

**Proposal to the Deep Carbon Observatory:
Planning Workshop, Oman Drilling Project**

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Summary

This proposal is for partial support of a planning workshop for scientific drilling in the Samail ophiolite, Sultanate of Oman (Oman Drilling Project), involving both coring and downhole observations. The Samail ophiolite is the world's largest sheet of oceanic crust and upper mantle exposed on land. It records past and ongoing interaction among the atmosphere, the hydrosphere, the oceanic crust and the mantle. Drilling will enable unprecedented studies of the subsurface reaction zone in active low temperature hydrothermal systems extending to depths of 600 m or more. This is directly relevant to the goals of the Deep Carbon Observatory because subsurface hydrothermal alteration systems in oceanic lithosphere have been invoked as providing likely sites for the origin of life, an important sink for carbon in the ocean, an ideal niche for chemosynthetic organisms, an active site of natural, abiotic hydrocarbon synthesis, and a natural model for engineered systems for geological CO₂ capture and storage.

The workshop will determine scientific priorities, choose the best drill sites based on these priorities, begin experimental design, anticipate environmental issues, initiate the permitting process, and lay the groundwork for a full drilling proposal to the International Continental Scientific Drilling Program (ICDP), to be submitted in January 2013. The planning workshop is sponsored and supported in part by the ICDP and will address a variety of scientific objectives. Support from Sloan's Deep Carbon Observatory will ensure broad international participation of scientists over the full range of professional experience who are interested in aspects of Earth's deep carbon cycle.

1. What is the main subject and why is it important?

Funding from the Sloan Foundation's Deep Carbon Observatory (DCO) is sought to defray lodging and travel costs for participants in an international workshop to plan scientific drilling of oceanic lithosphere exposed on land in Oman. Drilling will address a wide range of topics. Central among these are decadal goals of all four DCO Directorates: study of the deep biosphere, the rate and mechanism of carbon uptake during water rock reaction, abiotic hydrocarbon generation, and an inventory of carbon in oceanic lithosphere prior to subduction and recycling in the deeper mantle. In addition, the project will foster cooperation among Arab-, Asian- and western-based scientists. Finally, this project will test techniques in preparation for the MoHole to Mantle (M2M) project – to drill through intact oceanic crust and into the Earth's mantle – proposed to the Integrated Ocean Drilling Program (IODP Proposal #805-MDP). This goal is already supported by DCO through the BEAM (Borehole to the EArth's Mantle) scoping effort.

2. What is the major related work in this field? How does the proposed work differ?

2.1 Overview of oceanic lithosphere studies: Ocean drilling plus ophiolite observations

Oceanic lithosphere, formed at submarine spreading centers, comprises 2/3 of the solid Earth surface. Creation and recycling of oceanic lithosphere, on a time scale of ~ 100 million years, involves the most important geochemical cycles on Earth. This fascinating and fertile “life-cycle” –formation, alteration, biological colonization, transit across Earth's surface, and eventual subduction – is largely hidden. More than 99.9% of ocean crust never sees daylight. Even on the seafloor, because there is no fluvial erosion, the oceanic lower crust and shallow mantle are covered by a nearly unbroken carapace of lava and deep sea sediment.

This observational challenge has been met via two distinct methods. A major effort over the last 50 years has been exploration of *in situ* ocean lithosphere from deep ocean drill ships. The

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Deep Carbon Observatory is playing a role in this effort via support of the BEAM scoping process and participating in ocean drilling expeditions. The second method is study of oceanic lithosphere thrust onto the continents by tectonic plate collisions. Sections of oceanic crust exposed on land are called “ophiolites.” The largest and most complete is the Samail ophiolite in Oman, ~ 50,000 km³ of igneous crust and upper mantle formed at a submarine spreading center. The ophiolite is tilted and eroded, exposing rocks that originally crystallized at depths up to 15 km or more beneath the seafloor.

The Samail ophiolite is the most important natural laboratory on Earth for study of oceanic lithosphere. Hundreds of papers have been published on Samail ophiolite studies (e.g., Appendix V). However, some characteristics of ophiolites are not typical of “normal” oceanic lithosphere produced at modern mid-ocean ridges (e.g., Pearce et al., 1981).

