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

The Cyprus Crustal Study Project

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

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

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

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

Scientific Ocean Drilling: DSDP, ODP, IODP

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

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

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

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

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

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

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

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

Synergy with the Mohole to the Mantle Project (M2M)

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

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

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

Serpentinization and the extremes of life

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

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

Geological Carbon Capture and Storage through Mineral Carbonation

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

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

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

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

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

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

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

Summary

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

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

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

Workshop Proceedings and Results

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Five key conclusions were reached.

1. The potential for several different, engineered mineral carbonation methods should be explored in parallel, by integrated, international research networks, including (a) carbonation of ultramafic mine tailings and sediments, (b) in situ carbonation of ultramafic rocks (peridotite), and (c) in situ carbonation of mafic rocks (basalt). No one can foresee the size or urgency of the societal demand for CO_2 storage in the coming century, nor is it possible to predict the outcome of ongoing research on alternative or complementary methods.
2. It is necessary to understand the physical properties of potential mineral carbonation sites. Specifically, it is essential to quantify permeability, porosity, mineralogy (igneous minerals, plus extent and nature of existing alteration), fracture toughness and other material properties as a function of lithology and depth.
3. It is necessary to understand coupled chemical reaction and fluid transport in natural mineral carbonation systems better, especially in two key areas.
4. Scientific drilling has two key roles to play, (a) study of natural processes throughout the world, and (b) characterization of potential sites for CO_2 storage experiments.
5. The scientific community will probably need to take the lead in mineral carbonation research in the near future, developing and quantifying practical methods for use by government and industry when a consensus arises on the need for these techniques.

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

Support

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

Participation

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

Goals

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

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

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

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

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

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

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

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

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

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

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

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

cross-section A-A'

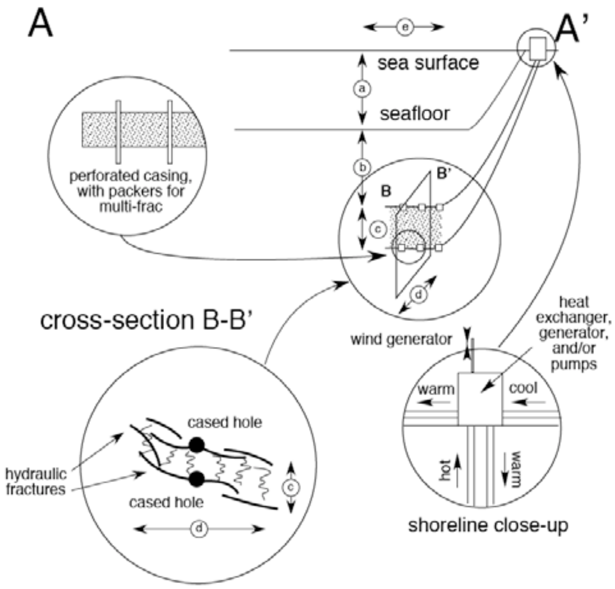

Figure A3-1: *Notional design of shoreline installation for capture and storage of CO_2 from thermal convection of seawater through sub-seafloor peridotite via thermal convection, with low-grade geothermal power as a by-product.*

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

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

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

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

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

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

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

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

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

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

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

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

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

General site selection criteria for geological capture and storage of CO_2

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

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

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

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Appendix 4: Information on drilling costs in Oman

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

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

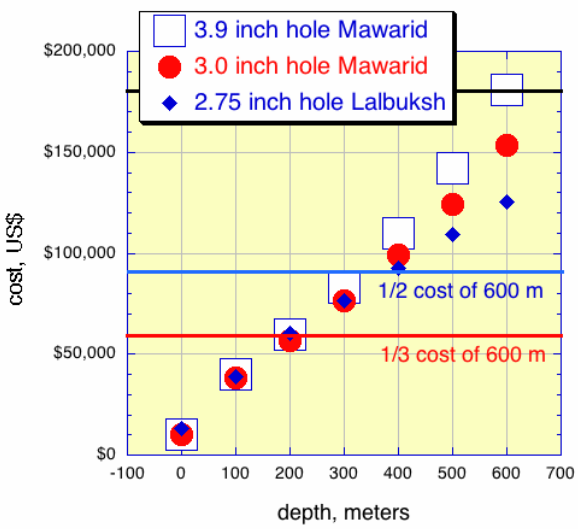


Figure A4-1: Drilling cost estimates from Mawarid Mining and Lalbuksh Irrigation and Drilling Company LLC, both Oman based wireline diamond drilling contractors.

