# Proposed Oman Drilling Project

## Summary of Results

science objectives & proposed sites
identified at Oman Drilling Workshop
Palisades NY, September 13-17, 2012

sponsored by International Continental Drilling Program (ICDP),
Sloan Foundation Deep Carbon Observatory (DCO)
US National Science Foundation (NSF)

Convener: Peter Kelemen
Arthur D. Storke Professor
Dept. of Earth & Environmental Sciences
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New York, NY

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

# Workshop on Scientific Drilling in the Samail Ophiolite, Sultanate of Oman

(Oman Drilling Workshop)

**Sponsored by:**

**International Continental Drilling Program (ICDP)**

**Sloan Foundation, Deep Carbon Observatory (DCO)**

**US National Science Foundation (NSF)**

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Distinguished participants:

His Excellency, Ambassador Adnan Al Ansari
Permanent Observer to the UN for the
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Dr. Sean Solomon
Director, Lamont Doherty Earth Observatory

Dr. Arthur Lerner-Lam
Associate Director, Lamont Doherty Earth Observatory

Original pre-proposal 1998
Approved for workshop by ICDP 2000
Mainly focused on formation and evolution of
oceanic crust and mantle
Proponents had too many other projects 2000-2005,
decided to postpone workshop and full proposal

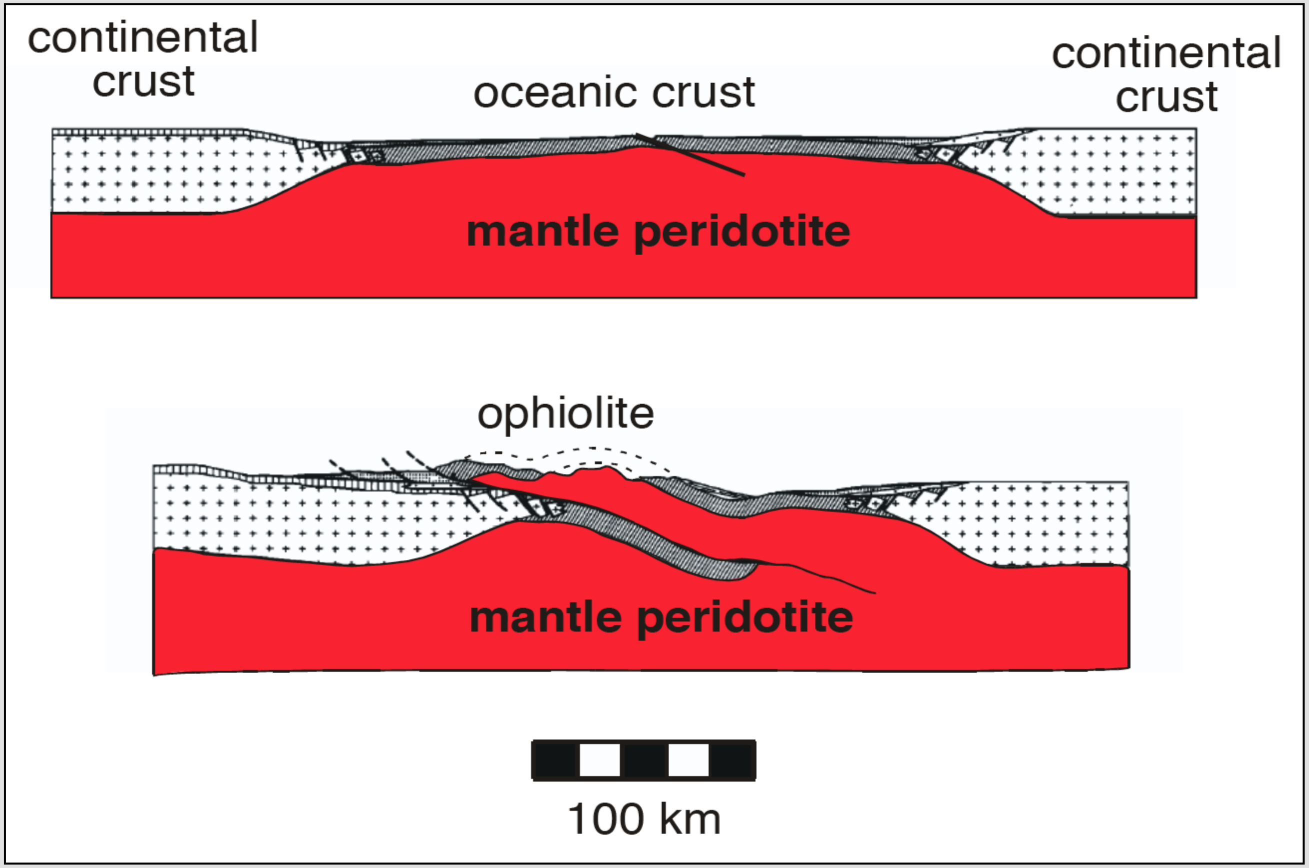
Second proposal 2011
Approved for workshop by ICDP 2011
Includes previous goals, but also a major focus on
ongoing alteration and weathering, carbon cycle, and
subsurface biosphere

Planned full proposal to ICDP due January 15, 2013

Similar projects in the past:
Cyprus (Troodos) drilling program
Drilling in southern California Coast Ranges

The “Oman ophiolite” was formed during a collision of tectonic plates, which thrust oceanic crust and upper mantle onto the margin of the Arabian continent. This created

- deposits of copper, chrome and other commodities concentrated in oceanic plates
- a huge source of chemical potential energy, because the Earth’s mantle is not in equilibrium with the atmosphere and surface water, and
- a natural laboratory where scientists study creation and evolution of oceanic plates.