Thus, progress is made via an ongoing dialectic, combining seagoing and field-based methods. Limited submarine observations of, e.g., oceanic lower crust exposed along faults, are extrapolated to the lithosphere scale via similarity to extensive ophiolite outcrops, while other ophiolite observations are checked against extensive data on, e.g., seafloor lava compositions, to refine understanding of the differences between the two settings. Results of this process are summarized in the 2011 NAS Report on Scientific Ocean Drilling (http://www.nap.edu/catalog.php?record_id=13232), IODP science planning documents (<http://www.iodp.org/isp/>, <http://www.iodp.org/Science-Plan-for-2013-2023/>), and the IODP 2007 Mission Mohole and 2012 MoHole to Mantle proposals (<http://www.gm.univ-montp2.fr/spip/spip.php?rubrique185>).

2.2 Time for a hybrid method: Scientific drilling in the Oman ophiolite

In the midst of all the effort outlined in Section 2.1, there has been little scientific drilling of ophiolites, based on the reasoning that subaerial sampling should be sufficient. However, drill core yields a continuous sample that can provide the basis for statistically meaningful

observations (e.g., what are the mean, standard deviation, and spatial variability of carbonate vein abundance in oceanic lithosphere). Establishing a well-characterized borehole also provides a backbone that places disparate outcrop observations in context. Perhaps most importantly, there is intense interest in ongoing processes, active in the subsurface today, such as biological activity and carbon uptake during low temperature alteration, which can only be studied in boreholes.

Our proposed project to drill many 600 meter (or deeper) boreholes in both crust and mantle lithologies in the Oman ophiolite is unique. There has been study of boreholes in peridotite in the California Coast Ranges (Cardace and Hoehler 2010; Hoehler et al. 2011). However, these extend to a maximum of ~100 meters in a tectonic mélangé with relatively poor outcrop. In contrast, the Oman ophiolite is huge, homogeneous, thick, well-exposed and well-characterized.

2.3 Relevance to DCO I: Role of oceanic lithosphere in the Earth's deep carbon cycle

Near spreading ridges, newly erupted lavas effectively fix all volcanic, mantle-derived CO₂ in magmatic fluid inclusions and 'deuteric' carbonate minerals. Cooling of igneous crust and underlying mantle leads to brittle failure, forming faults and fissures that are pathways for hydrothermal convection of seawater-derived fluids that react with rocks to form minerals including carbonates and graphite as well as hydrous minerals and oxides. This hydration, carbonation and oxidation of oceanic lithosphere is a fundamental part of Earth dynamics.

During subduction, some carbon returns to the surface via devolatilization of the heating plate, supplying huge volumes of H₂O and CO₂ to arc volcanism, and a substantial fraction is carried deep into the mantle, maintaining or increasing the carbon and hydrogen content of the mantle.

Dasgupta and Hirschmann (2010) estimate that 40-70% of carbon contained in oceanic sediments, crust and mantle is retained beyond volcanic arcs. Although this represents an important source for Earth's deep carbon reservoirs of diamond, carbides, high pressure

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carbonates, carbonatite melts, and even polymerized CO₂ (e.g., Santoro et al. 2012), constraints on the amount of carbon entering subduction zones remain poor, in part because there are so few localities where a complete section of oceanic lithosphere can be inventoried for carbon.

Formation of carbonate minerals and graphite occurs as a result of disequilibrium between igneous crustal rocks and seawater (e.g., Alt and Teagle, 1999; Jarrard, 2003). While oceanic crust figures significantly in the terrestrial volatile budget, oceanic mantle rocks may play an even more important role. In shallow environments (≤ 10 km depth), mantle peridotite is unstable in the presence of water below $\sim 600^\circ\text{C}$, in the presence of CO₂-rich fluids below $\sim 500^\circ\text{C}$, and at any temperature at the highly oxidizing conditions that prevail near the Earth's surface. As originally described by Barnes and O'Neil (1969), modeled by Bruni et al. (2002), and observed in Oman (e.g., Neal & Stanger 1985), reaction of surface water with peridotite precipitates large volumes of serpentine, Mg-carbonate and perhaps graphite in the subsurface, and travertines composed of calcite on the surface. The strong drive for CO₂ uptake suggests that peridotite carbonation could be important for CO₂ storage, and might provide a practical and inexpensive route to geological CO₂ capture (Kelemen & Matter, 2008; Kelemen et al., 2011).

