Reaching the Mantle Frontier: Moho and Beyond
A Three-Day Workshop

Integrated Ocean Drilling Program
&
Carnegie Institution of Washington
Deep Carbon Institute

reading: Attempts to Reach the *Pristine Mantle*

Deep Energy, Environment and Climate

subtitle 1: How deep is your carbon?

subtitle 2: How deep is your pristine mantle?

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

September, 2006 - Mission Mohole Workshop,Portland Oregon, Slide #1

"your topic: Mission Moho, updating our vision for ocean lithosphere drilling

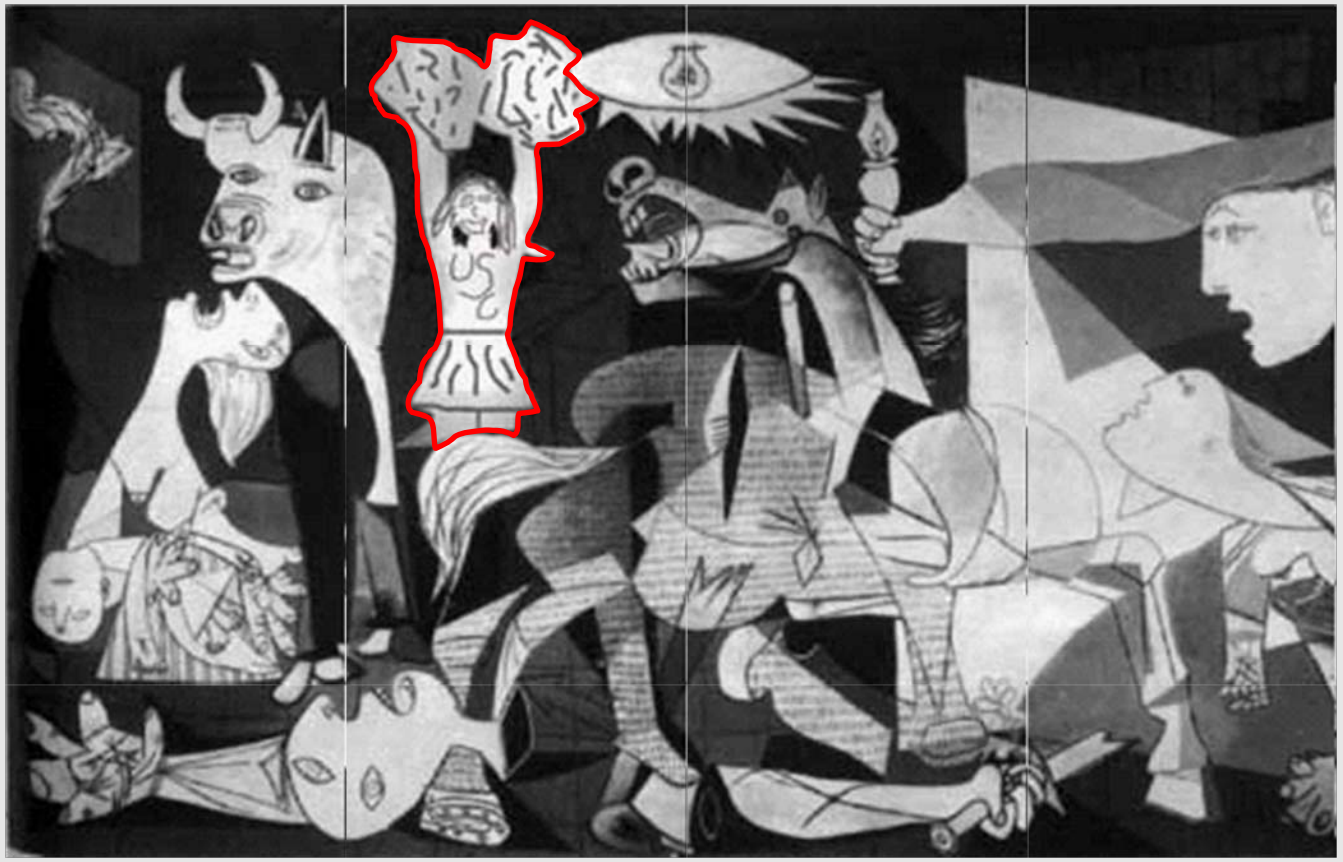
You are scheduled for 30 minutes …

Dress code: visionary cheerleader

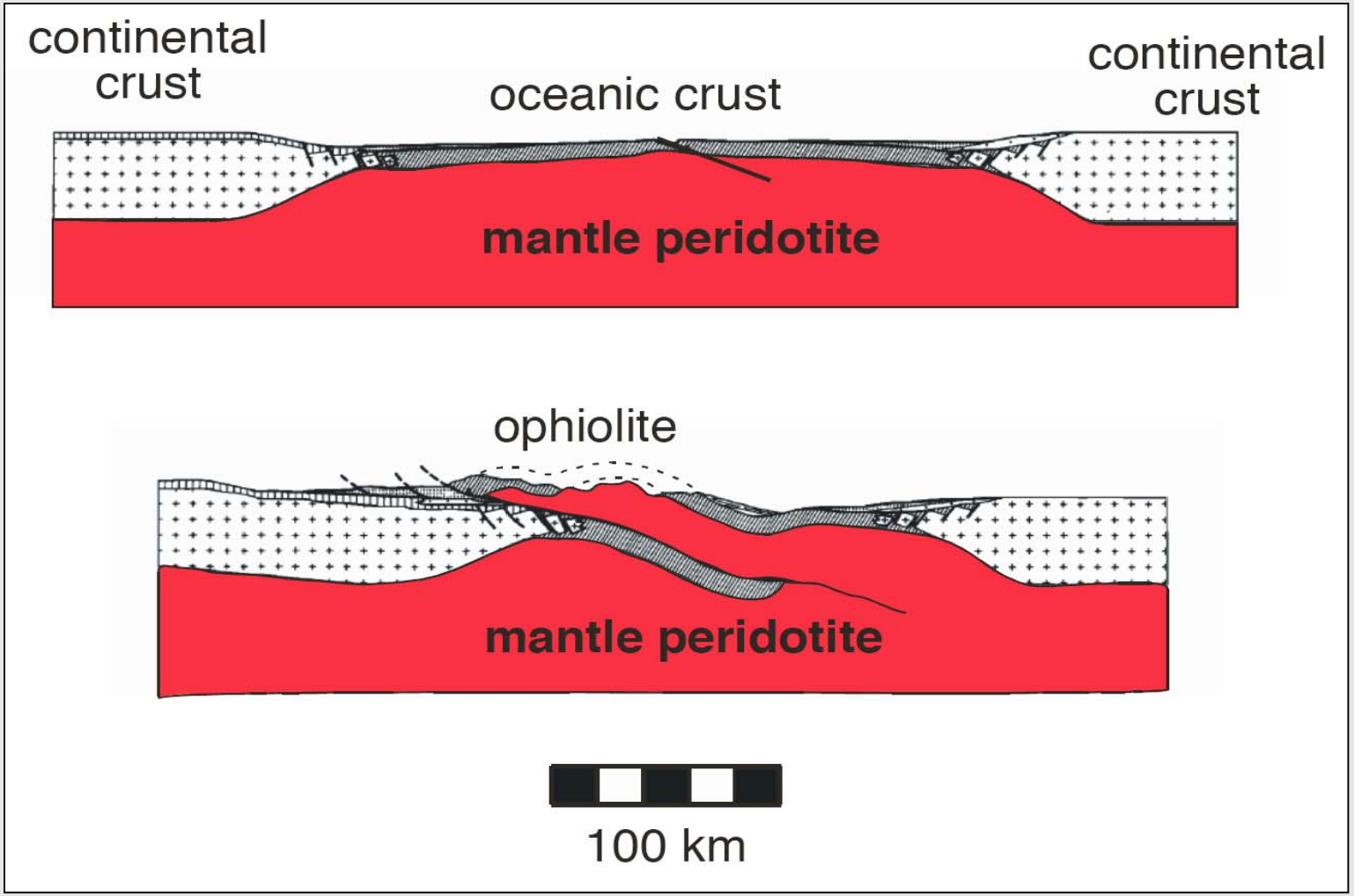
52 slides!

Time limits will be enforced by firehose"

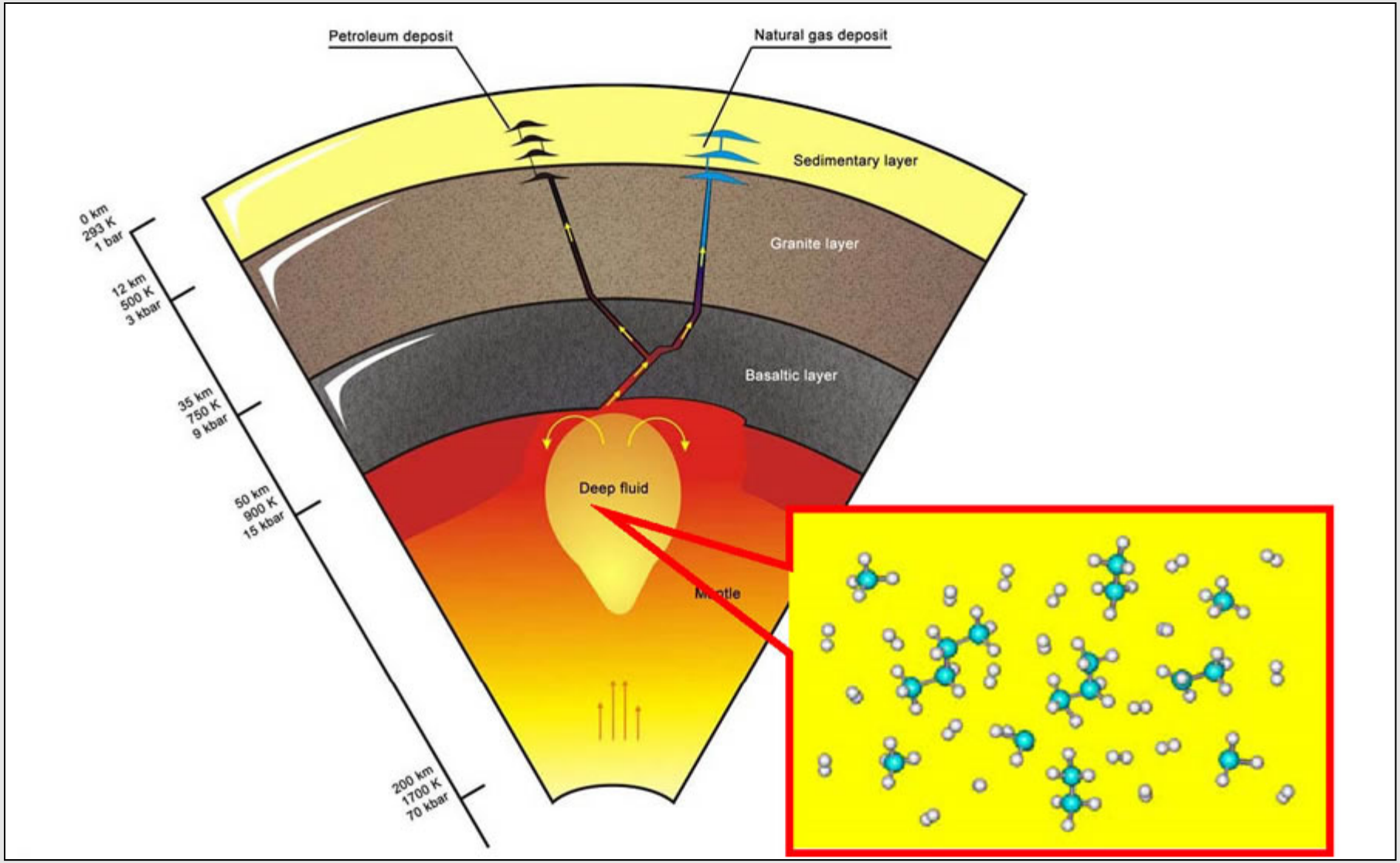
postmodern cheerleading



Do you really want to do this?