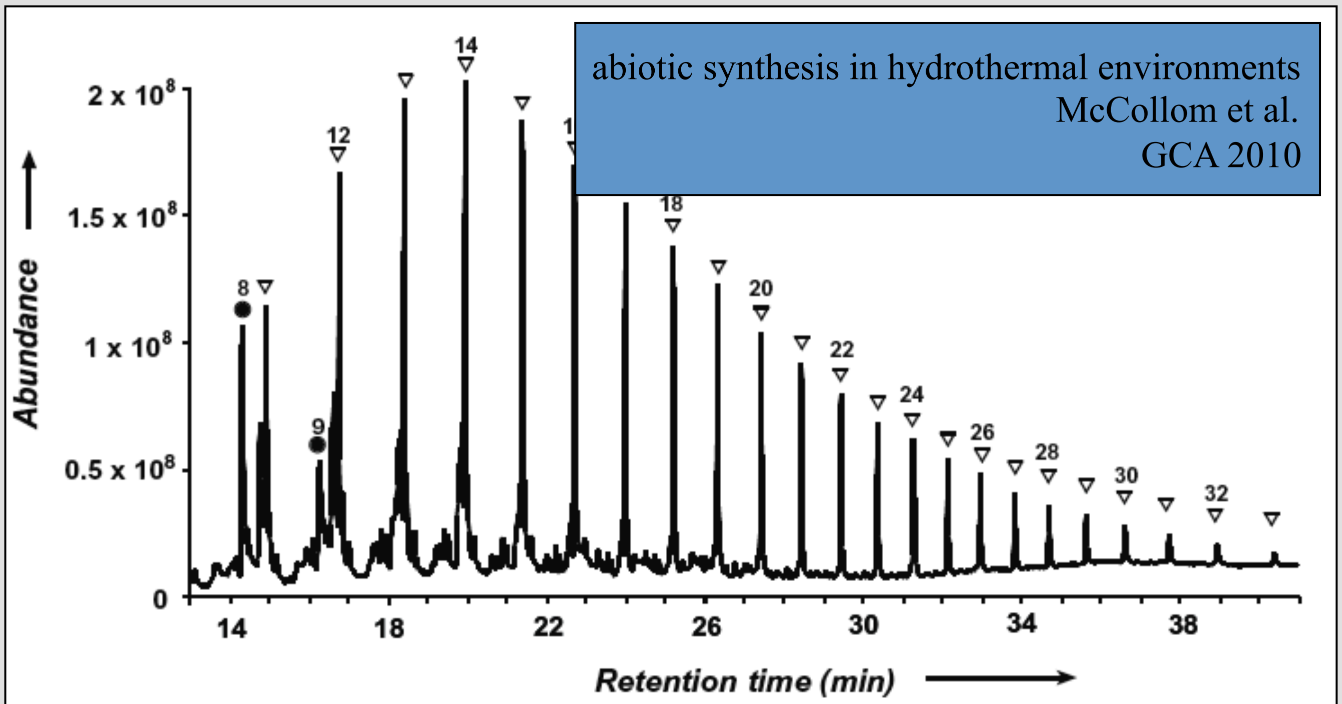



modified from Coleman, Ophiolites, Kluwer, 1977

Hydration of mantle rocks reacting with surface waters provides the optimal geological conditions for abiotic synthesis of hydrocarbons. Such an environment may Have hosted the evolution of the earliest life on Earth.

“Mount Chimaera” western Turkey

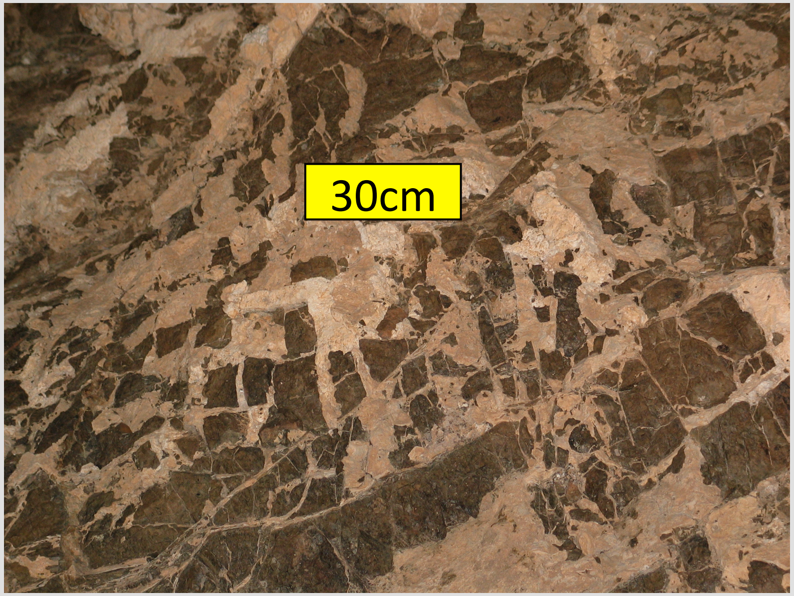
abiotic methane formed during mantle hydration has been burning for thousands of years on the slopes of Mt Chimaera near the coast of Turkey




abiotic synthesis in hydrothermal environments
McCollom et al.
GCA 2010

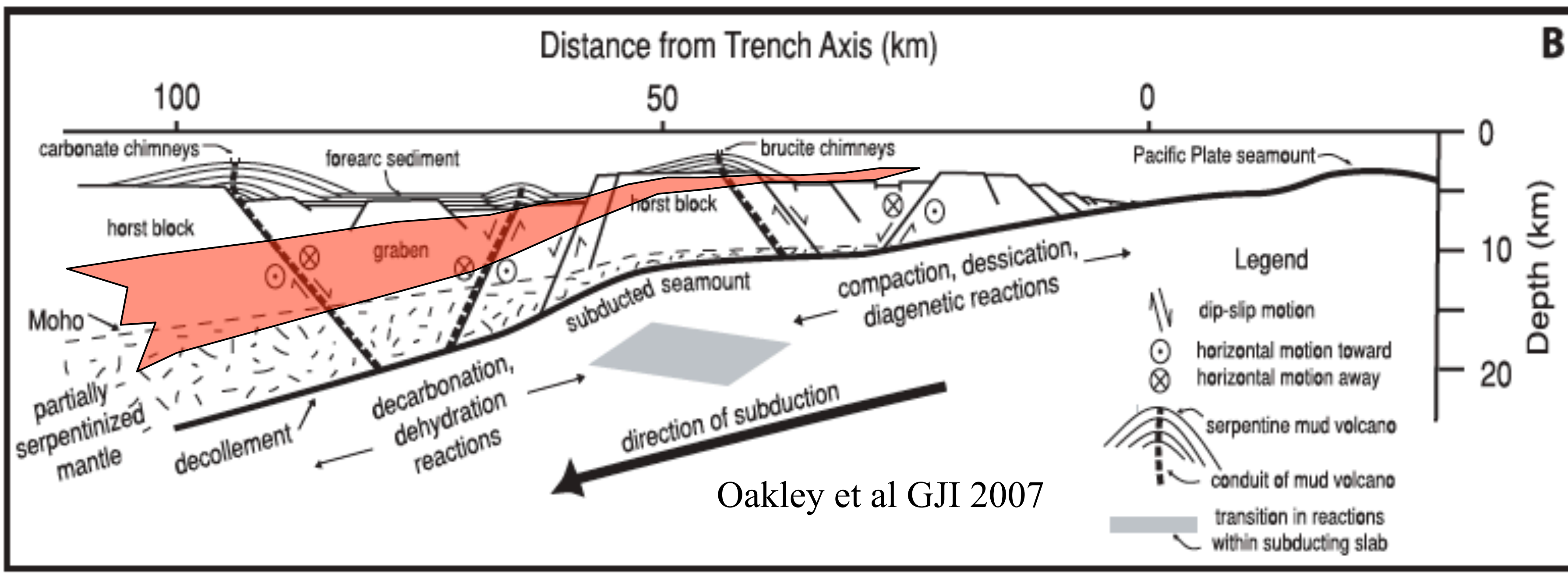
McCollom et al. showed that hydration of mantle rocks produces ideal conditions for abiotic synthesis of complex hydrocarbons including alkanes and alkenes, as well as methane.