Radiocarbon data and other constraints indicate that carbonation of mantle peridotite in Oman consumes ~ 1 ton of atmospheric CO₂ per km³ of rock per year (Kelemen & Matter 2008, Kelemen et al. 2011). Based on existing water wells, we know that 600 m drill holes will penetrate the reaction zone for ongoing mineral carbonation in Oman. However, the maximum depth extent of this CO₂ uptake zone is unknown. Further, it is a mystery how the carbonation process remains active in one place for $> 50,000$ years, maintaining permeability and access to solid reactants, despite the propensity for mineralization to fill porosity and armor reactive surfaces. Observations on core and in boreholes will provide the answers.

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One long-standing goal of ocean drilling and ophiolite studies has been a geochemical inventory of oceanic plates prior to subduction, determine mantle outputs to the ocean and seawater inputs to the mantle. In our ICDP pre-proposal (<http://www.ldeo.columbia.edu/gpg/projects/icdp-workshop-oman-drilling-project>), we outlined two phases of drilling. In phase 2, extensive outcrops in Oman will be used to site ~ 10 boreholes that together provide a continuous section through the lithosphere, to obtain the long-sought geochemical inventory. This will be an important prelude to proposed IODP drilling through intact oceanic crust to reach the mantle. In Oman we can assess the extent to which observations in a 1D borehole are representative of 3D variability in oceanic lithosphere.

2.4 Relevance to DCO II: Deep biosphere and abiotic hydrocarbons in oceanic lithosphere

Observations in Oman boreholes will also be fundamental to understanding Earth's deep biosphere, and the potential for abiotic hydrocarbon production. Alteration of oceanic lithosphere is partly driven by oxidation of mantle iron and concomitant reduction of fluids, converting CO₂ and H₂O to CO, graphite, H₂, CH₄, and more complex hydrocarbons. Reduced fluids become saturated with FeNi alloys. Chemosynthetic organisms in the subsurface extract energy via catalyzing these fluid reduction reactions, and by oxidizing abiogenic hydrocarbons. Because the seafloor was shielded from UV radiation at the surface, prior to formation of an ozone layer, it has been proposed that life arose via abiogenic synthesis during alteration of ancient oceanic lithosphere, and chemosynthesis supported the food chain as the earliest organisms evolved.

In addition to producing reduced components, peridotite alteration occurs far from chemical equilibrium (e.g., Lazar et al. 2012). The peridotite alteration system in Oman produces oxygen fugacity gradients ranging from 0.2 bars to $< 10^{-30}$ bars over length scales as small as 1 cm, e.g., in host rock around cracks with flowing surface water. Chemosynthetic organisms thrive as they catalyze reactions that reduce disequilibrium. In this way, the peridotite alteration environment

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could be one of the best habitats on Earth for chemosynthetic organisms in a deep biosphere.

It is known that both ridge-axis hydrothermal systems and off axis oceanic lithosphere host important subsurface ecosystems (e.g., Kelley et al. 2005; Santelli et al. 2008; Schrenk et al. 2010), supported by the strong reduction of CO₂ and H₂O as mantle peridotite is hydrated to form serpentine, providing important pathways for abiogenic production of methane and other hydrocarbons (e.g., Bradley & Summons 2012; Brazelton et al. 2010; Charlou et al. 1998, 2002; McCollom and Seewald 2007; McCollom et al. 2010; Proskurowski et al. 2008). However, there are very few subsurface observations of these systems. Their veneer was scratched on IODP Expedition 336 last fall (2011), where boreholes penetrated 50 to 90 m of deep sea sediment and continued up to 160 m into the uppermost lavas in Atlantic ocean crust. One can confidently predict higher recovery and greater depths of penetration via diamond drilling in Oman. As always, Oman observations will be combined with seafloor data to reach robust conclusions.