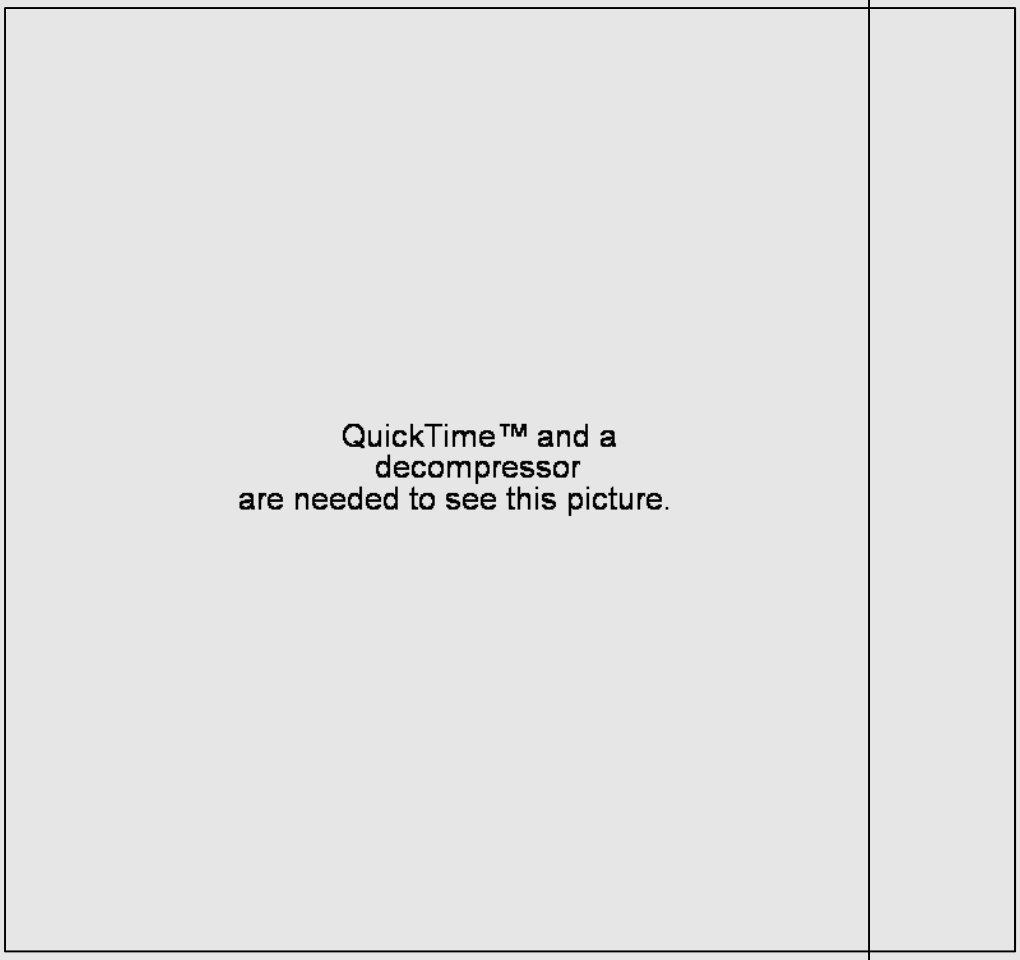


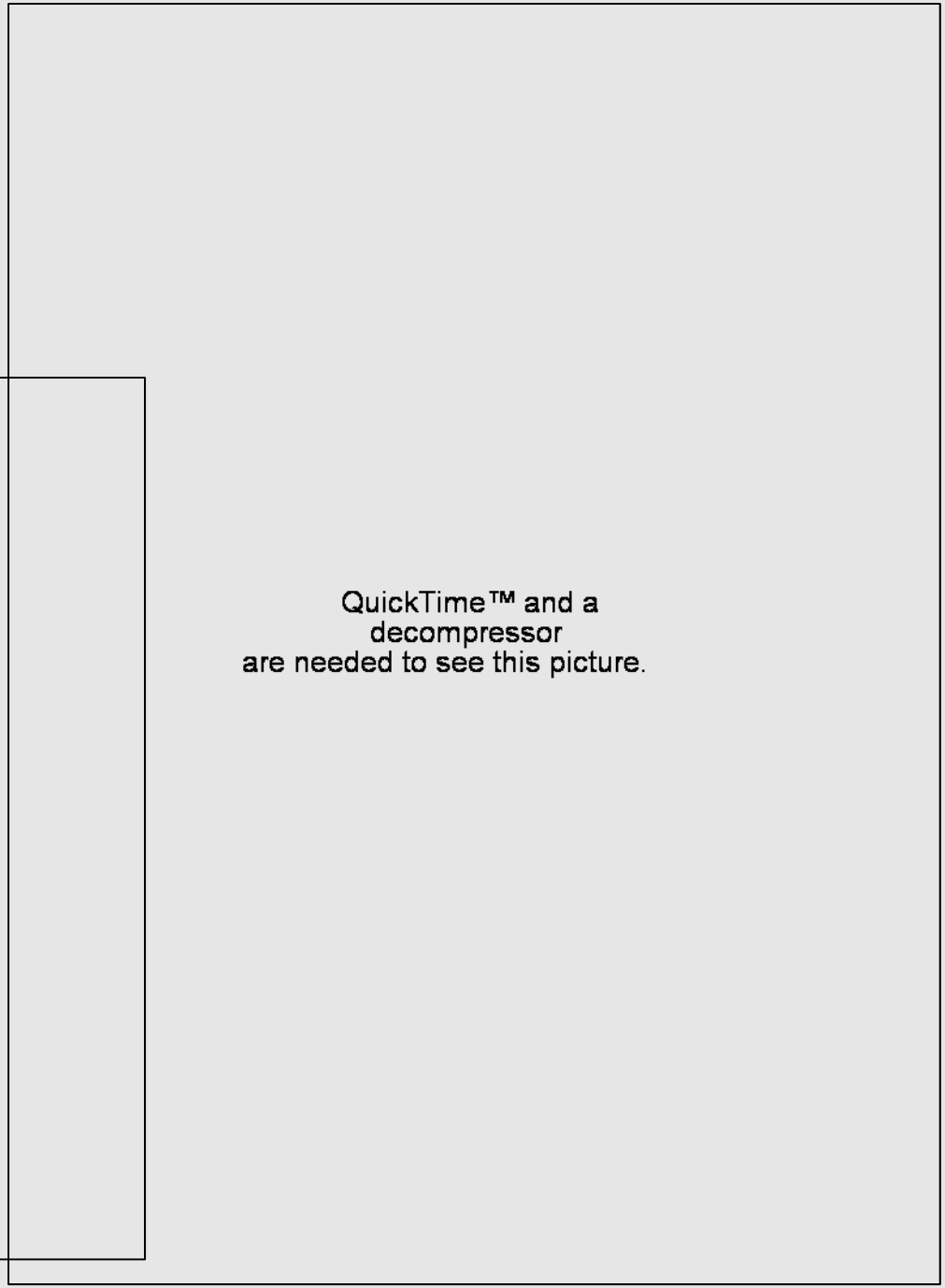
modified from Coleman, Ophiolites, Kluwer, 1977



Hydrocarbons in Deep Earth? Alexander Goncharov, Geophysical Laboratory, Deep Carbon Institute, CIW

Kolesnikov et al.,
Nature Geoscience 2008





Horita & Berndt 1999, 200 to 300°C, 50 MPa

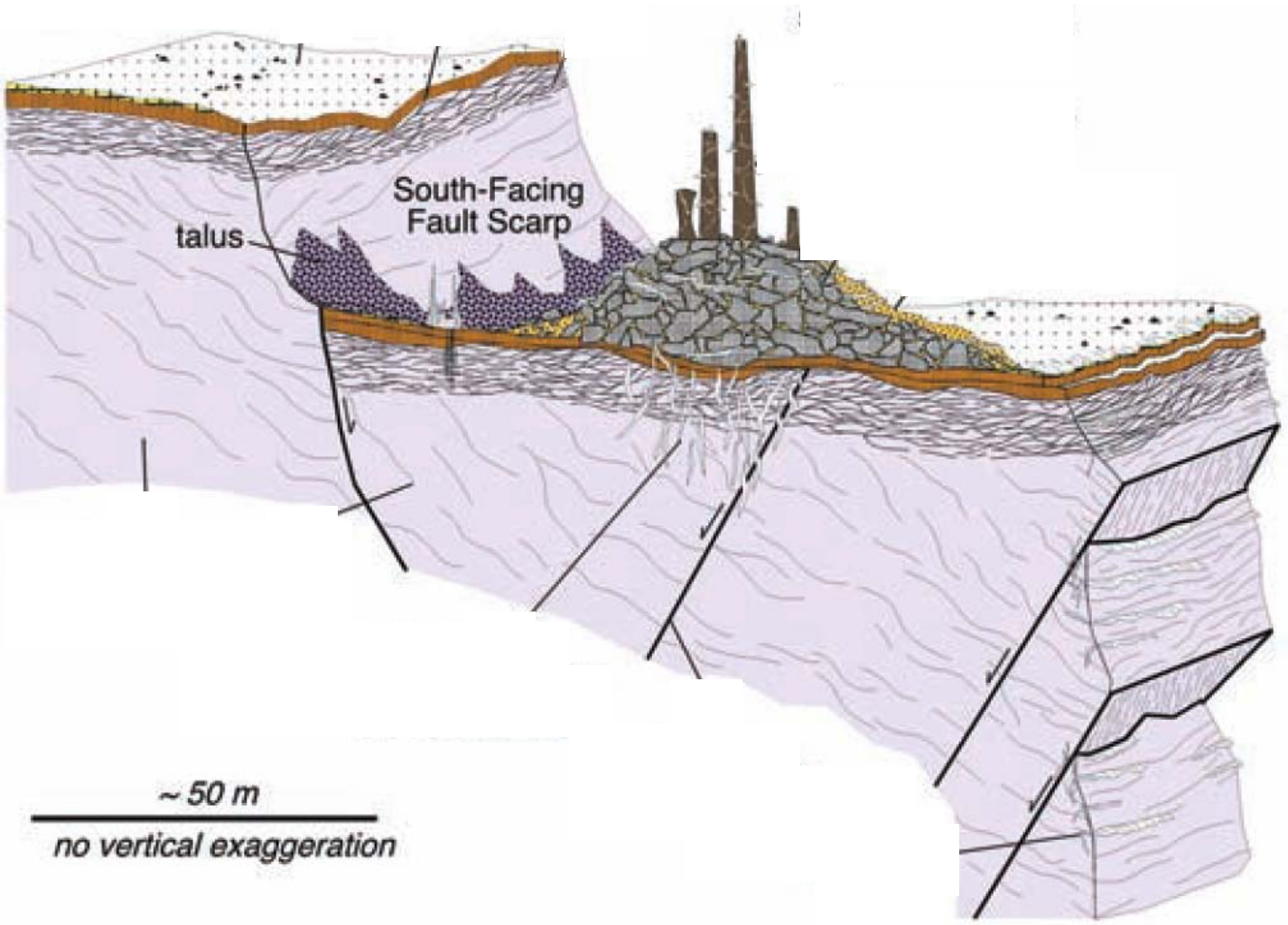
"Mount Chimaera" western Turkey

in situ mineral carbonation in peridotite

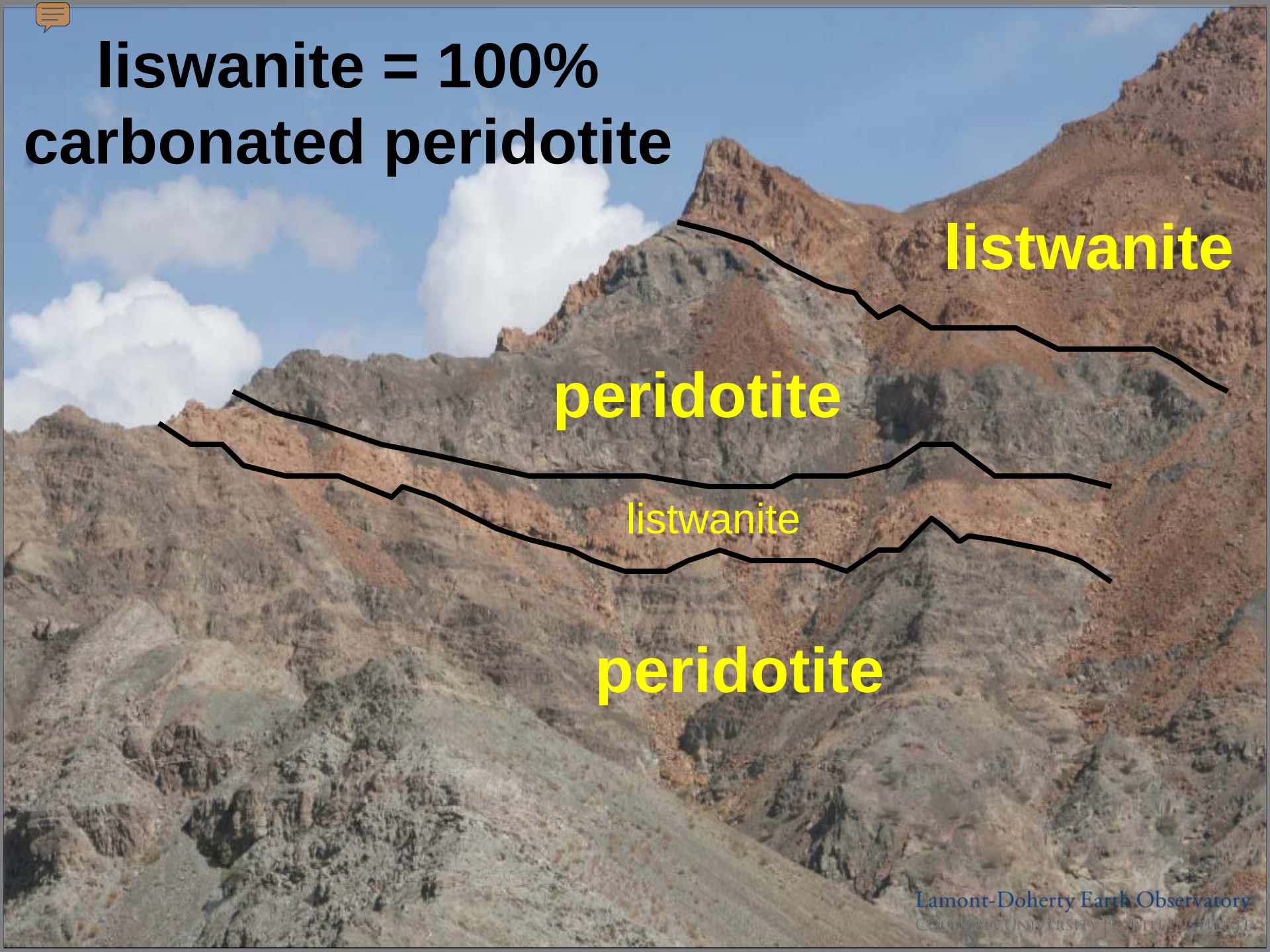
Lamont-Doherty Earth Observatory
Columbia University | Earth Institute