Ongoing mineral carbonation, by reaction of surface waters and atmospheric $CO_2$ with mantle rocks in the Oman ophiolite, forms spectacular travertine terraces, "blue pools" in the wadis, and related, subsurface carbonate veins. This consumes 10,000-100,000 tons of $CO_2$ per year. There is enough peridotite in the Oman ophiolite to solidify 33 trillion tons of $CO_2$, equal to the mass of human output for 1000 years (if present-day emission rates continue unchanged). Mineral carbonation could be accelerated to play an important role in mitigating greenhouse gas emissions. Two proposed methods are to (1) heat reacting rock volumes to about 185°C, where reaction rates are a million times faster, and/or (2) increase the flux of water circulating through the rocks via drilling and fracturing. In Oman, both methods would have the least impact using boreholes drilled from the shore into mantle rocks beneath the seafloor.

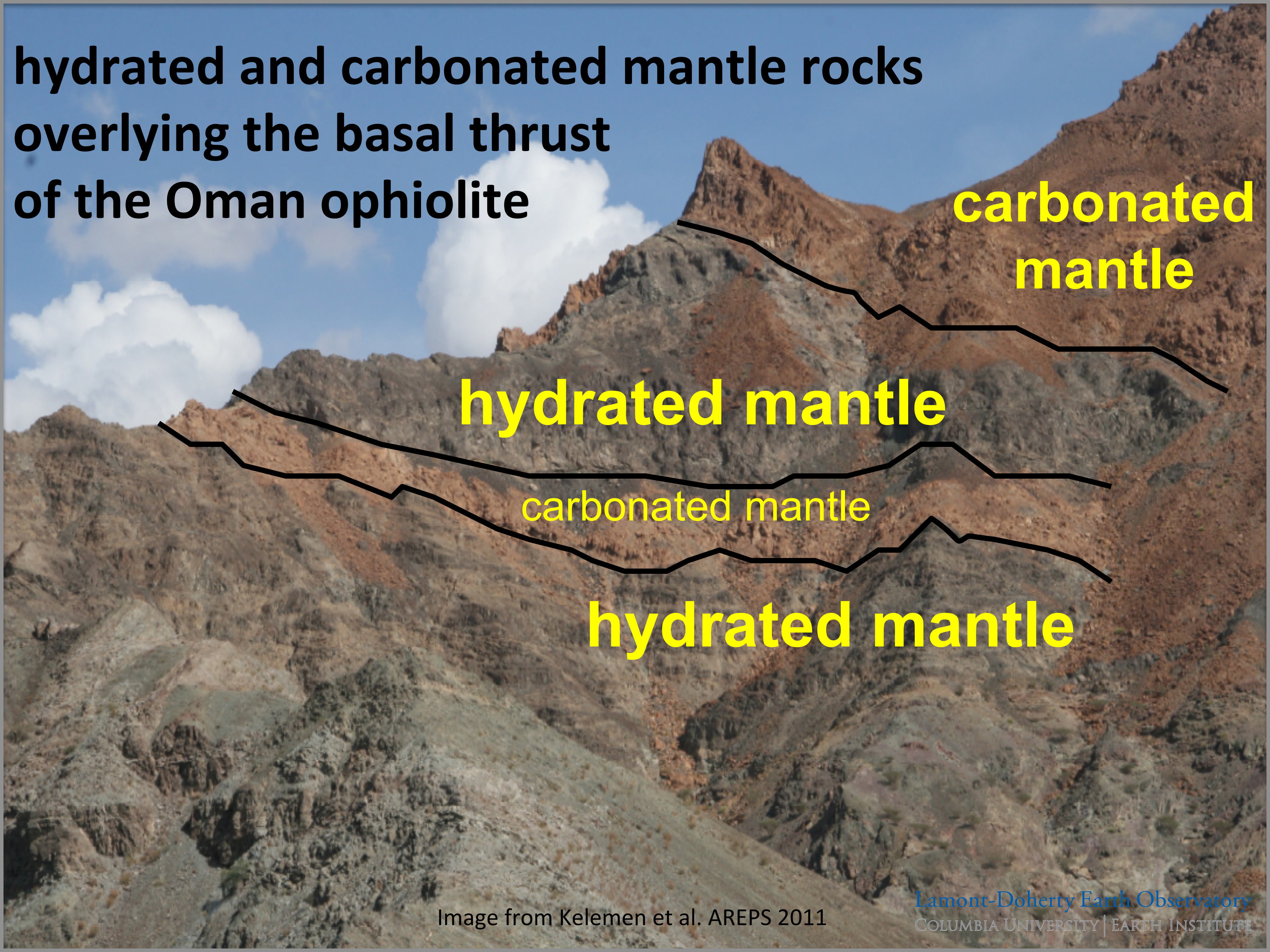




Images from Kelemen & Matter PNAS 2008

Hydration and carbonation of mantle rocks, where they are thrust over seafloor sediments in subduction zones, is thought to be essential for many aspects of plate tectonics and global geochemical cycling: lubricating fault zones, providing a source of $H_2O$ and $CO_2$ for explosive volcanism, representing an overlooked but significant part of the global carbon cycle, and maintaining the volatile content and viscosity of the mantle. The processes of hydration and carbonation, especially at depths > 10 km where cracks are ordinarily thought to be closed, are uncertain. Study of the basal thrust of the Oman ophiolite, where mantle rocks were thrust over oceanic sediments, will reveal the nature of these processes.