To limit projected costs, our pre-proposal to ICDP envisioned 600 meter boreholes, using equipment and contractors already in Oman. However, the ophiolite is > 5 km thick in some places. Given the mean annual air temperature of 30°C, and assuming a geothermal gradient of 20-30°C per km, drilling to 3-5 km depth could reach the notional “biotic fringe” at ~ 120°C (Kashefi and Lovley 2003; Takai et al. 2008). This would be costly, but still orders of magnitude less expensive than drilling to comparable depth at sea. Discussion of the costs and benefits of importing equipment for this purpose will be a central topic of the workshop.

3. Why is the proposer qualified to address the subject?

Kelemen has participated as a keynote speaker, discussion leader and scribe in planning workshops for ODP, IODP, and NSF initiatives including FUMAGES, RIDGE, MARGINS, and GeoPRISMS. He convened a GSA Penrose Conference on Arc Lower Crust, an AGU Chapman

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Conference on Shallow Mantle Processes, an IODP/ICDP Workshop on Mineral Carbonation for CO₂ Capture and Storage, and various AGU Fall Meeting symposia on similar topics, and will convene the 2012 Gordon Conference on Rock Deformation. He has worked on the genesis and evolution of oceanic lithosphere since 1988, including studies of the Oman ophiolite from 1994-2001, and 2007-2012. He was Co-Chief Scientist on the MODE 94 submersible expedition and on ODP Leg 209, sampling mantle peridotite on the Mid-Atlantic Ridge, and lead PI on the large Talkeetna Continental Dynamics Project 1999-2004. He has developed new hypotheses on reactive flow of melt in the mantle beneath oceanic spreading ridges (review in *Scientific American*, Kelemen, 2009; also Appendix V), the creation of oceanic lower crust by sill injection (reviews in IODP 2003-2013 Science Plan, IODP MoHole proposals 2007, 2011; Appendix V), widespread injection of sills into the shallow mantle beneath slow spreading ridges (summary in Kelemen et al. 2007; Appendix V), and CO₂ uptake during low temperature alteration of mantle peridotite (review in Kelemen et al. 2011; Appendix V).

4. What is the approach being taken?

The ICDP-sponsored workshop on scientific drilling in the Samail ophiolite, in the Sultanate of Oman, will be held at the IBM Dolce Center in Palisades, New York, September 14-16. There will be a few keynote science talks, alternating with breakout sessions and plenary discussions to address specific topics ranging from science priorities (days 1 and 2), to choice of drill sites (day 2), to cost/benefit of different depth targets, environmental and societal risks to be avoided or minimized, and the nature of the permitting process in Oman (day 3).

Partial support of the upcoming workshop was obtained as part of a successful pre-proposal to the ICDP for scientific drilling in Oman (<http://www.ldeo.columbia.edu/gpg/projects/icdp-workshop-oman-drilling-project>; see Appendix IV in this Sloan proposal for a list of proponents on the ICDP pre-proposal). The pre-

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proposal outlined a plan for two phases of drilling, with four holes in a first phase, and - contingent on successful completion of phase one - ~ 10 more holes in a second phase. The first phase would include two holes in actively altering peridotite, one in the transition from fine-grained dikes to course-grained gabbros (dike-gabbro transition), and another in the transition from igneous crust to residual mantle peridotite (crust-mantle transition zone, MTZ). Phase two would take advantage of the extensive outcrop to site “offset holes” that together comprise a full section through the oceanic crust and shallow mantle. The plan was to use drilling equipment and personnel active in mineral exploration in Oman, with low costs but with depth ≤ 600 meters per hole. Sites were chosen in the southern ophiolite massifs, thought by many to have a simpler history and structure compared to the northern massifs. *ALL of these topics will be open for discussion by participants, and could be significantly revised as an outcome of the workshop.*

The workshop will be limited to ~ 60 participants. Attendees will span many nations and a diversity of expertise and professional experience. A first circular outlining the application process was sent by email to about 3000 people on March 25. The workshop and process will also be advertised in EOS, the weekly journal of the American Geophysical Union. Participants will be chosen by the steering committee (Appendix II). The Steering Committee, which includes several scientists involved with the DCO, will aim for attendance by scientists associated with the range of DCO interests relevant to the Oman drilling project. This group of scientists from 9 countries includes Dr. Ali Al Rajhi, Director of the Geological Survey of Oman, and Prof. Sobhi Nasir, Head of the Dept. of Geology at Sultan Qaboos University (SQU) in Oman. Journalists at the recent mineral carbonation workshop in Oman emphasized to us the importance of public perception of Arab scientists working with others from the US and EU. Undergraduates and graduate students from SQU will play a central role in core logging and

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analysis, working together with research scientists and graduate students from the international community. Omani student participation will be coordinated by Prof. Nasir.