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

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

Appendix 5: Description of drill sites & strategy

General remarks

Accessibility:

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

Contingencies:

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

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

Water table:

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

No available core from prior drilling:

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

1. Igneous and metamorphic processes at oceanic spreading centers

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

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

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

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

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

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

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

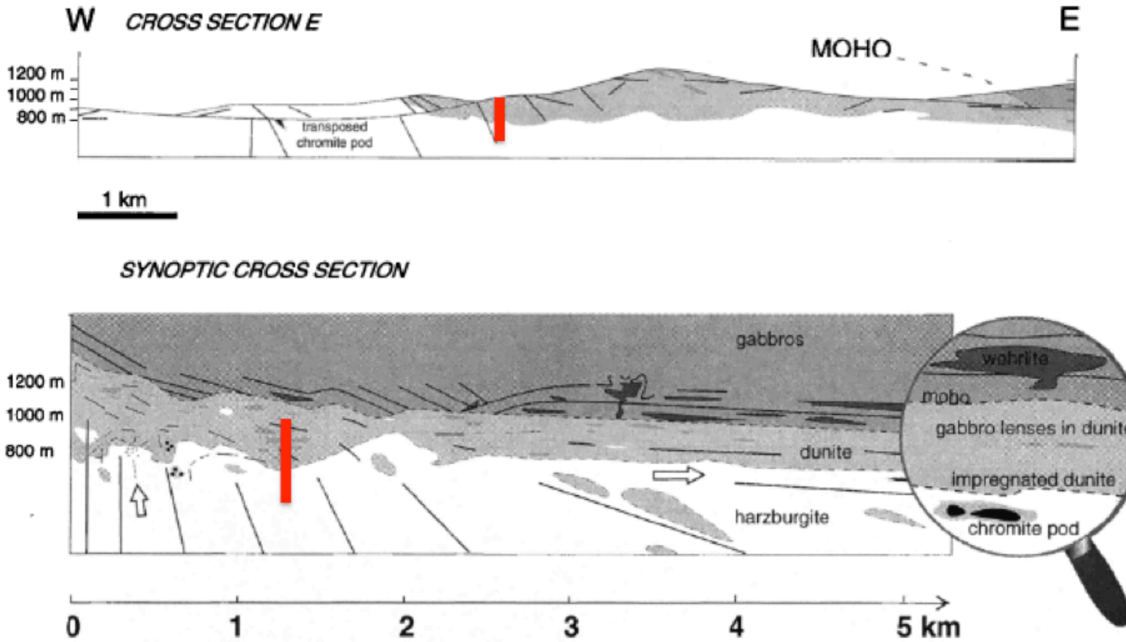


Figure A5-1.1: *Top: Cross section E from Jousselin et al. [1998} at the periphery of the "Maqsad diapir", a region with steep solid-state flow trajectories in the shallow mantle, extending into the crust-mantle transition zone, with proposed drill site marked. Bottom: Synoptic cross section from Jousselin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

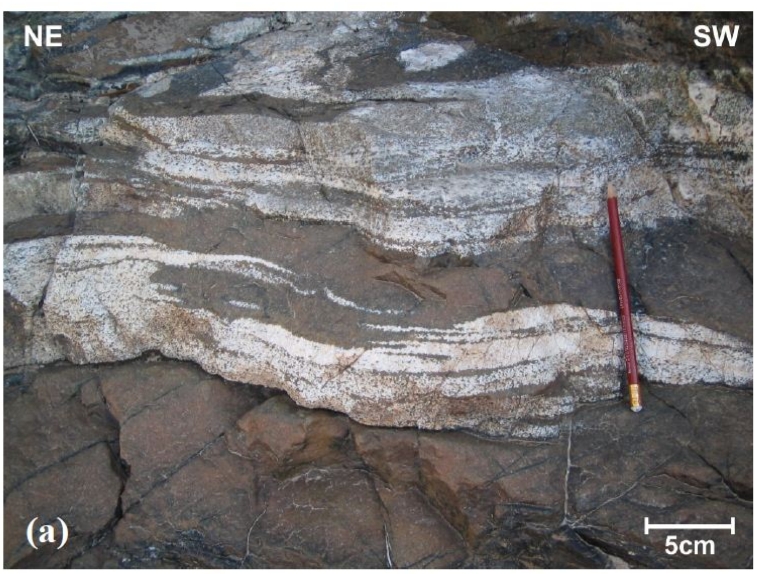


Figure A5-1.2: *Gabbroic lenses in the crust-mantle transition zone of the Maqsad diapir, near Site MD1. Geochemical studies of such lenses offer the opportunity to study melt transport in the uppermost mantle, and deformation structures that reveal the relative velocities of the upwelling mantle and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