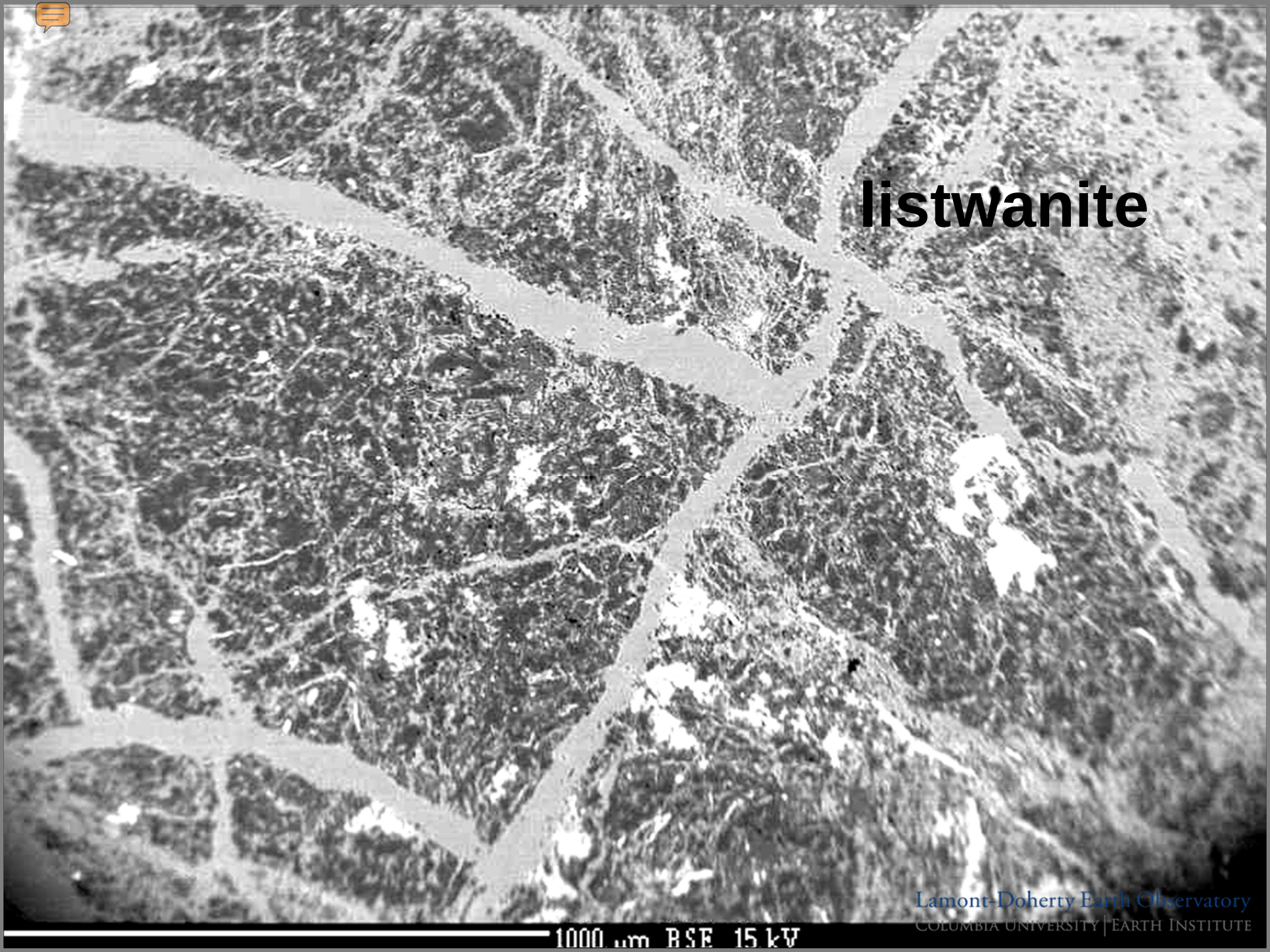

Lamont-Doherty Earth Observatory

geologic CO2 **capture** & storage



Lost City hydrothermal vents, Mid-Atlantic Ridge
Kelley et al., Nature 2001, Science 2005; Früh-Green et al., Science 2003


liswanite = 100%
carbonated peridotite
listwanite
peridotite
listwanite
peridotite
Lamont-Doherty Earth Observatory


listwanite
1000 µm BSE 15 kV
Lamont-Doherty Earth Observatory
Columbia University | Earth Institute

storage capacity in peridotite

peridotite in Oman > 350 km long, 15 km wide, 3 km thick
density 3300 kg/m^3

CO2/fresh peridotite ~ 0.6

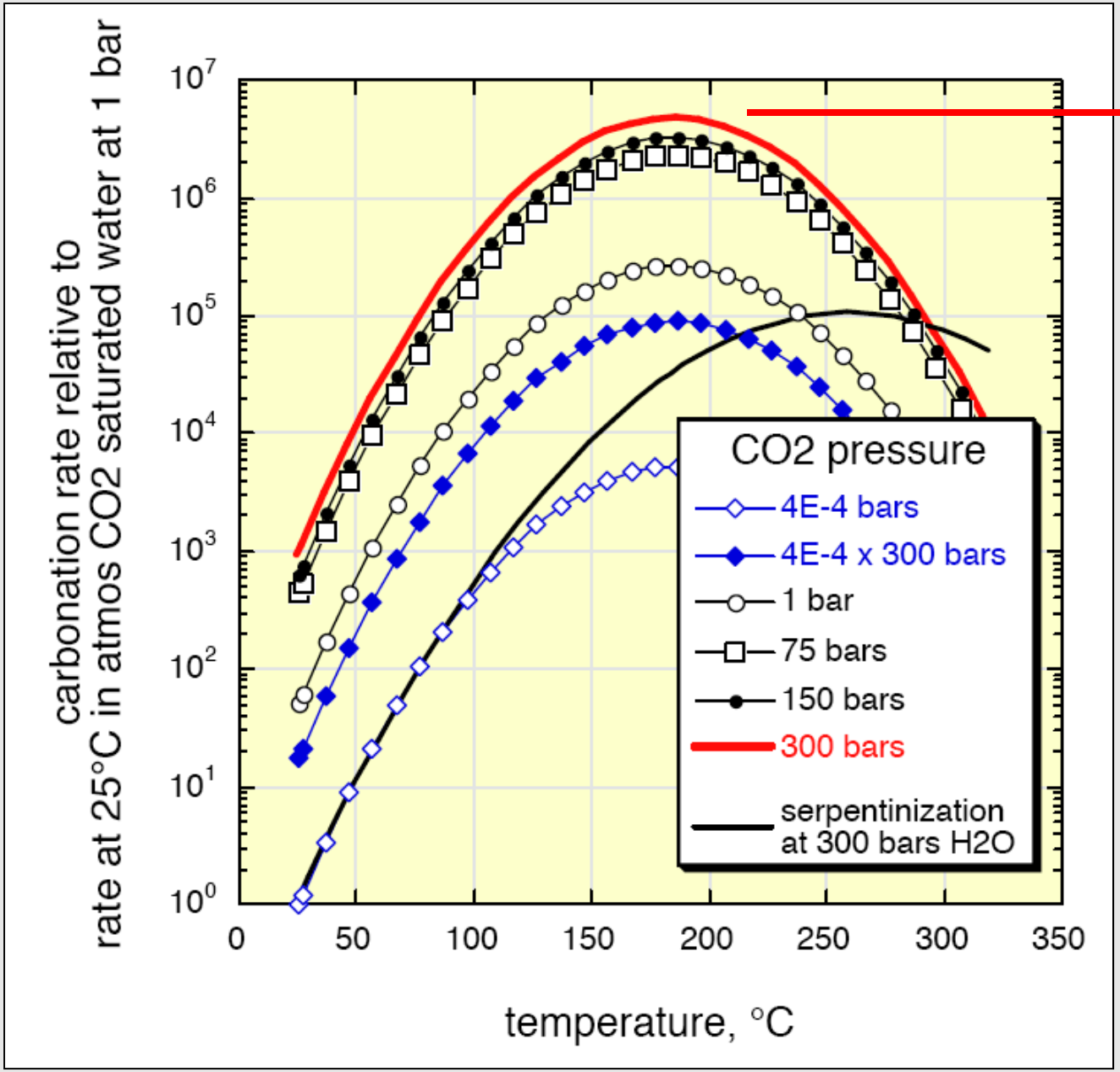
~ 33 trillion tons CO2 in Oman

350 wedges, could store all current CO2 output for 1000 years

could store > 100 trillion tons worldwide

> 10x more than “upper bound” for pore space

OK, but what about rates?



x 10^6 kg/km^3/yr

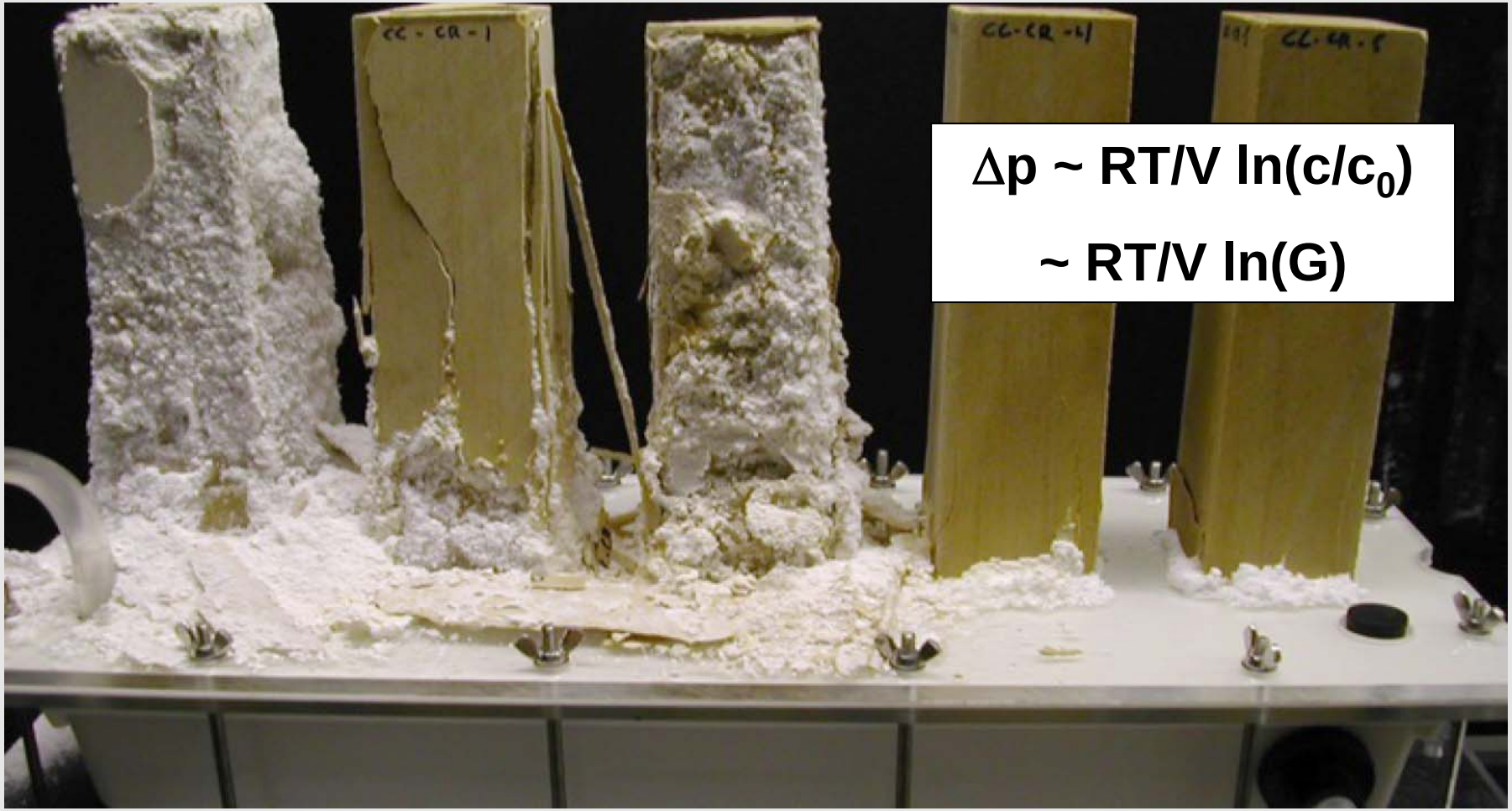
=

~ 1 Gt/km^3/yr

Kelemen & Matter, Proceedings of the National Academy of Sciences, 2008

Royne et al. EPSL 2008 (Fletcher & Brantley, EPSL 2006)