5. What will be the output from the project?

Results of the Workshop will be incorporated in a full proposal to the ICDP in January 2013, or January 2014 at the latest. If Workshop participants endorse the general plan outlined in the pre-proposal to ICDP, phase one will produce four 600 drill holes, two in mantle peridotite, one in the dike-gabbro transition, and one in the crust-mantle transition zone, with an expected 90% core recovery, combined with fluid samples from the entire depth interval below the water table, geophysical logs, and downhole experiments on hydrology (packer tests), biology (culture experiments). Extensive scientific research papers on these materials and data are anticipated. Pending successful completion of phase one, phase two will produce ten holes in the crust and mantle, culminating in a geochemical inventory in a complete section of oceanic lithosphere.

Steering Committee member Craig Manning will prepare a short report to the DCO secretariat about the implications of the workshop for the DCO.

6. What is the justification for the amount of money requested?

We are requesting \$30,000 from the Sloan Foundation. As can be seen from the budget documents in this proposal, Sloan funds – together with funds from the ICDP – would limit the total cost of the workshop to about \$1000 per person, including estimated travel costs.

7. What other sources of support are in hand or being sought?

ICDP committed \$50,000 to support of this workshop. Other than this proposal to the Sloan Foundation, there are no pending proposals for support. However, members of the steering committee will seek additional funding from US, European and Japanese sources, to ensure the participation of key personnel such as Oman government representatives and keynote speakers.

Appendix I. Deep Carbon Observatory Decadal Goals

The Deep Carbon Observatory decadal goals as of February 2012 are as follows:

1. To improve our understanding of the physical and chemical behavior of carbon at extreme conditions found in the deep interiors of Earth and other planets. This goal includes the following tasks:
 - a. Inventory possible C-bearing minerals in the mantle and core.
 - b. Characterize the physical and thermochemical properties of those phases at relevant P-T conditions.
 - c. Develop environmental chambers to access C-bearing samples in new regimes of P- T under controlled conditions (e.g., pH, fO₂) and with increased sample volumes and enhanced sample analysis and recovery capabilities.
 - d. Compile a comprehensive database of thermochemical properties and speciation of C-O-H-N fluids and phases to upper mantle P-T conditions.
 - e. Achieve a fundamental understanding of carbon bonding at core P-T conditions.

2. To identify the principal deep carbon reservoirs and to assess the total carbon budget of Earth. This goal includes the following tasks:
 - a. Real-time monitoring of volcanic activity and gas emissions from the Americas, Europe, Asia and Africa.
 - b. Estimate total carbon in Earth's mantle accurate to within a factor of two.
 - c. Estimate rates of carbon sequestration at subduction zones.

3. To document the nature, sources, and evolution of subsurface organic molecules, including hydrocarbons and biomolecules. This goal includes the following tasks:
 - a. Develop techniques to resolve the relative roles of biotic versus abiotic hydrocarbon production, with experimental investigation of abiotic methane synthesis under lower crust and upper mantle.
 - b. Develop techniques to characterize nanoscale organic molecules from key samples (including the Moho and Mars), including their compositions, structures, and isotopic characteristics.
 - c. Explore the possible roles of subsurface organic molecules in the origins of life.
 - d. Investigate the carbon cycle in deep time, including the coevolution of the geosphere and biosphere.

4. To assess the nature and extent of the deep microbial biosphere. This goal includes the following tasks:
 - a. Conduct a global 3-D census of deep microbial life, presented in an interactive 3-D web-based platform.
 - b. Explore the extreme P-T limits of life through laboratory investigation of microbes under deep crustal.
 - c. Investigate biomolecular and biophysical adaptations under extreme conditions.