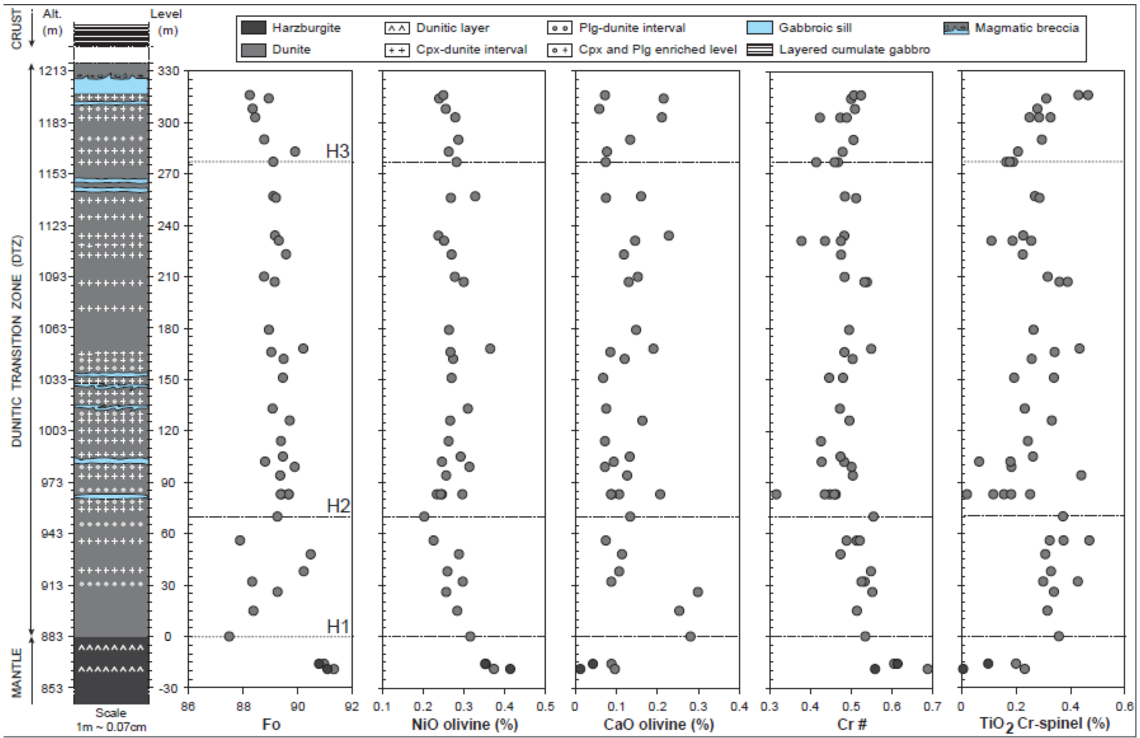


Figure A5-1.2: *Variation in mineral composition on the 10 meter scale, in the immediate vicinity of Site MD1. Figure from Abily & Ceuleneer [2013].*