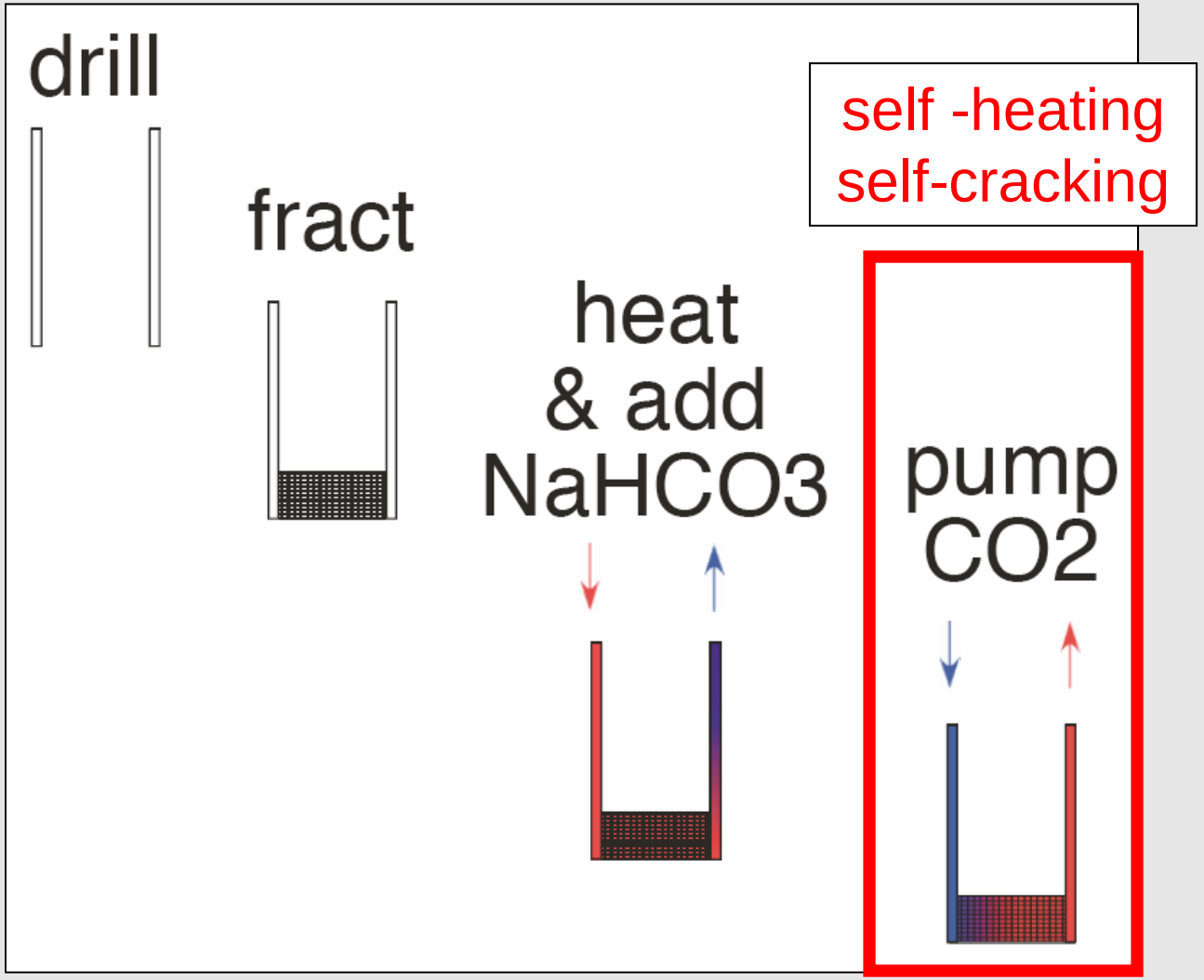
reaction-driven cracking: salt in limestone



Prof. George Scherer, Princeton University http://web.mac.com/gwscherer1/SchererGroup/Salt_Crystallization.html

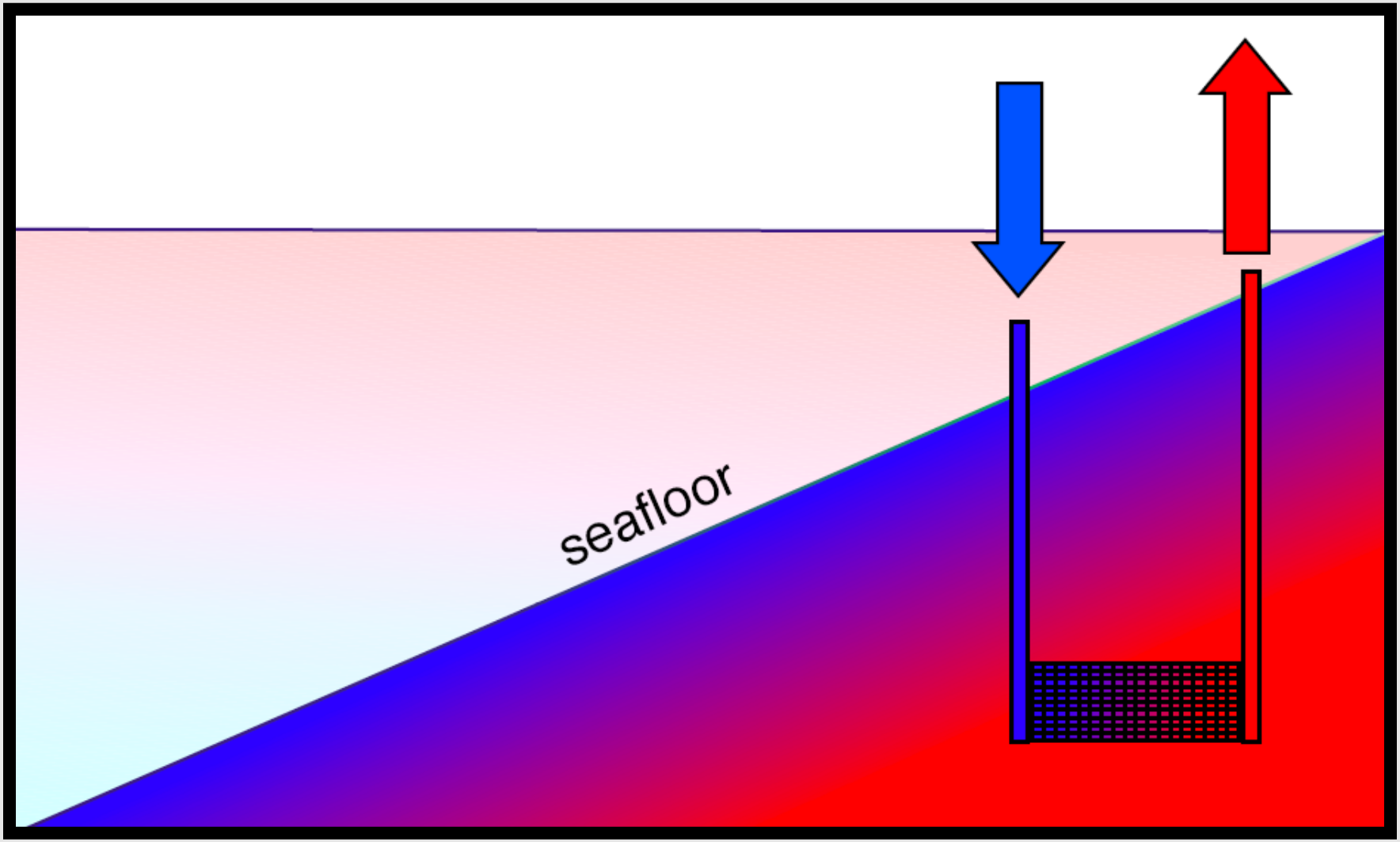
Scherer, G., J Crystal Growth 2004; Steiger, J. Crystal Growth, 2005; Saldi et al., GCA 2009

in situ mineral carbonation with pre-heating



Kelemen & Matter, Proceedings of the National Academy of Sciences, 2008

seawater as a CO2 transport fluid?



Kelemen & Matter, Proceedings of the National Academy of Sciences, 2008

Eocene limestone overlying peridotite, contact dipping offshore

Géologie de la France,
n° 1, 1985, pp. 83-100, 6 fig., 9 photos

Les sources thermales de Prony (Nouvelle-Calédonie) et leurs précipités chimiques. Exemple de formation de brucite primaire

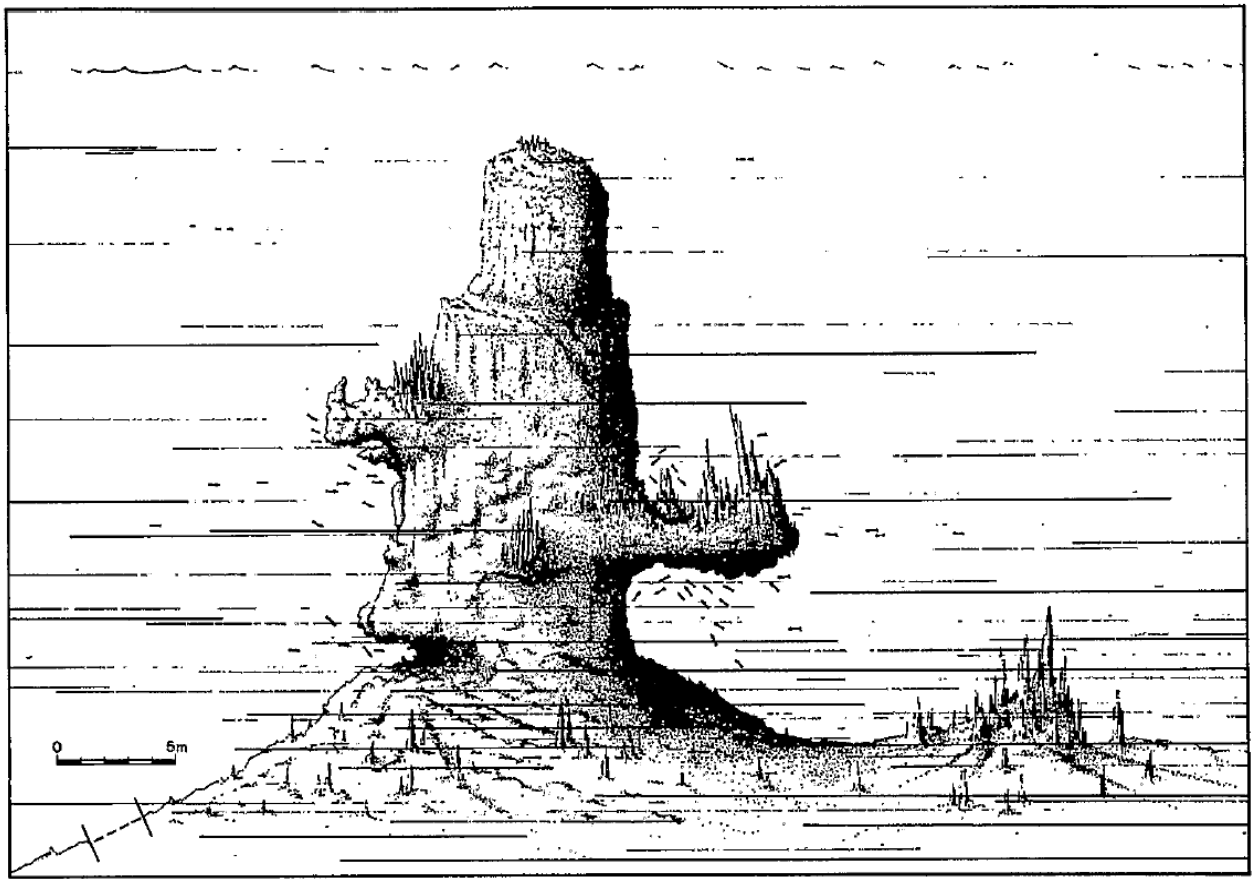


FIG. 3. — *Schéma de l'édifice sous-marin «Roc Aiguille» construit par l'émergence de la source thermale. L'échelle des hauteurs est la même que celle des longueurs.*

0-2 km below the seafloor in tectonically exhumed mantle peridotite (mainly at slow-spreading ridges, also offshore from ophiolites)

in pristine rocks:

Os, Sr, S, Cl, O, C, B, Li, He, H concentrations & isotopes in MORB residue

sulfide saturation in MORB residue?

along the way:

concentration & depth variation of CO2, H2O, H2, CH4, hydrocarbons, and their isotope ratios in alteration products

permeability distribution, relationship to alteration

downhole experiments on CO2 capture & storage

proportion of gabbro, peridotite, serpentine in “lower crust” with Vp < 8.2 km/s

Sampling Fresh, Residual Mantle Peridotite from the Mid-Atlantic Ridge at the Atlantis "Core Complex"

