved with the least societal impact and lowest cost in sub-seafloor peridotites, accessed from boreholes along the coast [e.g., Kelemen *et al.*, 2011].

References cited in Appendix 5

- Braun, M. G., and P. B. Kelemen (2002), Dunite distribution in the Oman ophiolite: Implications for melt flux through porous dunite conduits, *G-cubed*.
- Coogan, L. A., K. A. Howard, K. M. Gillis, M. J. Bickle, H. Chapman, A. J. Boyce, G. R. T. Jenkin, and R. N. Wilson (2006), Chemical and thermal constraints on focussed fluid flow in the lower oceanic crust, *Am. J. Sci.*, *306*, 389-427.
- Ghent, E. D., and M. Z. Stout (1981), Metamorphism at the base of the Samail ophiolite, southeastern Oman mountains, *J. Geophys. Res.*, *86*, 2557-2571.
- Hacker, B. R., and E. Gnos (1997), The conundrum of Samail: Explaining the metamorphic history, *Tectonophysics*, *279*, 215-226.
- Hacker, B. R., J. L. Mosenfelder, and E. Gnos (1996), Rapid emplacement of the Oman ophiolite: Thermal and geochronologic constraints, *Tectonics*, *15*, 1230-1247.
- Ildefonse, B., S. Billiau, and A. Nicolas (1995), A Detailed Study of Mantle Flow away from Diapirs in the Oman Ophiolite, in *Mantle and Lower Crust Exposed in Oceanic Ridges and in Ophiolites*, edited by R. L. M. Vissers and A. Nicolas, pp. 163-177, Kluwer Academic, Amsterdam.
- Jousselin, D., A. Nicolas, and F. Boudier (1998), Detailed mapping of a mantle diapir below a paleo-spreading center in the Oman ophiolite, *J. Geophys. Res.*, *103*, 18153-18170.
- Katz, R. F., M. Spiegelman, and B. Holtzman (2006), The dynamics of melt and shear localization in partially molten aggregates, *Nature*, *442*, 674-679.
- Kelemen, P. B., J. Matter, E. E. Streit, J. F. Rudge, W. B. Curry, and J. Blusztajn (2011), Rates and mechanisms of mineral carbonation in peridotite: Natural processes and recipes for enhanced, in situ CO₂ capture and storage, *Ann. Rev. Earth Planet. Sci.*, *39*, 545-576.
- Nicolas, A., E. Boudier, B. Ildefonse, and E. Ball (2000), Accretion of Oman and United Arab Emirates ophiolite: Discussion of a new structural map, *Marine Geophys. Res.*, *21*(3-4), 147-179.
- Nicolas, A., F. Boudier, and B. Ildefonse (1996), Variable crustal thickness in the Oman ophiolite: Implication for oceanic crust, *J. Geophys. Res.*, *101*, 17,941-917,950.
- Pallister, J. S., and C. A. Hopson (1981), Samail ophiolite plutonic suite: Field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber, *J. Geophys. Res.*, *86*, 2593-2644.
- Rabinowicz, M., and G. Ceuleneer (2006), The effect of sloped isotherms on melt migration in the shallow mantle: a physical and numerical model based on observations in the Oman ophiolite, *Earth Planet. Sci. Lett.*, *229*, 231-246.
- Ravaut, R., R. Bayer, R. Hassani, D. Rousset, and A. Al Yahya'ey (1997), Structure and evolution of the northern Oman margin: gravity and seismic constraints over the Zagros-Makran-Oman collision zone, *Tectonophysics*, *279*, 253-280.
- Spiegelman, M., and P. B. Kelemen (2003), Extreme chemical variability as a consequence of channelized melt transport, *Geochemistry Geophysics Geosystems*, *4*.

Appendix 6: Geophysical wireline logging budget (US\$)

	Year 1	Year 2	Total
Mobilization/Demobilization	\$6,427	\$6,427	\$12,854
Logging & insurance	\$55,525	\$37,017	\$92,542
Tools stand-by cost	\$23,135	\$19,279	\$42,414
Tool shipping and shipping insurance	\$25,706	\$25,706	\$51,412
Travel for two loggers	3,856	\$3,856	\$7,712
Lodging in Oman for 2 loggers	\$3,856	\$3,856	\$7,712
Vehicle rent in Oman	\$10,847	\$10,847	\$20,564
Salary and wages for 2 loggers	\$30,847	\$30,847	\$61,694
Subtotal	\$159,634	\$137,270	\$296,904
Overhead (20%)	\$31,927	\$28,688	\$59,381
Total	\$191,561	\$172,127	\$356,285

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

	Year 1	Year 2	Total
Mobilization/Demobilization	15,000	15,000	30,000
Borehole winch with 600 m cable	20,000		20,000
Straddle packer system including submersible pump	55,000		55,000
High pressure hose for submersible pump	12,000		12,000
Tripod for winch	5,000		5,000
Generator	4,000		4,000
Gas tight water sampler	9,360		9,360
Pressure transducer	5,000		5,000
Field supply	15,000	15,000	30,000
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	234,083	123,723	357,806
Overhead (53%) not on equipment (>US\$5,000)	67,693	65,573	133,266
Total	301,776	189,296	491,072

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 logging expenses

Estimate from Dr. Jay Miller, IODP Manager of Technical & Analytical Services at Texas A&M University, based on ~ 1 month per 900 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.