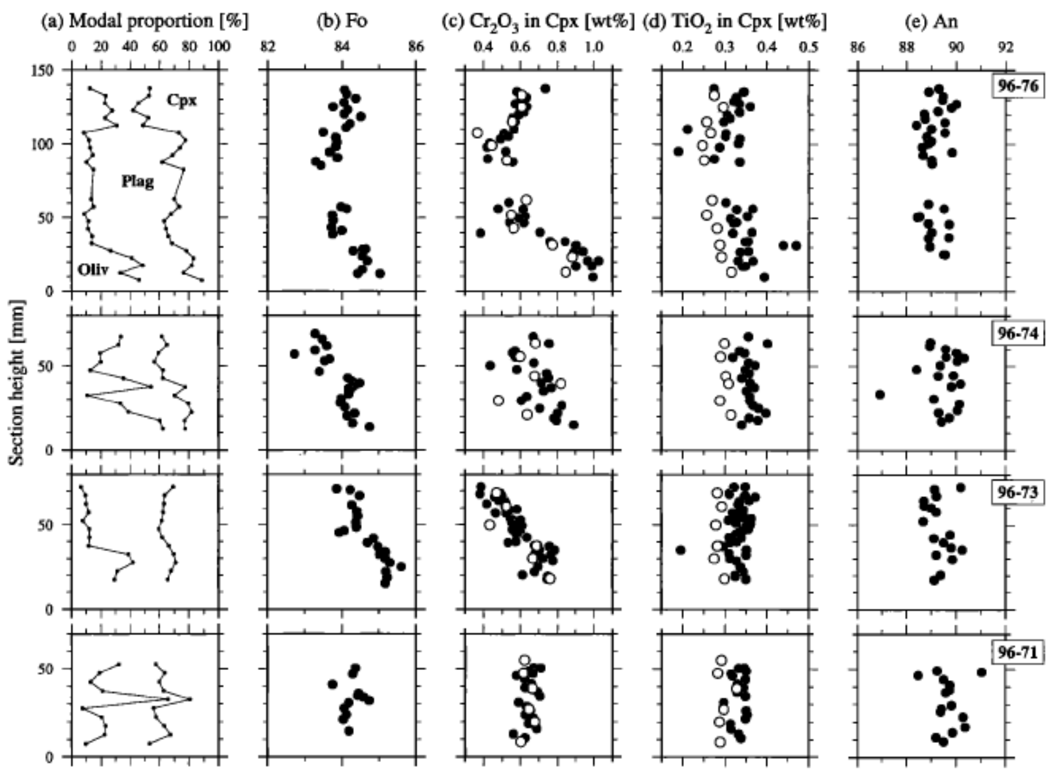


Figure A5-1.2: *Variation in mineral composition on the centimeter scale, in the immediate vicinity of Site MD1. Figure from Korenaga & Kelemen [1997].*

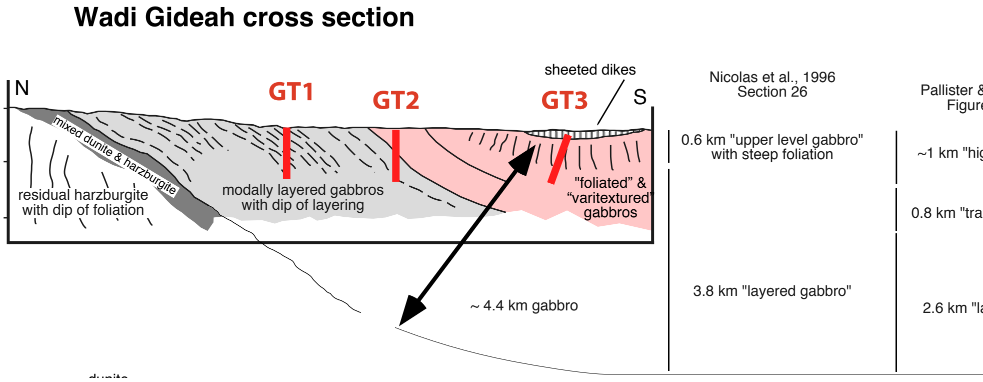


***Figure A5-2**: Cross section along Wadi Gideah, drawn based on published maps and cross-sections [Nicolas et al., 1996; Pallister and Hopson, 1981] and on data from Koepke et al. (pers. comm.) is about 12 km wide, with no vertical exaggeration; tick marks on left side are 1 km apart.*