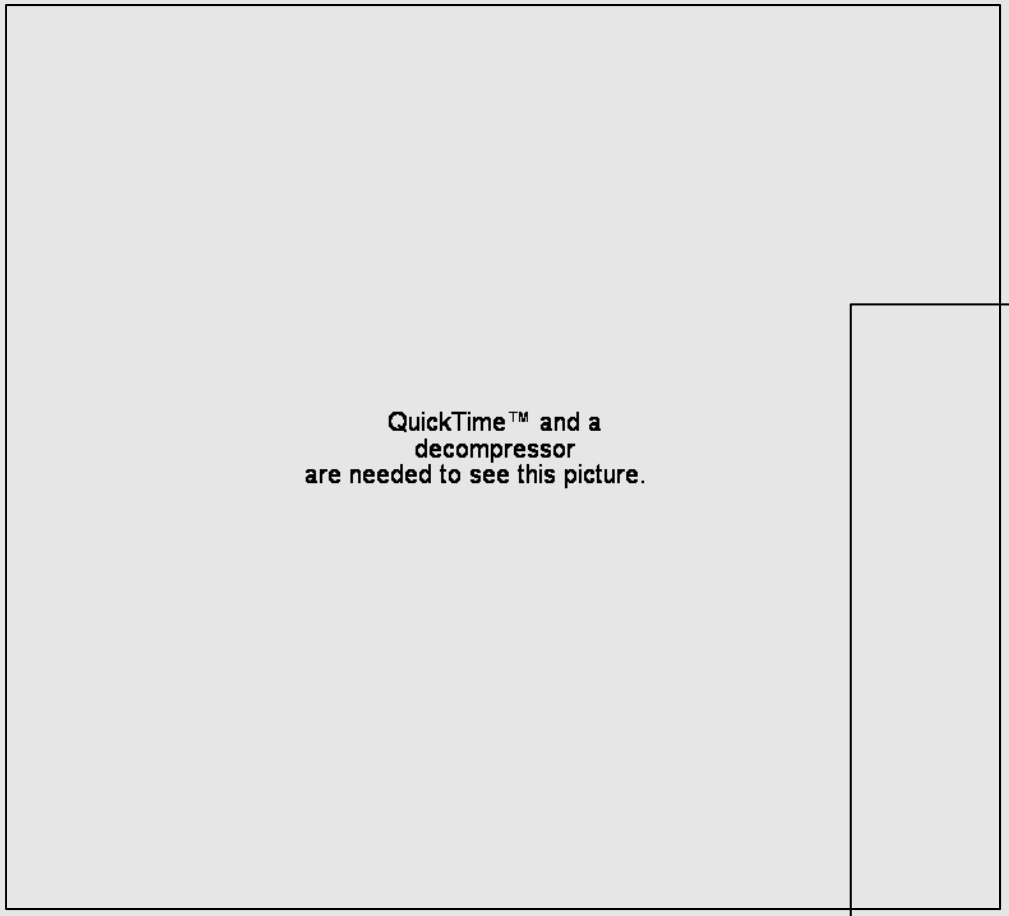
Peter Kelemen
Wolfgang Bach, Bernhardt Peucker-Ehrenbrink, John Eiler, Stanley Hart, Eric Hauri, Greg Hirth, Albrecht Hofmann, Deborah Kelley, Charles Langmuir, Mukul Sharma, Nobu Shimizu, and John Snow

May 6, 2000

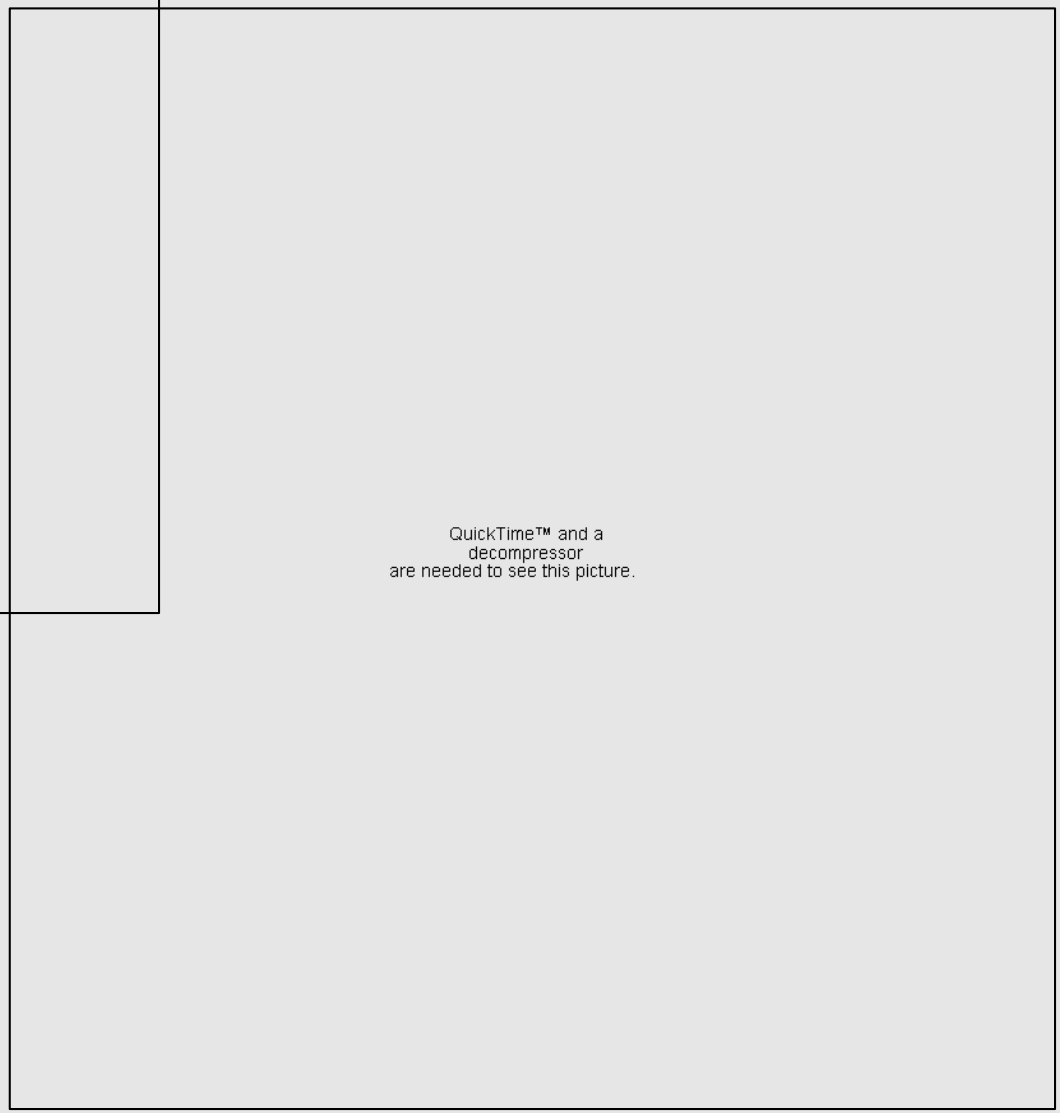
We are writing in support of IODP Proposal number: 512-Full2, "Quantifying the Processes of Oceanic Core Complex Formation", by D. Blackman et al. for an ODP Leg devoted to drilling the inferred "extensional core complex" north of the Atlantis Transform Fault along the Mid-Atlantic Ridge …

… as long as the interpretation of the presence of 8 km/s material within 1 km of the seafloor is correct, this represents an unprecedented opportunity for petrologists, geochemists, and structural geologists to obtain a sample of unaltered, residual mantle from beneath a spreading ridge. From a geochemical perspective, this opportunity for drilling is second in importance only to a full penetration of oceanic crust …

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute



Shaw et al. 2010



Saal et al. 2006

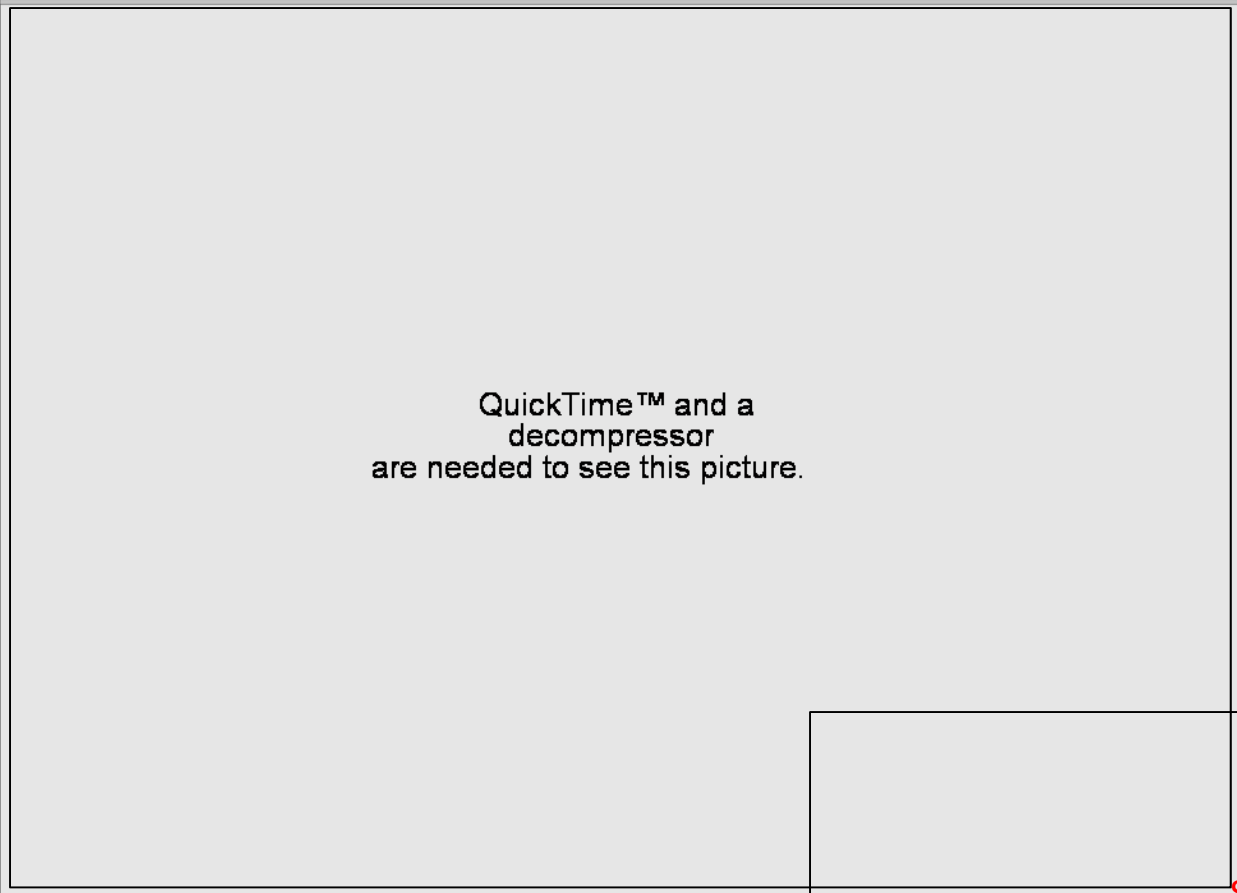
Shaw et al. 2010

QuickTime™ and a
decompressor
are needed to see this picture.

Moho

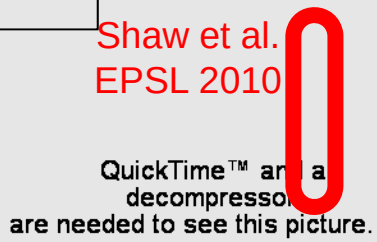
QuickTime™ and a
decompressor
are needed to see this picture.