Oakley et al GJI 2007


hydrated and carbonated mantle rocks
overlying the basal thrust
of the Oman ophiolite
carbonated
mantle
hydrated mantle
carbonated mantle
hydrated mantle
Image from Kelemen et al. AREPS 2011
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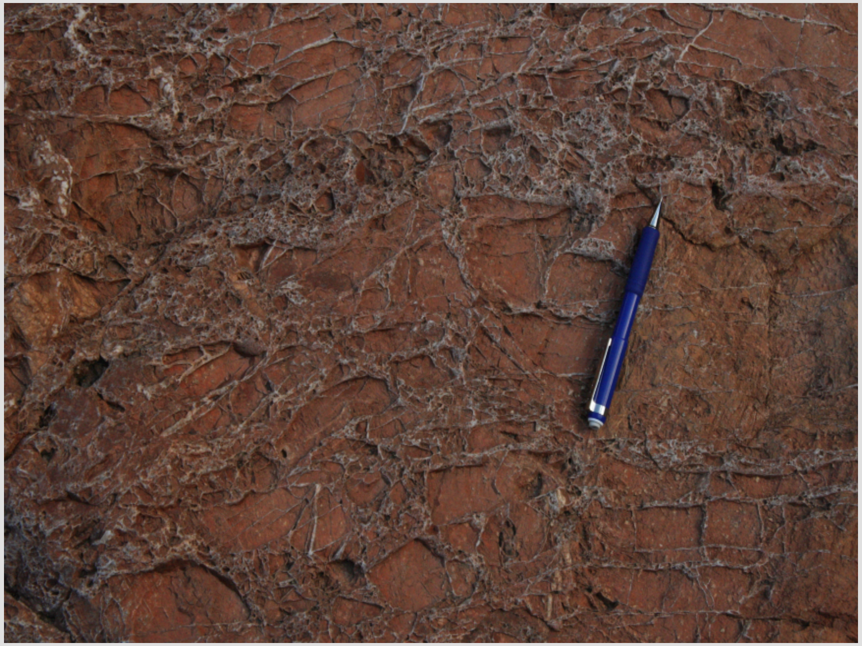
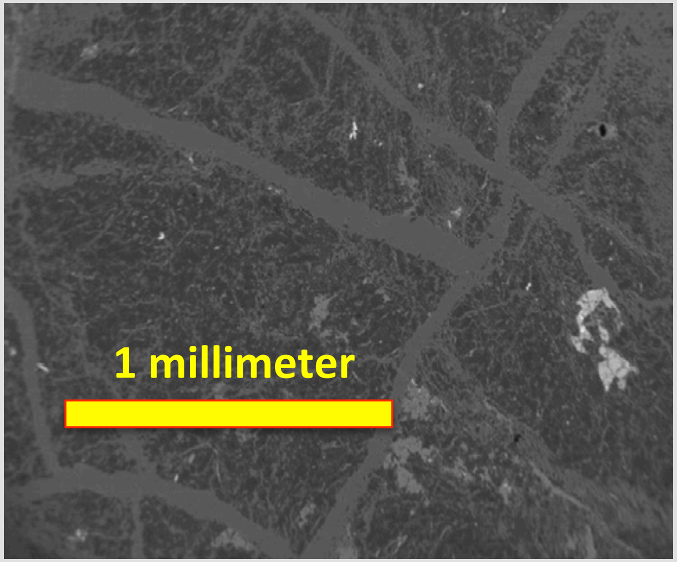
Interaction of the mantle with $CO_2$-bearing fluids at about 200°C with a fluid pressure of about 3000 atmospheres (as happened about 80 million years ago in the mountain side shown on the previous slide) occurs at the optimal conditions for rapid mineral carbonation. 100% of the magnesium and calcium in these rocks – originally in solid silicates - was converted to solid carbonates, while the silica formed quartz. Fluid access and reaction continued because volume changes created new cracks, increasing permeability and reactive surface area.

100% carbonation is the goal of engineered mineral carbonation for carbon capture and storage. To design such systems, while avoiding the cost of grinding the rock reactants, we need to understand the natural mineral carbonation process, including reaction-driven cracking. Reaction-driven cracking could also be important in extracting unconventional hydrocarbon resources (shale gas, shale oil) and in creating fracture networks for geothermal power generation.

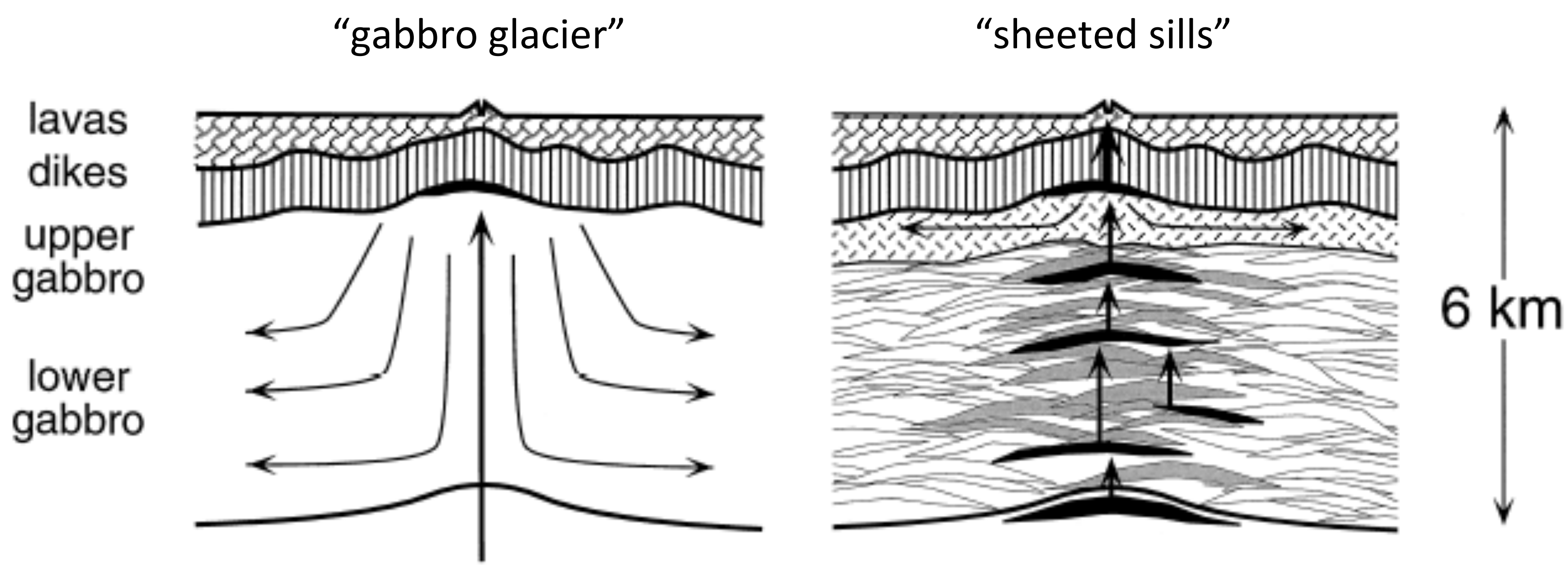
mantle rocks converted into magnesium carbonate (red on left, grey on right) plus quartz veins