A5.1.GT1 Lower crustal section in Wadi Gideah

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

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

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

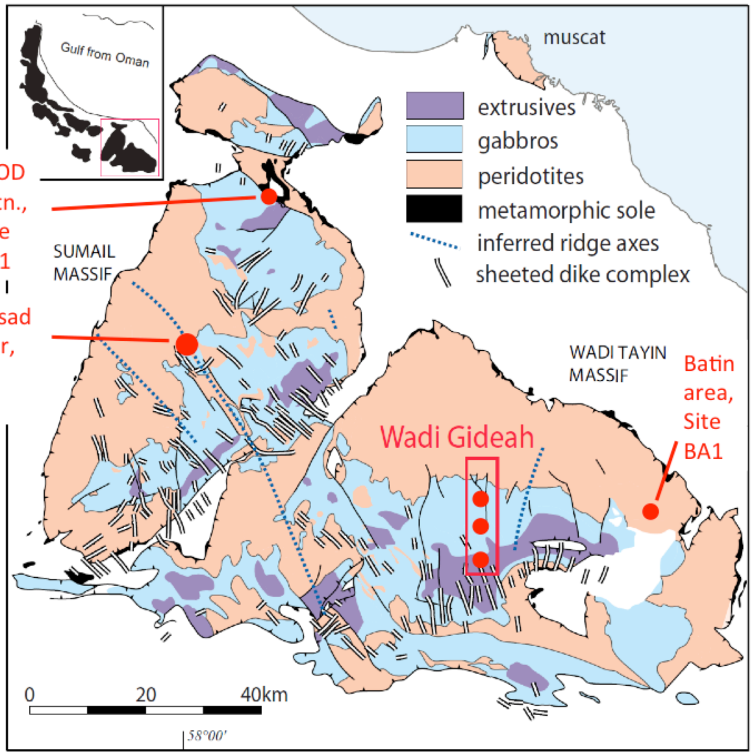
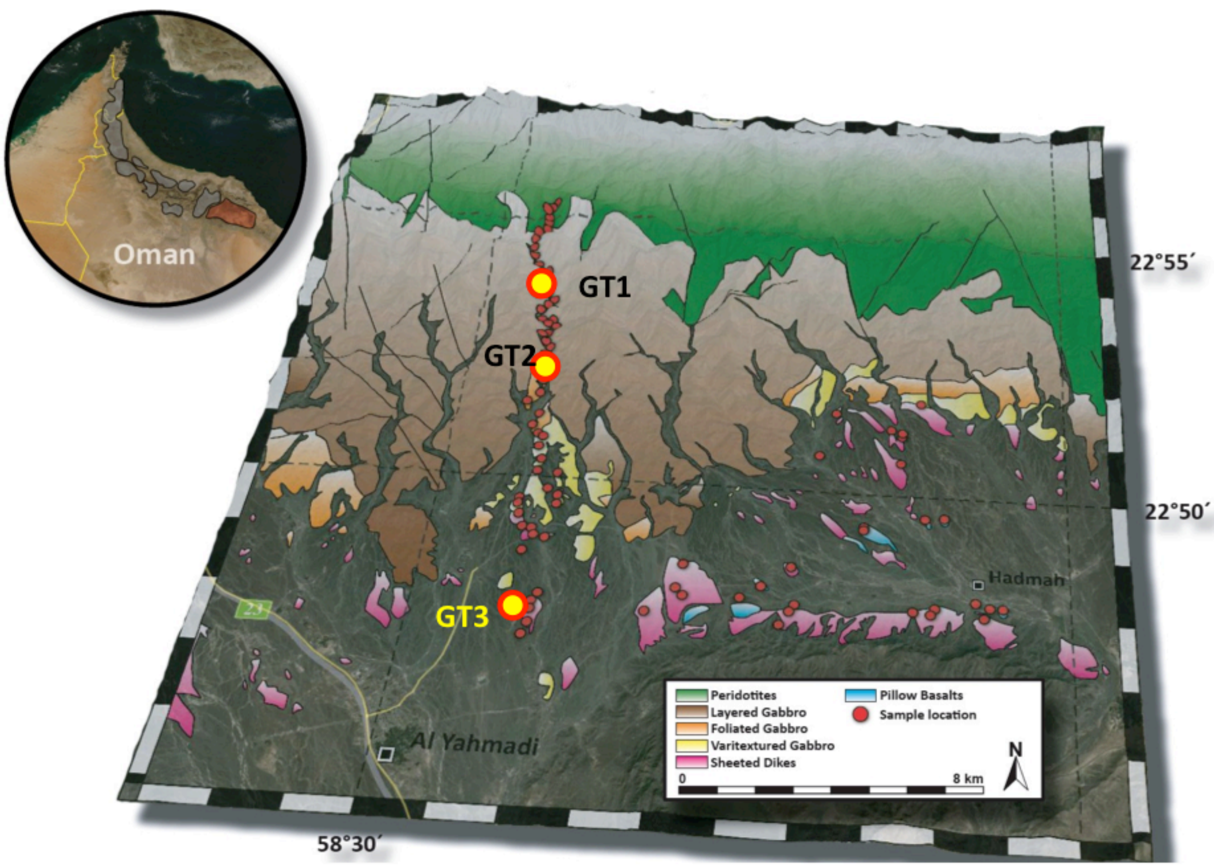


__Figure A5-3__: Two geologic maps showing locations of proposed drill sites in the Samail and Wadi Tayin massifs. Top, map from Nicolas et al. [2000]. Bottom, map based on recent work by Koepke and co-workers (personal communications) showing their sample locations and the proposed drill sites of the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