Saal et al. 2006



Saal et al. 2006

Shaw et al.
EPSL 2010



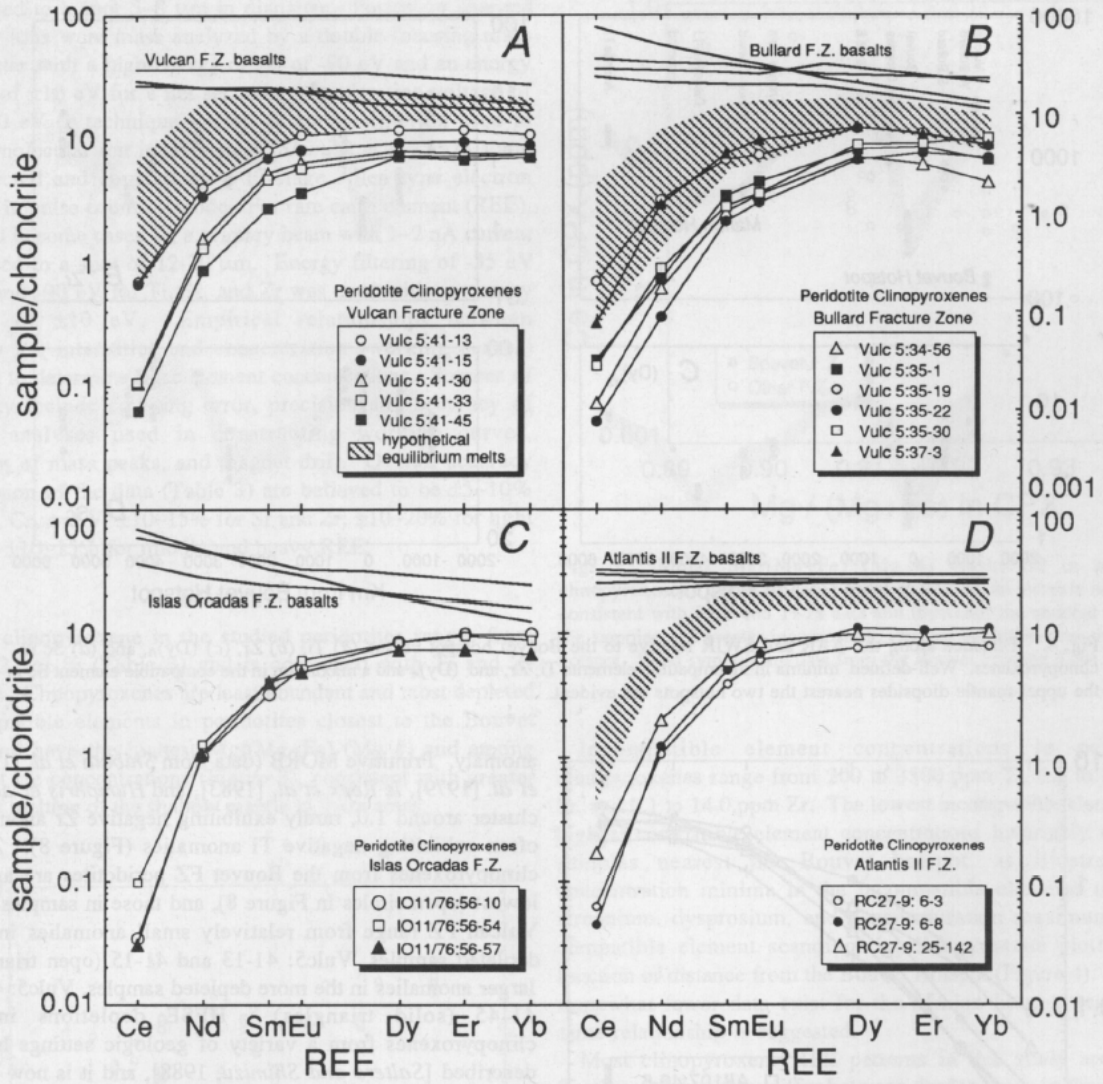
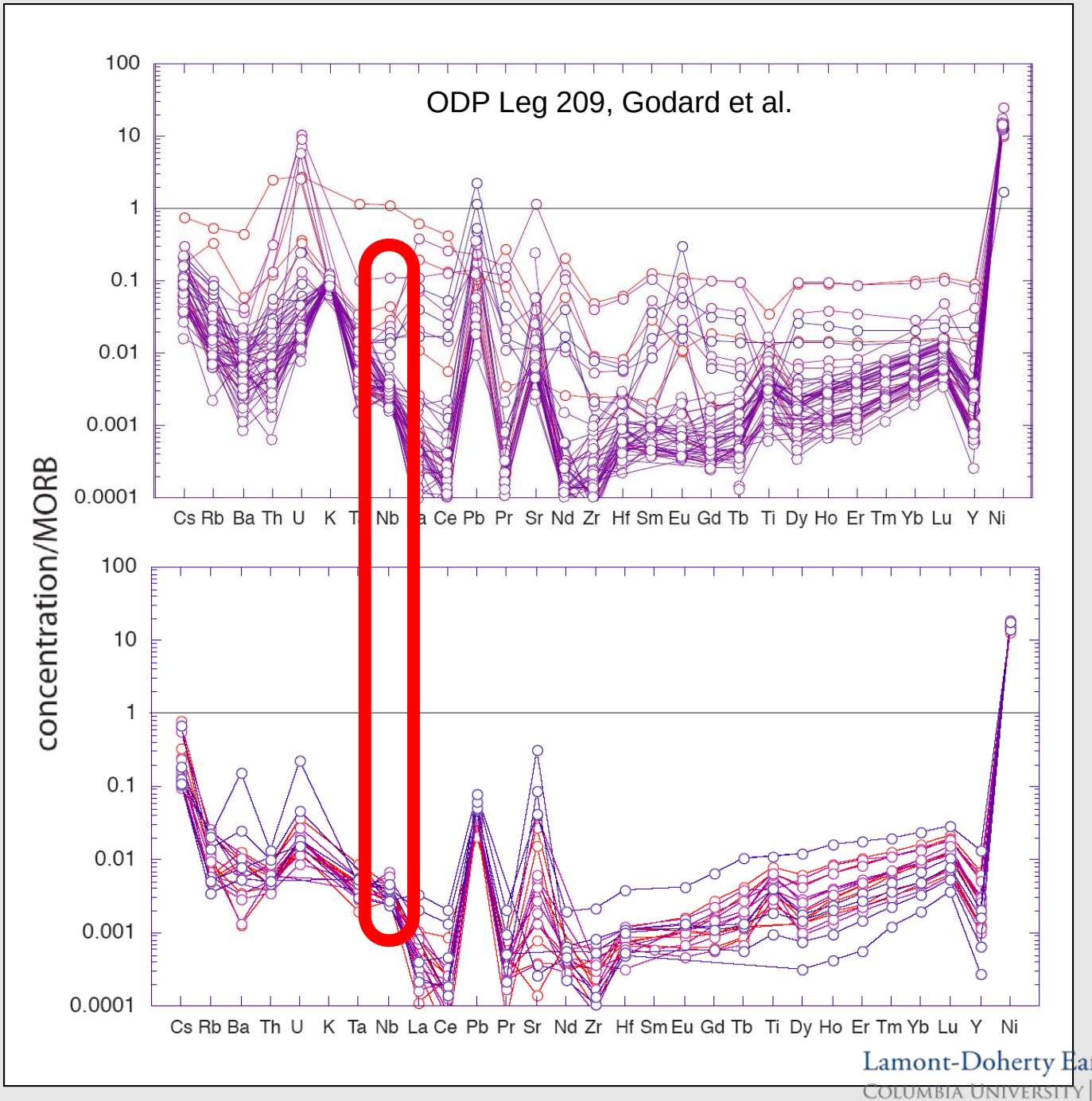
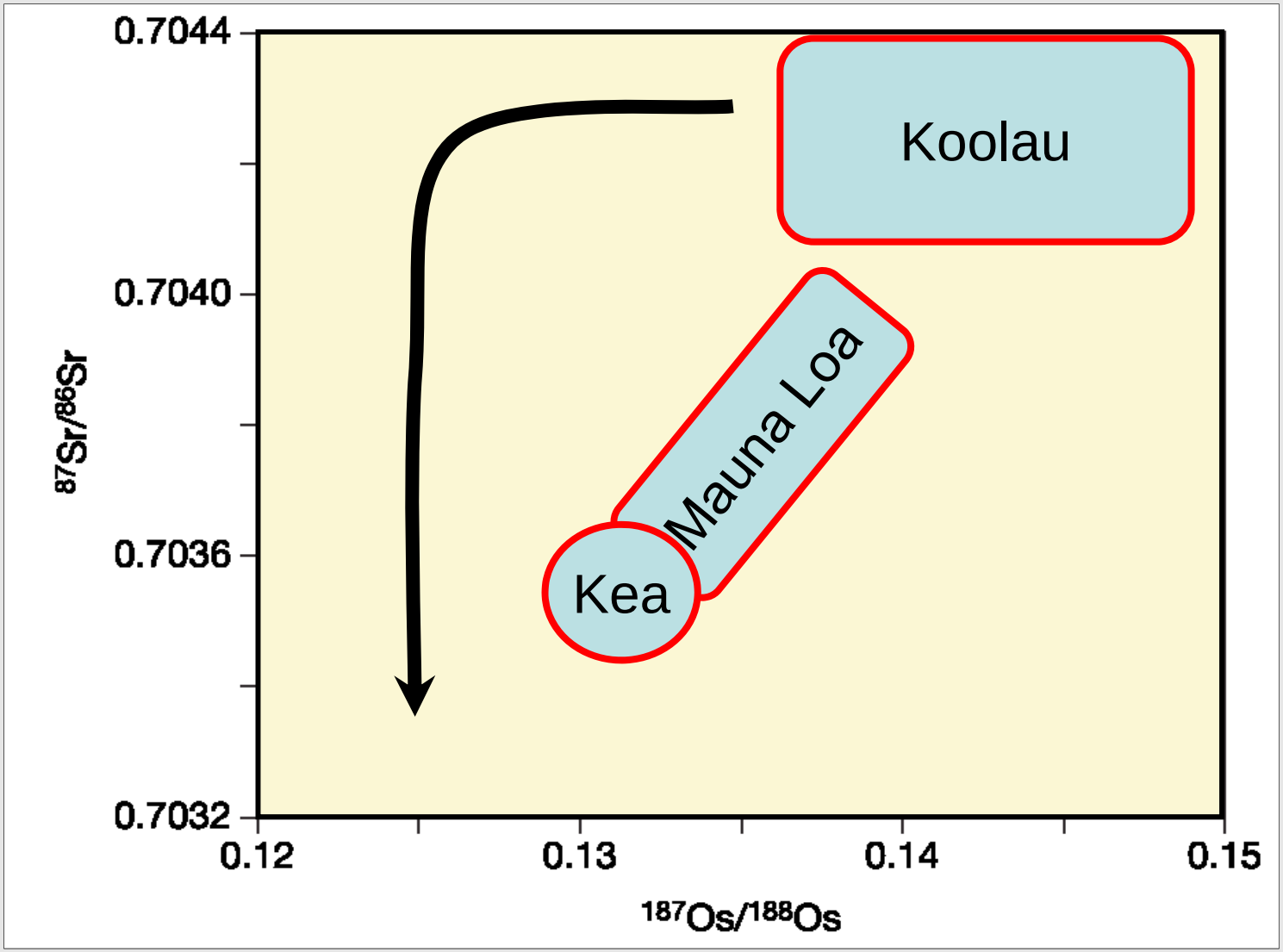


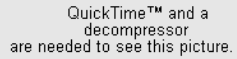
Fig. 6. Chondrite-normalized REE concentrations in nonhotspot peridotite clinopyroxenes. (*a*) Five samples from a single dredge haul in the Vulcan Fracture Zone on the AAR. Note flat HREE and sharp LREE depletions. (*b*) Six samples from three dredge hauls in East Bullard FZ (34 and 35) and West Bullard FZ (37). Note pronounced LREE depletions and hump at Dy (see text for detailed discussion). (*c*) three samples from the Islas Orcadas FZ, and (*d*) three samples from the Atlantis II FZ. Also shown are REE patterns in spatially associated basalts (data from *leRoex et al.* [1983, 1985] and K. Johnson, unpublished data, 1989) and fields representing hypothetical melts in equilibrium with the peridotite clinopyroxenes (cross-hatched).




0.7044
0.7040
0.7036
0.7032
$^{87}Sr/^{86}Sr$
0.12
0.13
0.14
0.15
$^{187}Os/^{188}Os$
Koolau
Mauna Loa
Kea