Images from Kelemen et al. AREPS 2011

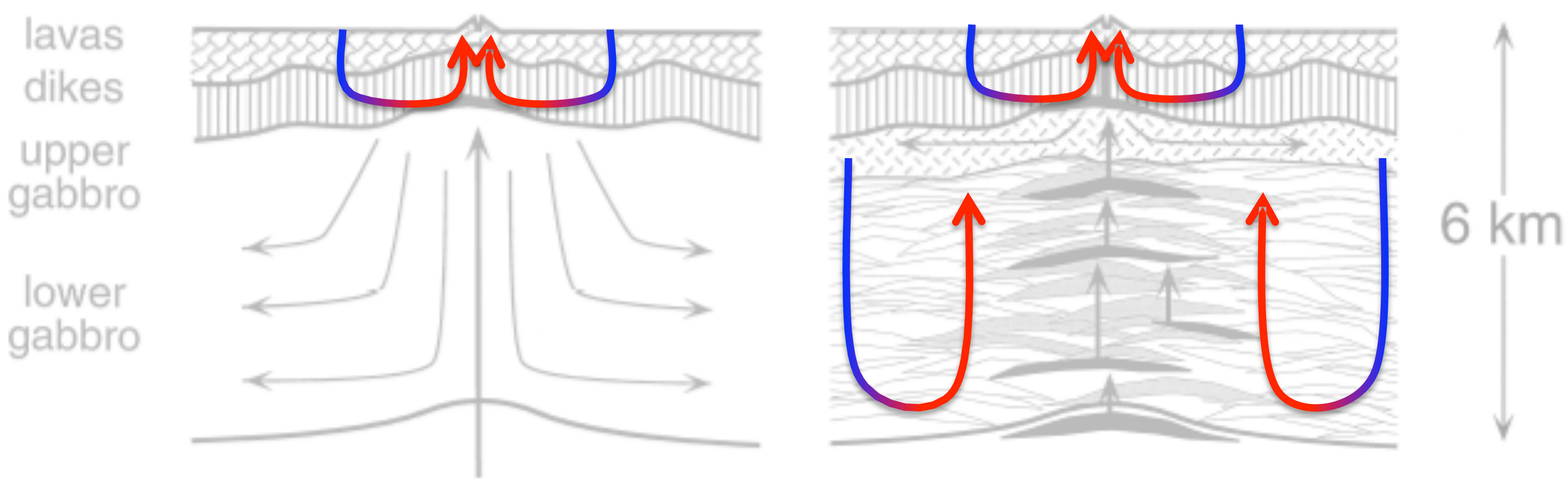
The lower oceanic crust forms from crystallization of igneous rocks in the subsurface beneath spreading centers, forming "plutonic" rocks called gabbros. The site of crystallization is poorly known. Does all of the crystallization occur in a "shallow melt lens" near the surface, where heat can be extracted efficiently, or do the gabbros crystallize in a series of stacked lenses, called sills, throughout the crust? Study of chemical variation and crystal orientation in the lower crust of the Oman ophiolite can resolve this question.




Nicolas et al. 1988, 1993; Phipps Morgan & Chen, 1993; Quick & Denlinger, 1993

Kelemen et al. 1997; Kelemen & Aharonov, 1998; Korenaga & Kelemen, 1997, 1998

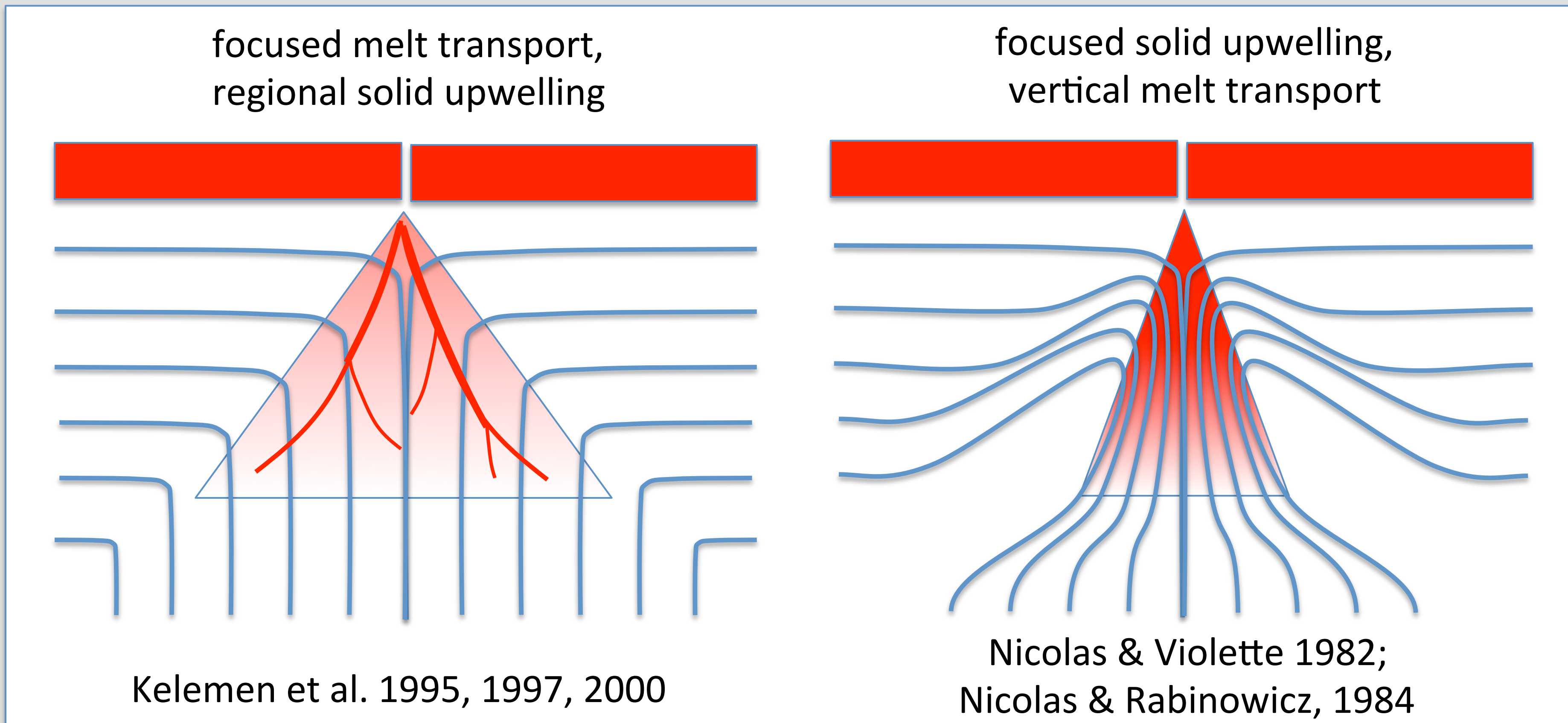
Crystallization of gabbros in a shallow melt lens requires rapid removal of heat by active hydrothermal convection in the upper crust. Crystallization of gabbros at a range of depths requires hydrothermal circulation extending to the base of the crust. Measurement of mineral zoning in Oman gabbros, interpreted in terms of cooling rates, will resolve which type of hydrothermal alteration and cooling was predominant.