Appendix II. Oman Deep Drilling Steering Committee

Name	Country
Ali Al Rajhi (Director, Geol. Survey of Oman)	Oman
Margot Godard	France
Benoit Ildefonse*	France
Peter Kelement*	USA
Jürgen Koepke	Germany
Chris MacLeod	UK
Craig Manning	USA
Katsu Michibayashi*	Japan
Sobhi Nasir (Head, Dept. of Geology, Sultan Qaboos University, Oman)	Oman
Everett Shock	USA
Eiichi Takazawa*	Japan
Damon Teagle*	UK

*Also proponents of the recently submitted IODP MoHole to Mantle drilling proposal.

Appendix III. References Cited

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Appendix IV: Proponents of Oman Drilling Project Workshop Proposal to the International Continental Scientific Drilling Program, January 2011

first	last	position	host institution	host country	workshop steering committee
Ali	Al Rajhi	Director	Geological Survey of Oman	Oman	yes
Shoji	Arai	Professor	Kanazawa University	Japan	
Wolfgang	Bach	Professor	University of Bremen	Germany	
Donna	Blackman	Research Geophysicist	Scripps Institution of Oceanography	USA	
Françoise	Boudier	Emeritus Professor	Université de Montpellier		
Georges	Ceuleneer	Directeur de Recherche	CNRS Toulouse	France	
Laurence	Coogan	Associate Professor	University of Victoria	Canada	
Kathryn	Gillis	Professor	University of Victoria	Canada	
Margot	Godard	Directeur de Recherche	CNRS Université Montpellier	France	yes
Steve	Goldstein	Professor	Columbia University/Lamont	USA	
Phillipe	Gouze	Chargé de Recherche	CNRS Université de Montpellier	France	
Greg	Hirth	Professor	Brown University	USA	
Al	Hofmann	Emeritus Professor	Universität Mainz	USA	
Benoit	Ildefonse	Directeur de Recherche	CNRS Université Montpellier	France	yes
Bjorn	Jamtveit	Professor	University of Oslo	Norway	
Peter	Kelemen	Arthur D. Storke Professor	Columbia University/Lamont	USA	yes
Frieder	Klein	Assistant Scientist	Woods Hole Oceanographic Institution	USA	
Jürgen	Koepke	Professor	Institut für Mineralogie - Leibniz Universität	Germany	yes
Charles	Langmuir	Professor	Harvard University	USA	
Chris	MacLeod	Professor	Cardiff University	UK	yes
Craig	Manning	Professor, Chair of Dept.	University of California Los Angeles	USA	yes
Jürg	Matter	Associate Lamont Research Professor	Columbia University/Lamont	USA	
Katsu	Michibayashi	Professor	Shizuoka University	Japan	yes
Jay	Miller	Adjunct Professor, Manager of Technical & Analytical Services	IODP, Texas A&M University	USA	
Sumio	Miyashita	Professor	Kanazawa University	Japan	
Sobhi	Nasir	Professor, Head of Dept.	Sultan Qaboos University	Oman	yes
Adolphe	Nicolas	Emeritus Professor	Université de Montpellier	France	
Phillipe	Pézarid	Directeur de Recherche	CNRS Université de Montpellier	France	
Barbara	Sherwood Lollar	Canada Research Chair, University Professor	University of Toronto	Canada	
Everett	Shock	Professor	Arizona State University	USA	yes
Satish	Singh	Professor	Institut de Physique du Globe de Paris	France	
Eric	Sonnenthal	Staff Geological Scientist	LBL, University of California at Berkeley	USA	
Eiichi	Takazawa	Associate Professor	Niigata University	Japan	yes
Damon	Teagle	Professor	University of Southampton	UK	yes
Susumu	Umino	Professor	Kanazawa University	Japan	
Jessica	Warren	Assistant Professor	Stanford University	USA	
Wenlu	Zhu	Associate Professor	University of Maryland	USA	

**Appendix V: Papers by PI Peter Kelemen
on origin and evolution of oceanic lithosphere**

**mineral carbonation and hydration
during low temperature hydrothermal alteration**

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