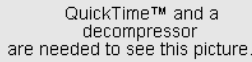
Mavrogenes & O'Neil 1999

1400°C

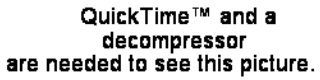


Mavrogenes & O'Neil 1999

1800°C

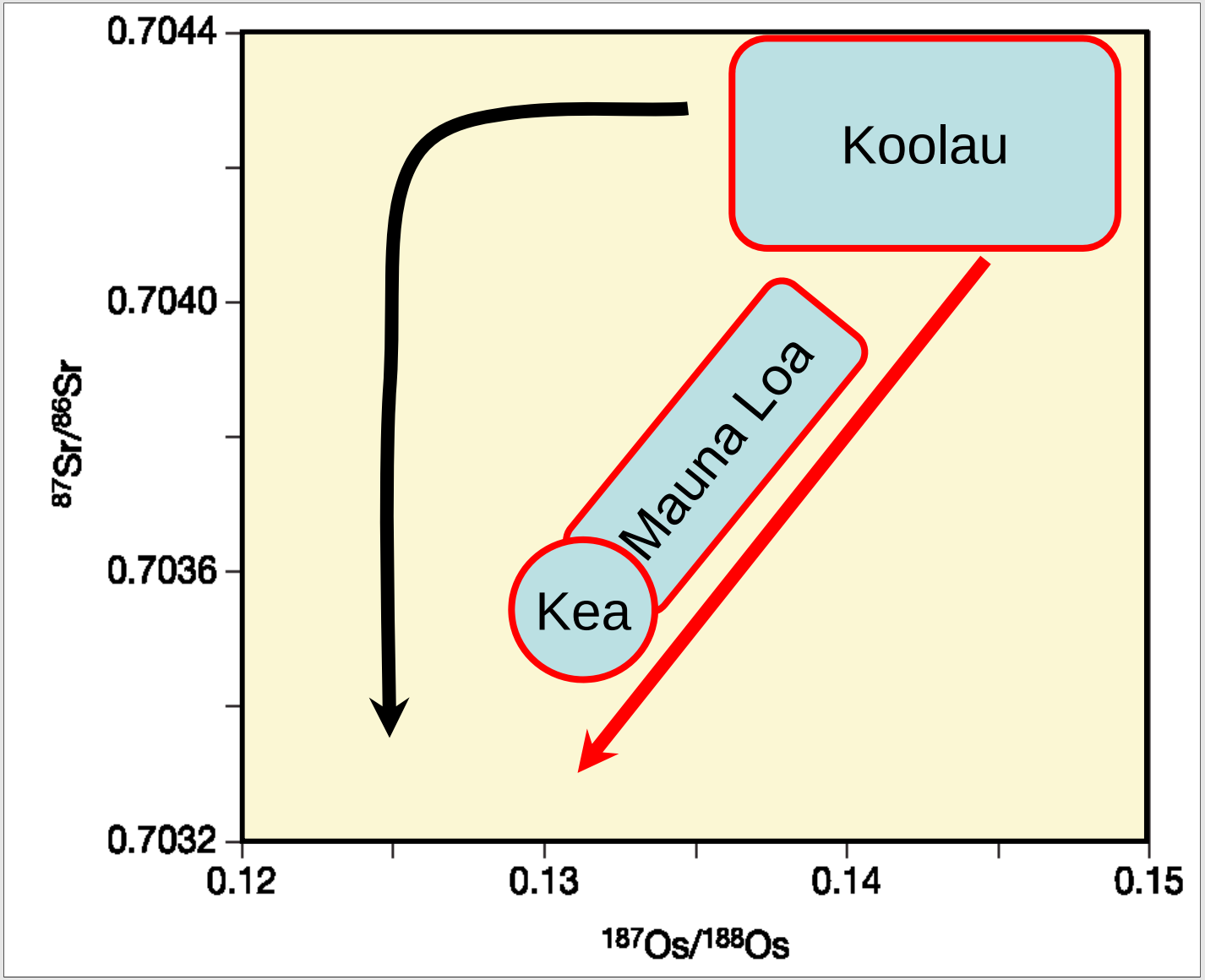


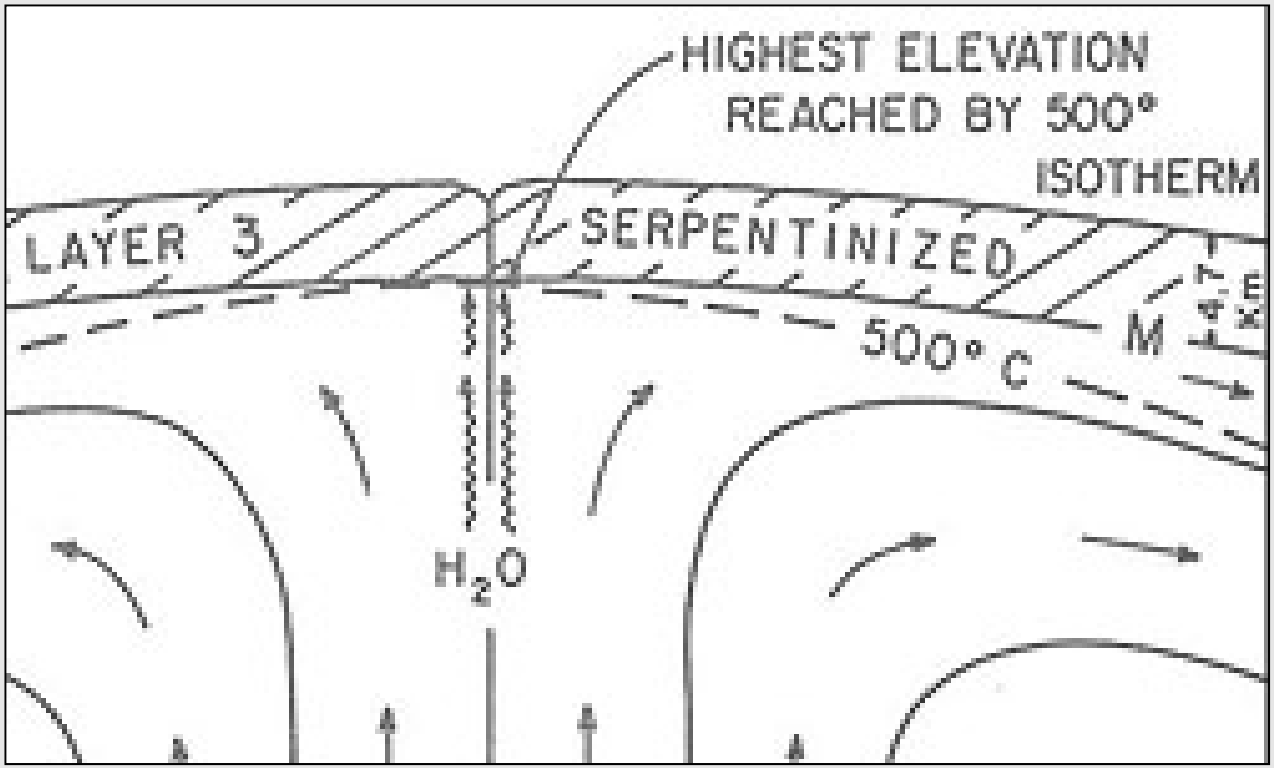
S (ppm)



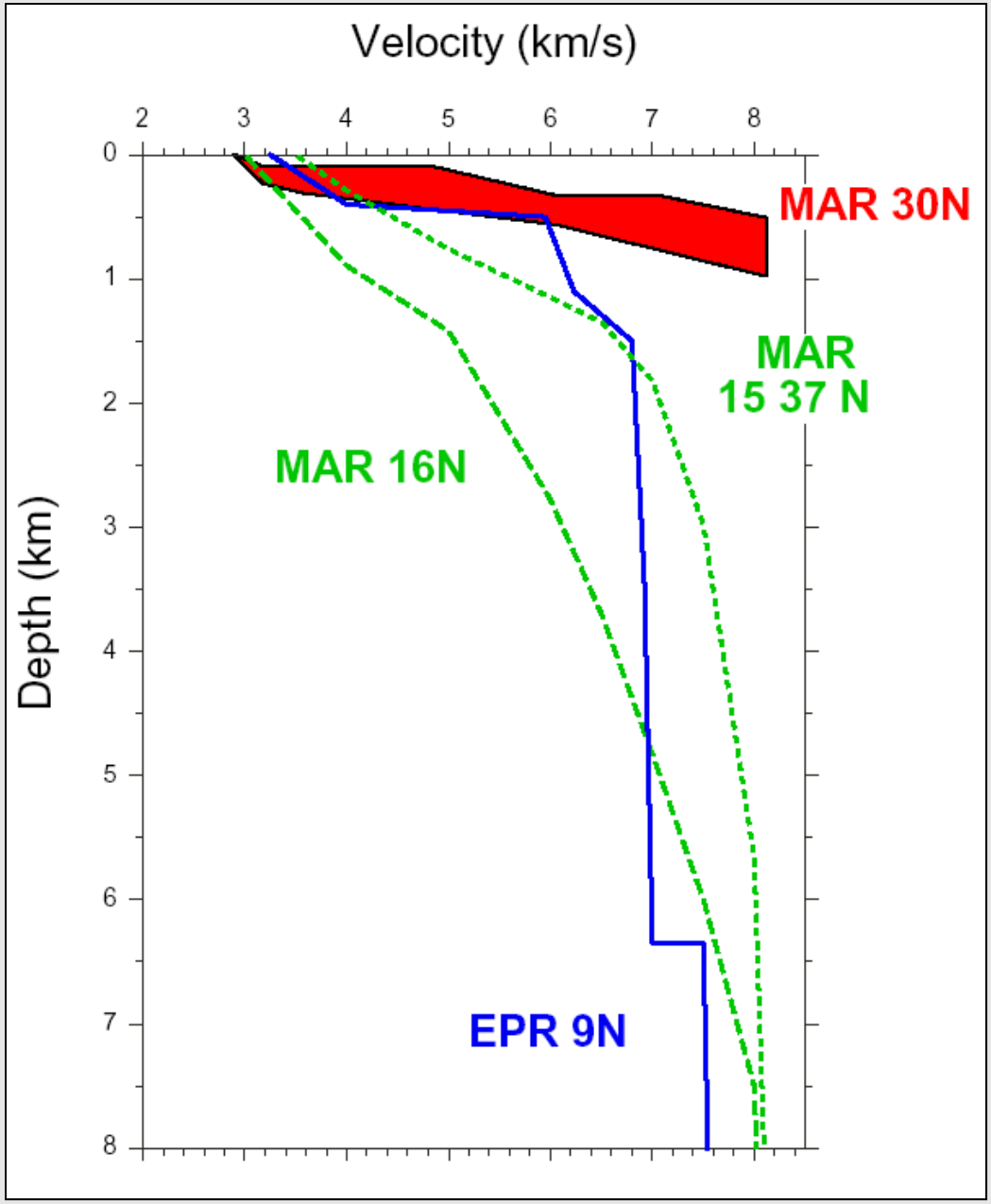
Holzeid & Grove 2002

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

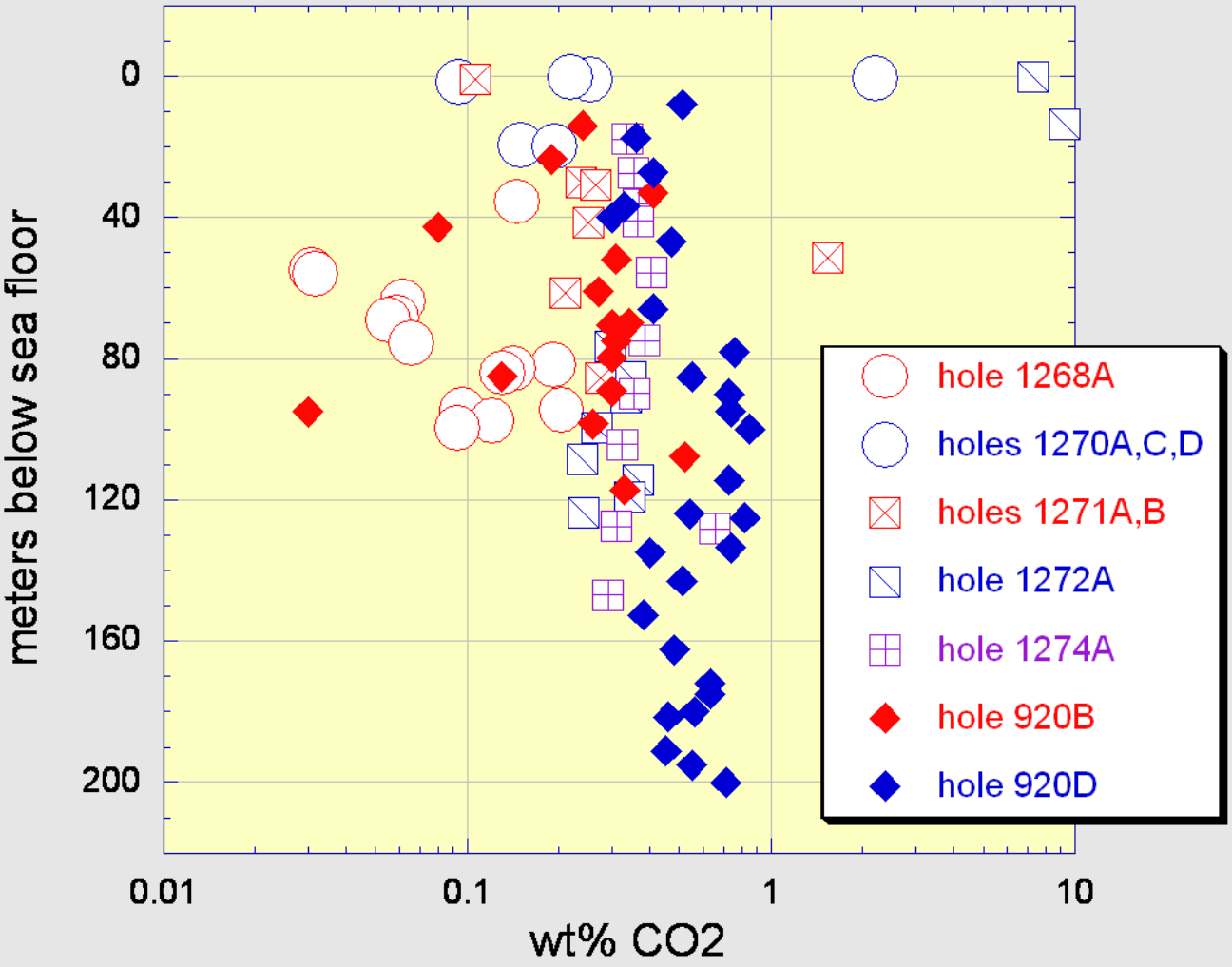

0.7044
0.7040
0.7036
0.7032
$^{87}Sr/^{86}Sr$
0.12
0.13
0.14
0.15
$^{187}Os/^{188}Os$
Koolau
Mauna Loa
Kea