Coogan et al. 2006

Garrido et al. 2001;
VanTongeren et al. 2009

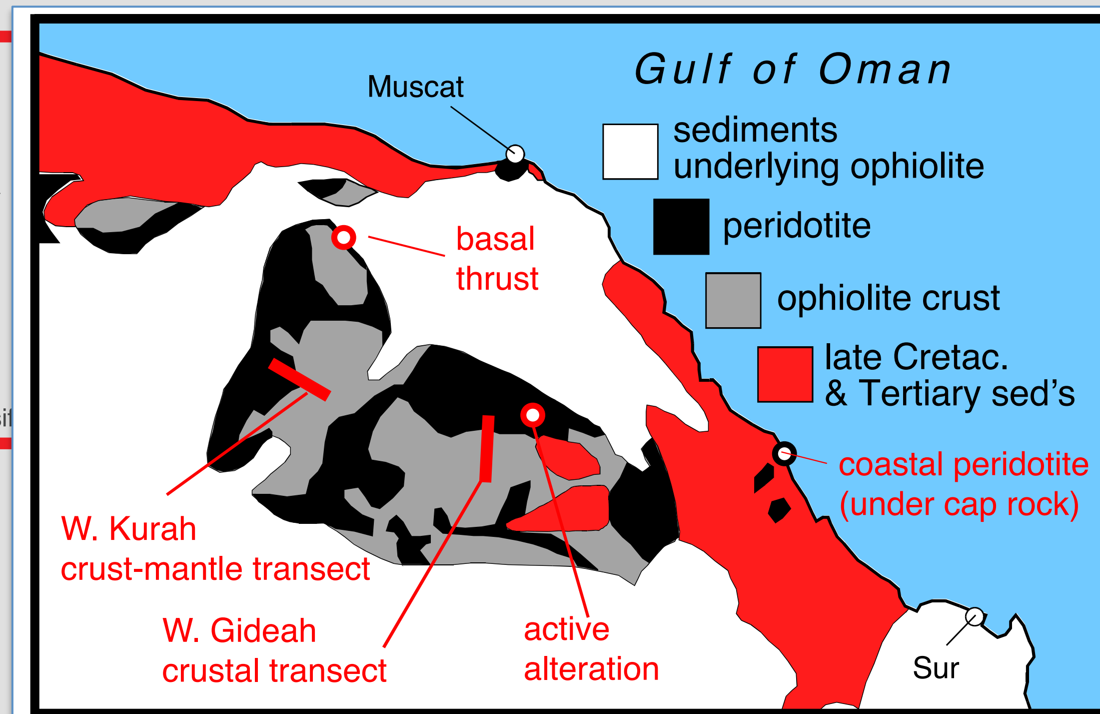
Oceanic crust is composed of igneous rocks. The magmas from which they crystallize forms due to partial melting of the mantle as it rises and decompresses beneath spreading centers, driven by the divergence of the tectonic plates on either side. The mechanism that drives focusing of the partial melts, to form igneous oceanic crust over a narrow region, just a few kilometers wide at the spreading center, is not well understood. Does this occur due to focused melt transport coalescing within a wide region of solid mantle upwelling, or as a result of highly focused solid upwelling? Study of melt transport veins and solid deformation structures in the mantle portions of the Oman ophiolite can resolve this question.