6 months total, in three 2 month increments	travel	room & board	salary	total
technical staff (8 people per 2 km section of core)	\$84,000	\$90,000	\$192,000	\$366,000
scientists (20 people per 2 km section of core)	\$210,000	\$216,000		\$426,000
			other	
laboratory supplies onboard JR			\$18,000	\$18,000
purchase of XRF core scanner from Aavatech or Itrax for JR			\$400,000	\$400,000
shipping from Oman to JR and then AMNH			\$240,000	\$240,000
totals	\$294,000	\$306,000	\$850,000	\$1,450,000

Appendix 10: 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 11: 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 30 scientists for one week editorial meeting	\$105,000
technical support and web publication at TAMU	\$100,000
total cost	\$205,000

Appendix 12: Project management costs

Estimate from Dr. Jay Miller, IODP Manager of Technical & Analytical Services at Texas A&M University, based on comparable positions and standard travel cost estimates at IODP TAMU. We expect that the Project Manager and Assistant will be employed by IODP TAMU or Columbia University.

	year 1	year 2	year 3	year 4	total
project manager, annual salary & benefits \$156,000	\$156,000	\$104,000	\$39,000		\$299,000
six months travel, per diem and vehicle rental in Oman in years 1 and 2	\$75,000	\$75,000			\$150,000
administrative assistant, annual salary & benefits \$124,000	\$124,000	\$82,667	\$31,000		\$237,667
total pay and travel for project managers	\$355,000	\$261,667	\$70,000		\$686,667
23% overhead project management	\$81,650	\$60,183	\$16,100		\$157,933
meetings in Oman for 60 members of the project team, with overhead		\$210,000		\$210,000	\$420,000
additional annual meeting for 14 Project Steering Committee members plus 2 others	\$56,000	\$56,000	\$56,000	\$56,000	\$56,000
total cost	\$847,650	\$849,517	\$212,100	\$266,000	\$2,007,267

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. Hirth, G. Manning, C. Matter, J. Savage, H. Scherer, G. Schrenk, M.	Mechanism and consequences of shallow mantle hydration and carbonation: feedback between alteration, fluid flow, and the subsurface biosphere	U.S. NSF, Frontiers in Earth System Dynamics	4.99M	March 4, 2013 (pre-proposal submitted July 2012, approved December 2012)	Will include matching funds for geophysical logging and core logging (US\$ ~2.0M)
Shock, E. Poret-Peterson, A. Cox, A. Boyd, E.	The geochemistry of habitability: case study of serpentinization	NASA, Exobiology	600K	2014	Scientific research funds
Manning, C. Kelemen, P.	Insights into Earth's deep carbon cycle from drilling the Oman Ophiolite	Sloan Foundation, Deep Carbon Observatory	500K	2013	Scientific research funds including matching funds for drilling
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 2013	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. McCullom, T. Schrenk, M. Santelli, R.	Active serpentinization in Oman: investigating H ₂ -dependent microbial communities that may populate the	NASA Exobiology and Evolutionary Biology Program	850K	July 2013	Scientific research funds and matching funds for drilling

Cardace, D.	deep subsurface of Earth and Mars				
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	Submitted November 2012	Scientific research funds (mainly salary for PhD students and postdocs)
Godard, M. MacLeod, C. Gouze, P. Teagle, D. Ceuleneer, G Ildefonse, B. et al.	Training network on mantle drilling in the Oman ophiolite (NEMO)	European Union, Marie Curie Initial Training Network	4.0M	2014	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	2.9M	March 2013	Scientific research funds including matching funds for drilling
Matter, J. Teagle, D. Powrie, W.	Enhanced carbonation of mantle peridotite for carbon storage: feedback between	UK Engineering and Physical Sciences Research	2.5M	June 2013	Scientific research funds including matching funds for drilling,

	fluid flow, alteration and geomechanics	Council			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	Sept 2013	Matching funds for drilling
Bach, W. Strauss, H. Koepke, J	Metasomatic rocks as witness of fluid flow	DFG, German Research Foundation	130K	Sept 2013	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	Sept 2013	Scientific research funds

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 ophiolite.

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 the American Museum of Natural History, the US National Science Foundation, and the Integrated Ocean Drilling Program at Texas A&M University

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.

1. Long-term (in perpetuity) institutional commitment. 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.
2. Support structure. 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.
3. Infrastructure. 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.
4. Relation to existing collections. The core would fit well within the existing petrology collection, the current strengths of which are mafic and ultramafic systems. For example, other

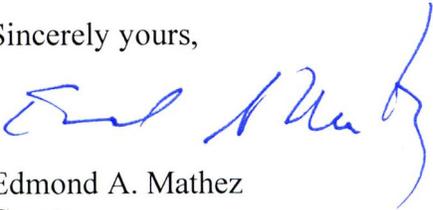
important collections in addition to the ICDP Hawaiian drill core include those of numerous volcanic/xenolith localities (e.g., Jagoutz, Irving, Prinz) and mafic intrusions such as the Skaergaard (McBirney), Nain (Morse), Noril'sk (Federenko/Czamanske), and Bushveld (Mathez).

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 = $\$60\text{kyr}^{-1}/222\text{d yr}^{-1} = \2200])	2200
Total	\$17900

January 7, 2013

Dear Peter,

This letter acknowledges that NSF supports, in principle, the use of the laboratories aboard the drill ship JOIDES Resolution (JR) to process and log the core obtained during the Oman drilling program. We understand that this will involve use of the JR while in port and not otherwise in use. The work will be done over 2 months in each of three years, scheduled at the convenience of IODP. The understanding is that this work, including travel, shipping, staffing, and use of all laboratory and other facilities aboard the JR, will result in no additional cost to NSF or IODP.

Please feel free to contact me with any questions.

Sincerely,

Jim

James S. Beard
Program Officer NSF OCE/ODP
jbeard@nsf.gov
703 292-7583

Cc: David Divins, Jay Miller, Rodey Batiza, James Allen, Thomas Janacek.



January 10, 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 Integrated Ocean Drilling 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.org

Appendix 18: CV's of Principal Investigators