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

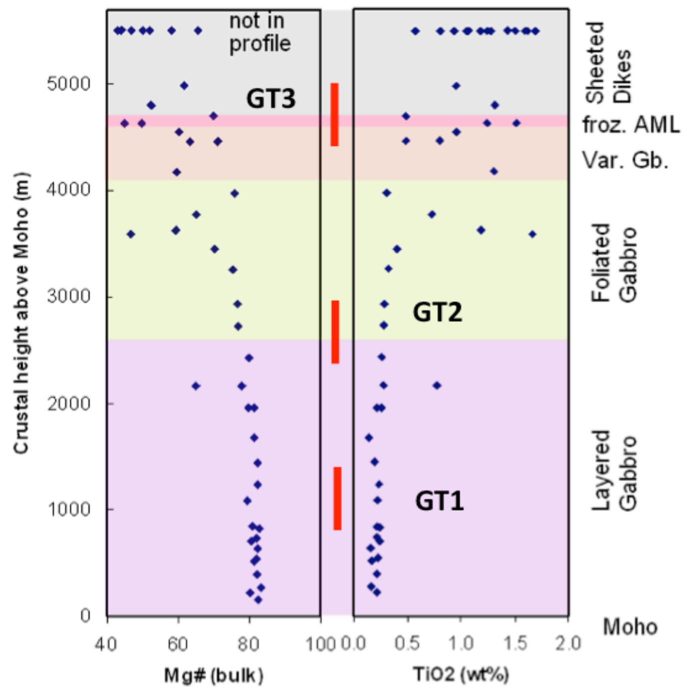


Figure A5-4*: Bulk composition of gabbro and sheeted dike samples from the Wadi Gideah transection of the Wadi Tayin massif, based on recent work by Koepke et al. (personal communication).*