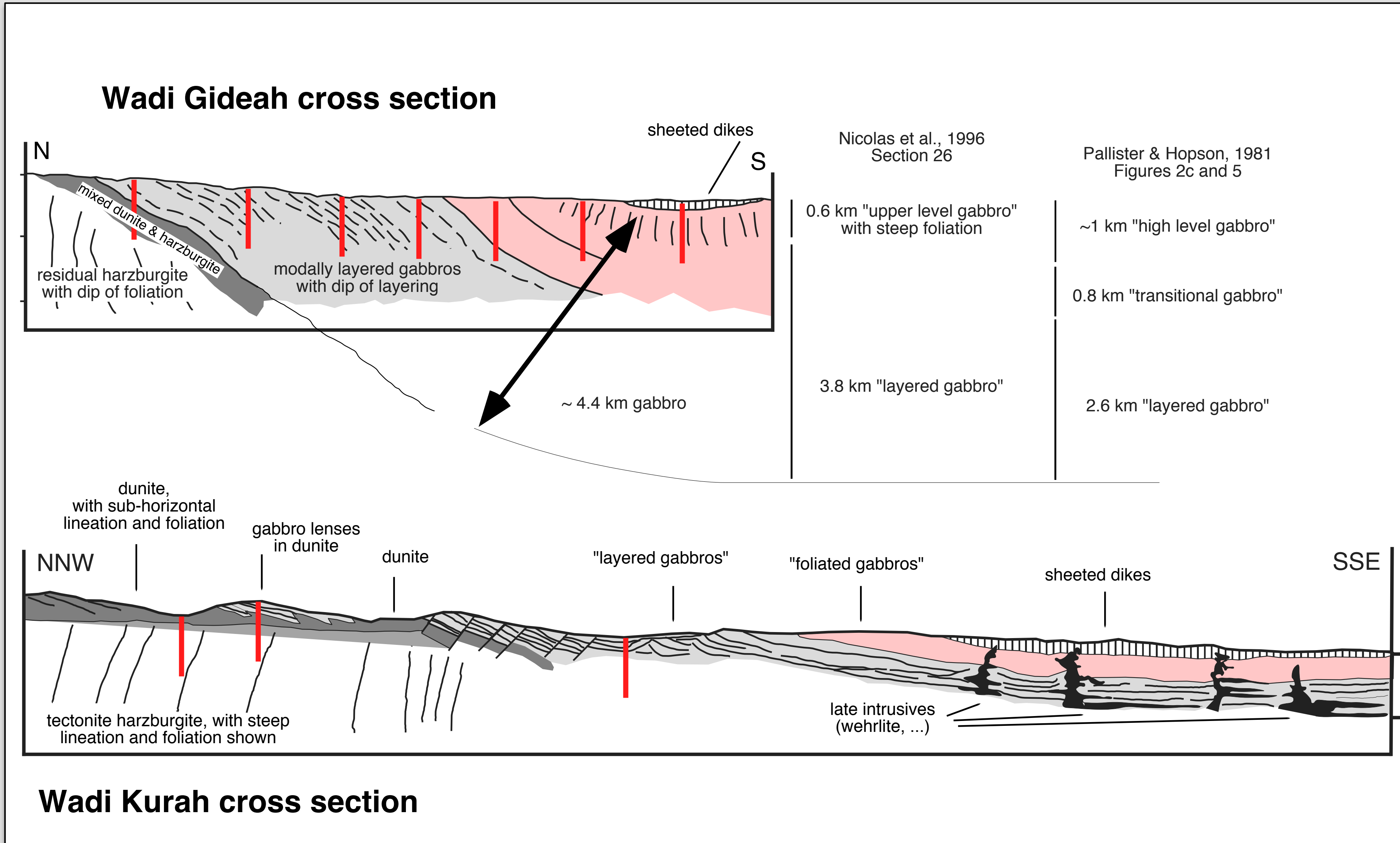

regional map of northern Oman, eastern UAE and Gulf of Oman

blocks of oceanic crust and upper mantle (the Oman ophiolite) are shown in grey

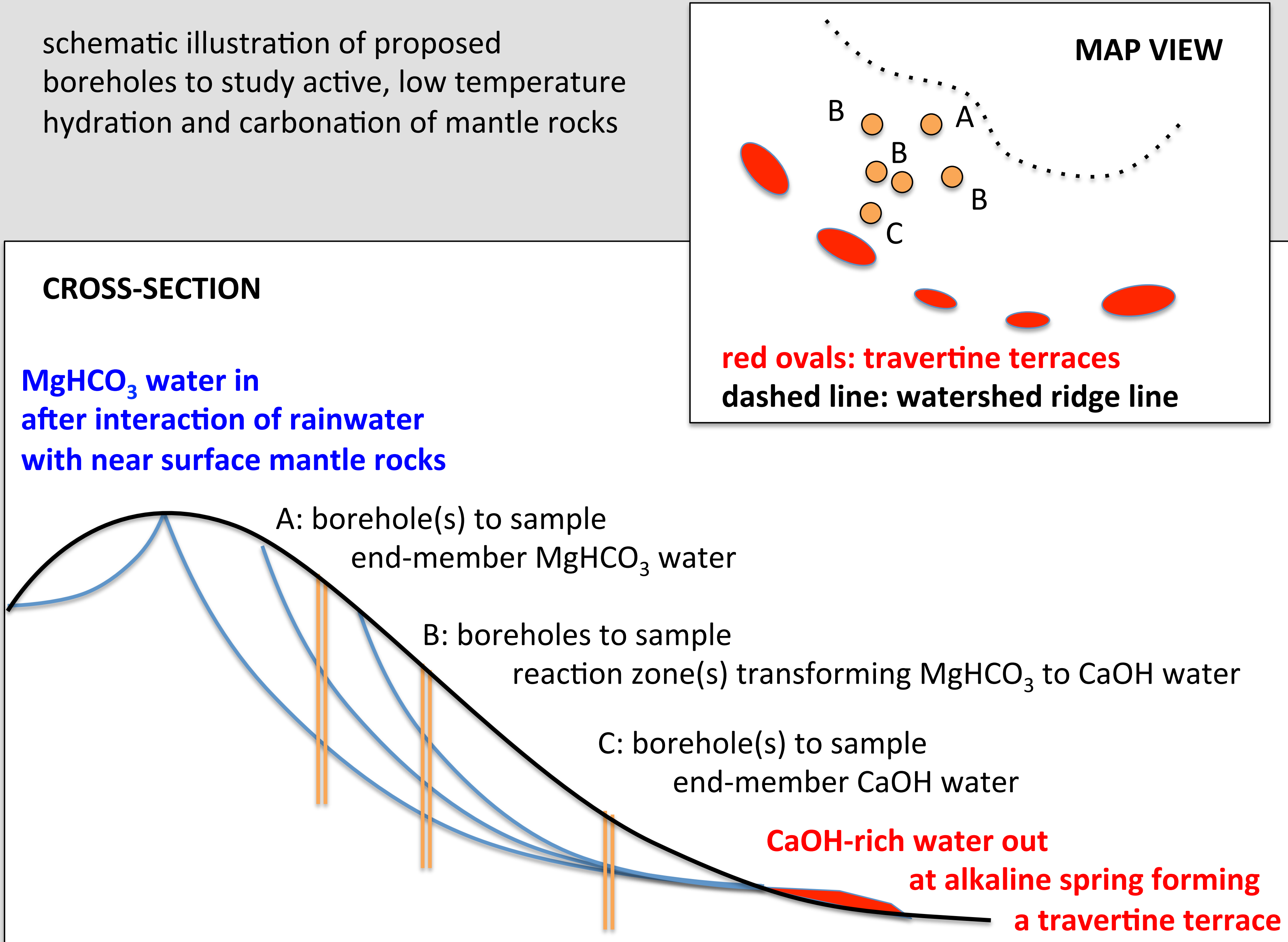
**geologic map shows five main sites for proposed drilling in red font**