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

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

A5.1.5 Dike-gabbro transition in Wadi Gideah

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

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

2. Mass transfer into the shallow mantle above subduction zones

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

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

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

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

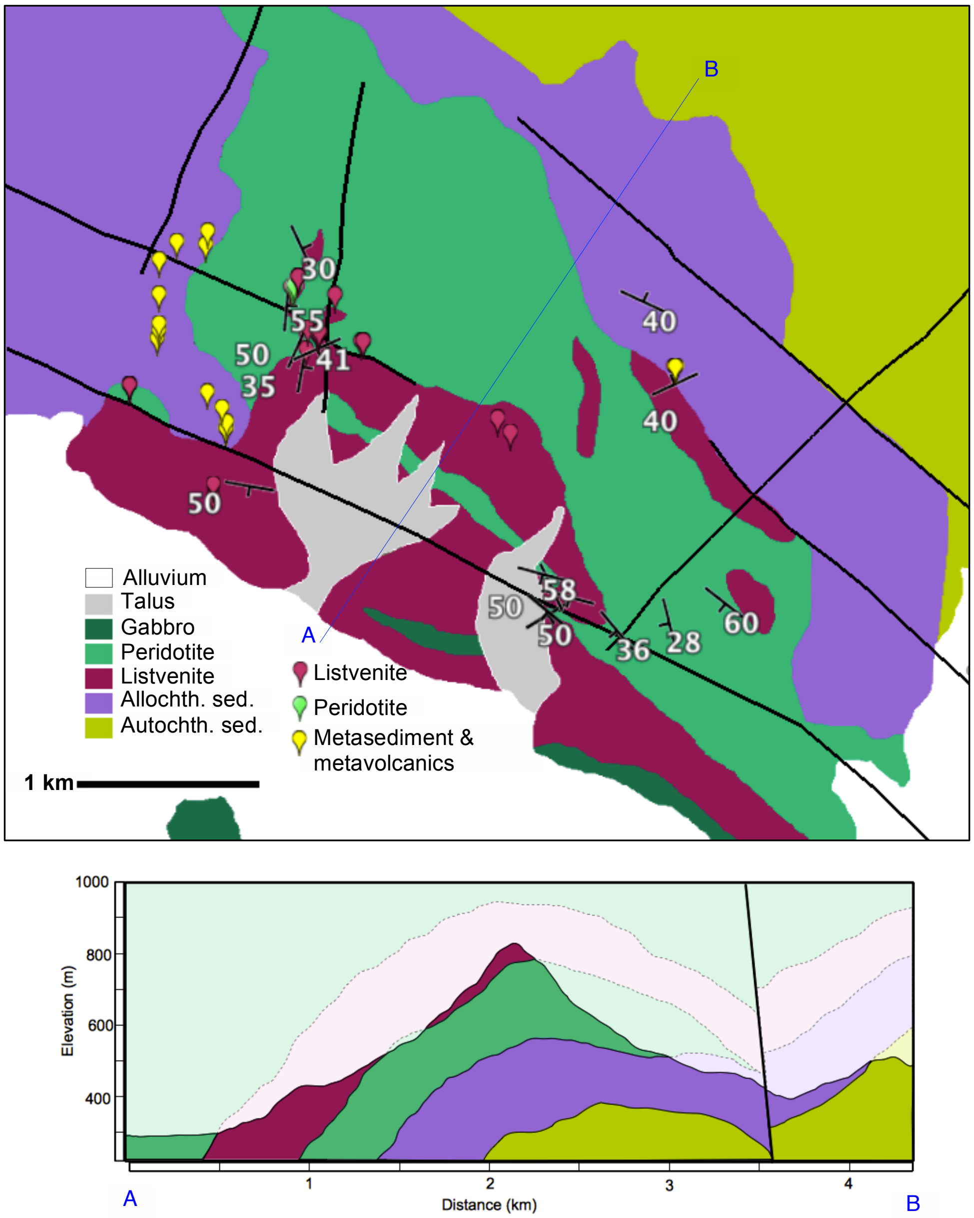


Figure A5-5: *Geologic map and representative cross-section of the MOD Mountain listvenite locality, including individual sample locations (placemarkers). Adapted from Villey et al. (1986), Google Earth data, and field observations (including hand-held GPS measurements and attitudes of composition banding,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

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

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

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

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

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

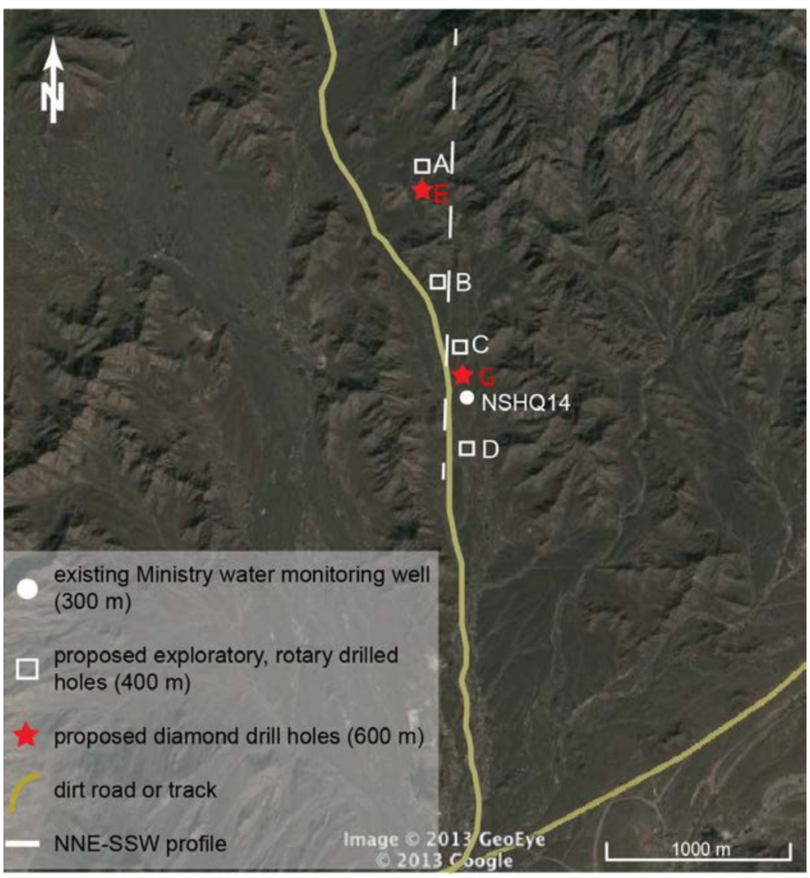


Figure A5-6. Map of proposed drilling site BA1 near the village of Batin. The site is located in partially altered mantle peridotite and includes an existing water monitoring well (NSHQ14) from the Omani Ministry of Regional Municipalities and Water Resources. Four proposed 400-m deep rotary drilled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

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

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

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

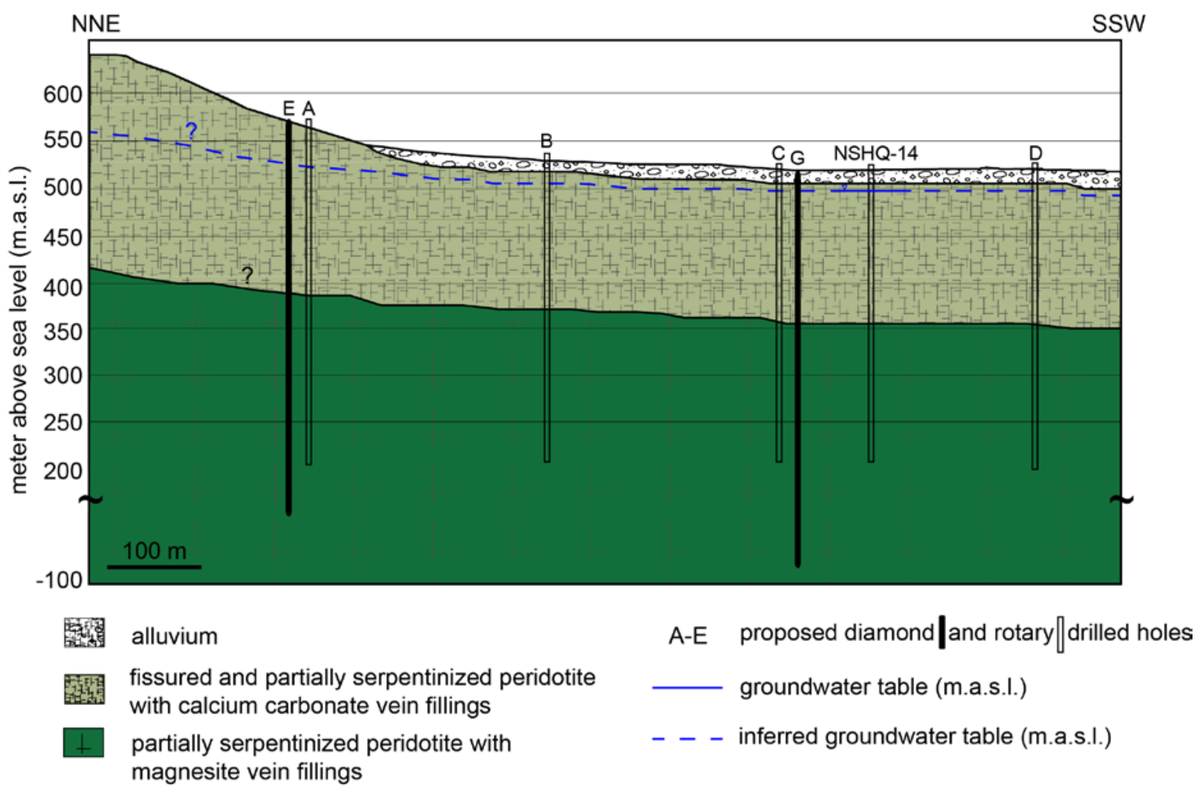


Figure A5-7. *Hydrogeological cross section of proposed drilling site BA1 near the village of Batin.*

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

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Appendix 6: Geophysical wireline logging budget (US$)

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

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

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

Appendix 8: Microbiology sampling budget (in US$)

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

Appendix 9: Core description expenses

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

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

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

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

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

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

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

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

Appendix 12: Project management and coordination costs

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

Appendix 12A: Project management

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

Appendix 12B: Project coordination meetings

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

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

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

Appendix 14: Sampling policy

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

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

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

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

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

Named ODP Investigator Pool

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

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

Immediate data availability

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

Sample availability by application

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

Inclusive work practices and publication

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

Formal acknowledgment of the Oman Drilling Project

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

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

Matching funds (planned proposals)

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

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

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

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

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

The applicant for a permit must provide:

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

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

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

Appendix 17: Supporting letters from:

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

AMERICAN MUSEUM OF NATURAL HISTORY

Department of Earth and Planetary Sciences

7 January, 2013

Dear Peter,

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

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

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

January13, 2014

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

Dear Peter,

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

Please feel free to contact me with any questions.

Sincerely,

Thomas Janecek

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

Cc:
James Allan, Brad Clement

Integrated Ocean Drilling Program
United States Implementing Organization

December 28, 2013

Dear Peter,

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

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

Sincerely,

Jay

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

Texas A&M University • 1000 Discovery Drive • College Station TX 77845-9547 USA
TEL 979-845-2673 • FAX 979-845-1026 • www.iodp-usio.o

DEEP CARBON OBSERVATORY
SECRETARIAT

9 January 2014

Dear ICDP Colleagues,

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

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

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

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

With best regards,

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

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

Appendix 18: References cited throughout this proposal

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