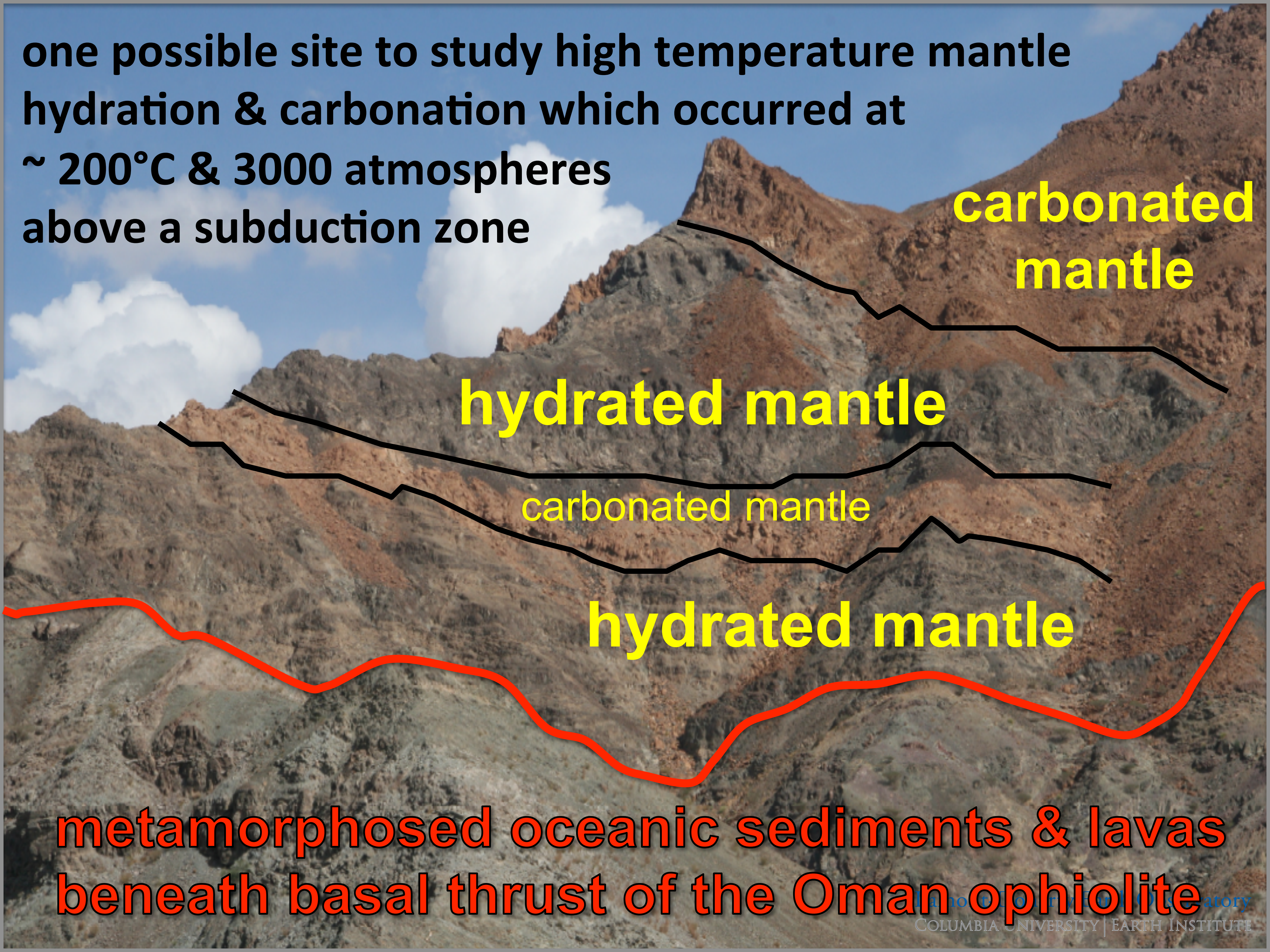


# geological cross-sections of Wadi Gideah and Wadi Kurah with possible drill sites in red

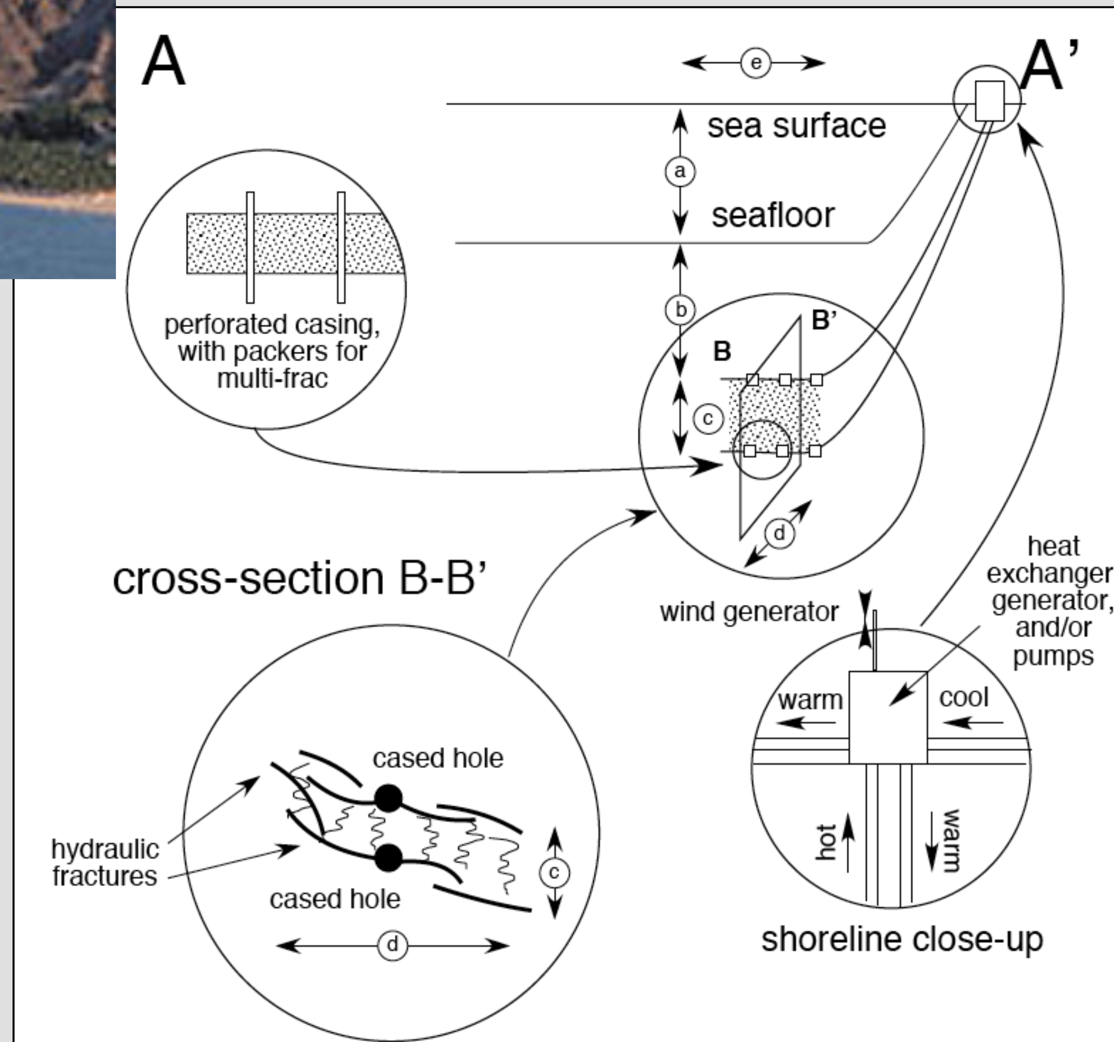


schematic illustration of proposed boreholes to study active, low temperature hydration and carbonation of mantle rocks




one possible site to study high temperature mantle hydration & carbonation which occurred at ~ 200°C & 3000 atmospheres above a subduction zone
carbonated mantle
hydrated mantle
carbonated mantle
hydrated mantle
metamorphosed oceanic sediments & lavas beneath basal thrust of the Oman ophiolite
Columbia University | Earth Institute

coast of Oman near Muscat where there are mantle rocks overlain by limestone cap rocks, with contact dipping offshore, illustrating structure at proposed shoreline drill site to the southeast, near Tiwi, to study subseafloor alteration of mantle rocks and evaluate a possible, future $CO_2$ injection site




highly schematic design of shore-based system for combined subseafloor mineral carbonation in mantle rocks and geothermal power generation

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|---|---|
| likely cost of wireline diamond drilling & coring: | US$ 2.0 million |
| likely cost of scientific personnel, geophysical logging, and chemical analyses: | US$ 4.0 million |
| likely cost of planned training of Omani students during all aspects of this project | US$ 0.5 million |
| likely cost for use of core logging facilities onboard Research Vessel Joides Resolution (International Ocean Drilling Program, IODP) including shipment of core to vessel | US$ 0.5 million |
| alternatively, likely cost to recreate comparable core logging facilities in Oman, where this would become a legacy laboratory | US$ 4.5 million |

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| likely level of support from International Continental Drilling Program (ICDP), approx. 50% of drilling cost | US$ 1.0 million |
| remainder to be raised from private foundations, national science foundations, international consortia | US$ 5 to 9 million |

Oman Drilling Workshop, Speakers

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| first | last | position | host institution | host country |
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