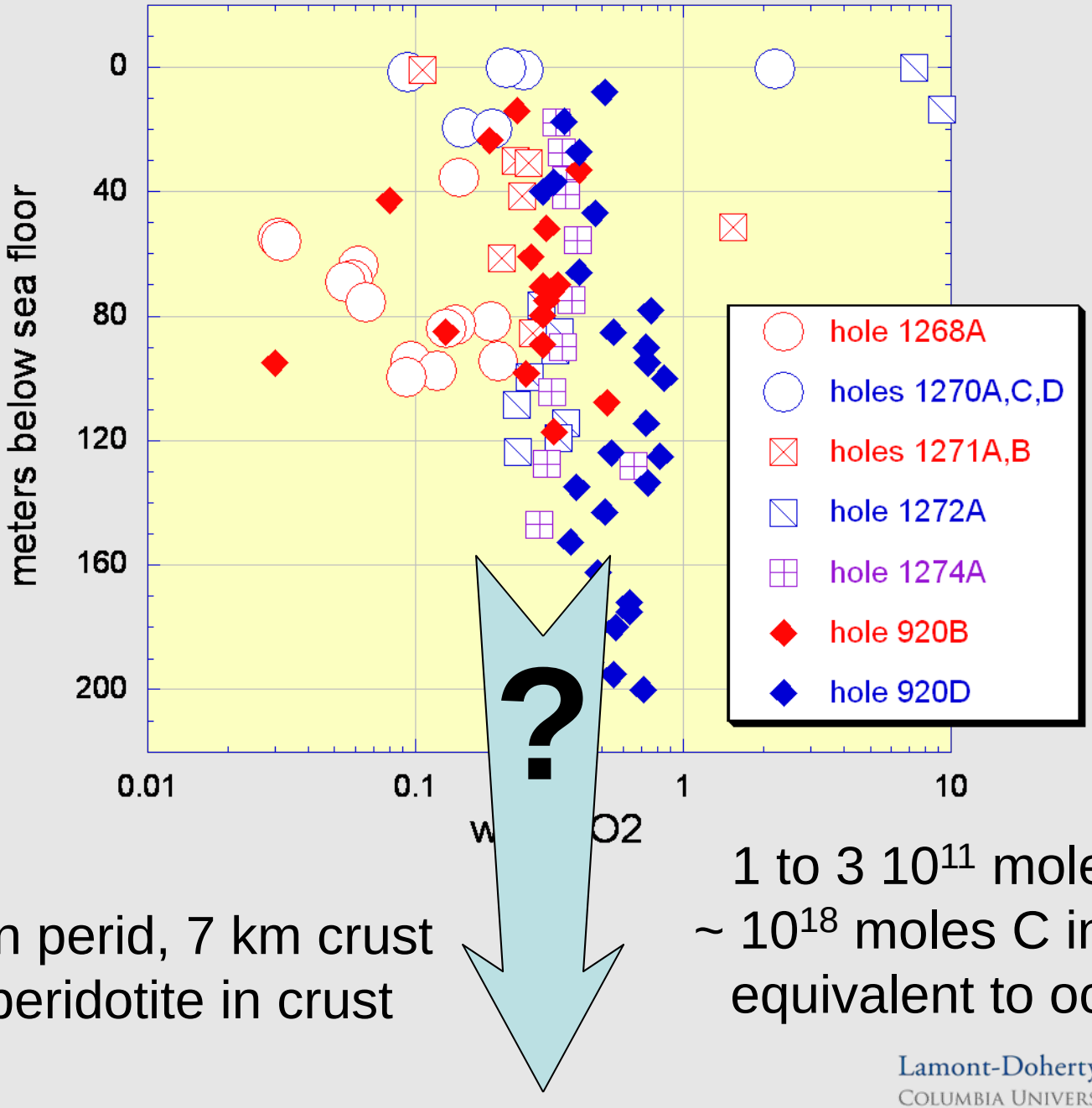


Harry Hess, 1960



Kelemen et al., ODP Leg 209 Initial Reports, 2004


meters below sea floor
0
40
80
120
160
200
0.01
0.1
1
10
wt% CO2
hole 1268A
holes 1270A,C,D
holes 1271A,B
hole 1272A
hole 1274A
hole 920B
hole 920D



0.3 wt% in perid, 7 km crust
5-15% peridotite in crust

1 to 3 10^{11} moles C/yr
~ 10^{18} moles C in 10 Myr
equivalent to ocean C

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute

additional lessons from hole 6-7 below the seafloor
beneath igneous crust at intermediate to fast-spreading ridges

in pristine mantle

nature of the Moho, proportion of gabbro, serpentine, in material with Vp < 8.2 km/s

differences in fabric, grain size, composition at fast vs slow spreading, and at fracture zones versus ridge segment centers

nature/size/frequency/spacing of melt conduits

along the way

fabrics, igneous emplacement processes, hydrothermal interaction extent & depth

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

Kelemen et al., ODP Leg 209 Initial Reports, 2004

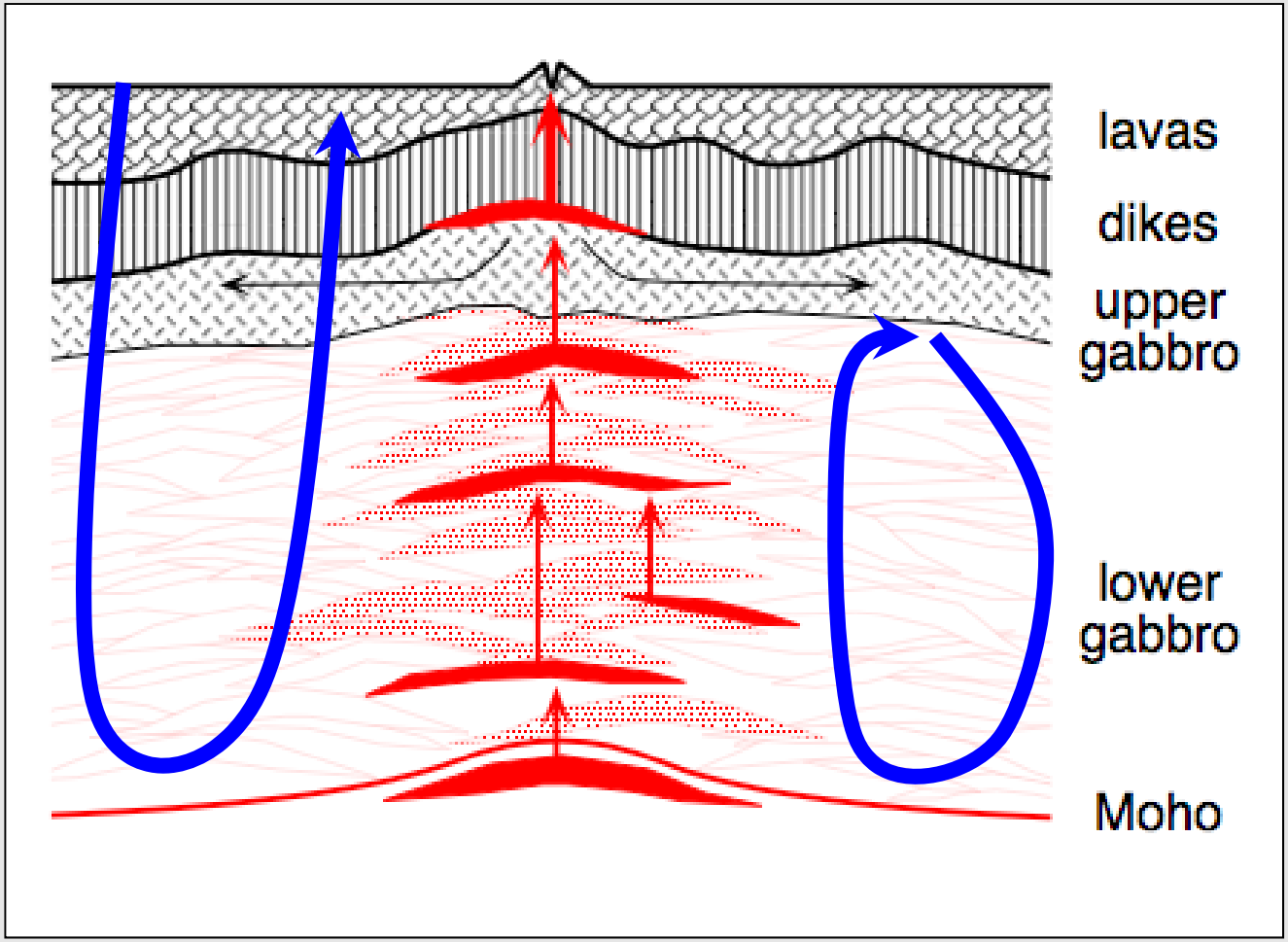
lower crust
VanTongeren et al. 2008

QuickTime™ and a
decompressor
are needed to see this picture.

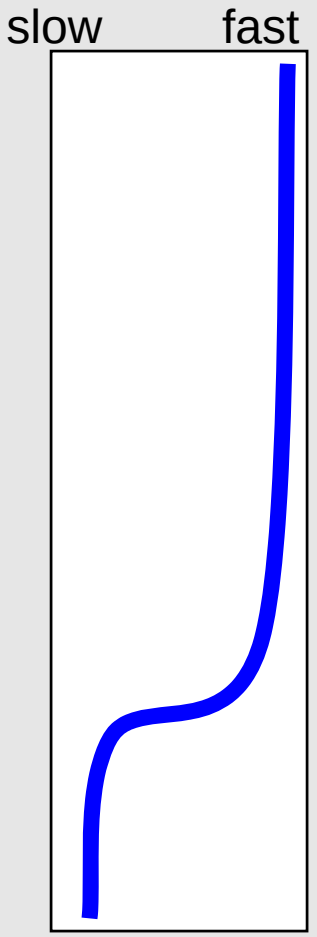
shallow mantle
Hanghøj et al. 2010

and a
or
this picture.

ınd a
or
:his picture.



cooling rate



additional lessons from 30-40 km hole through continental crust into cratonic upper mantle

deep mantle hydrocarbons

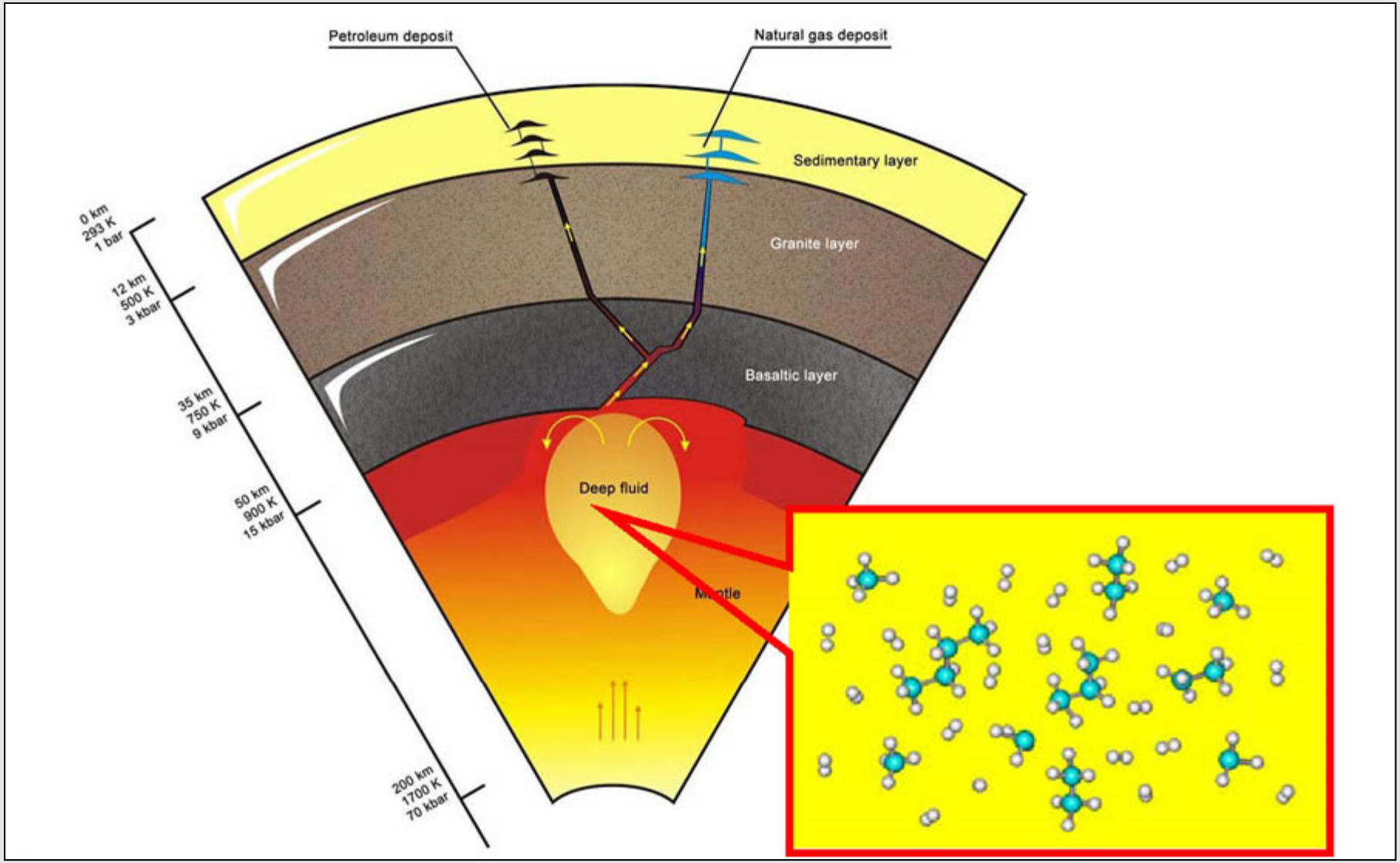
composition of shallowest spinel peridotites

Moho temperature …

along the way

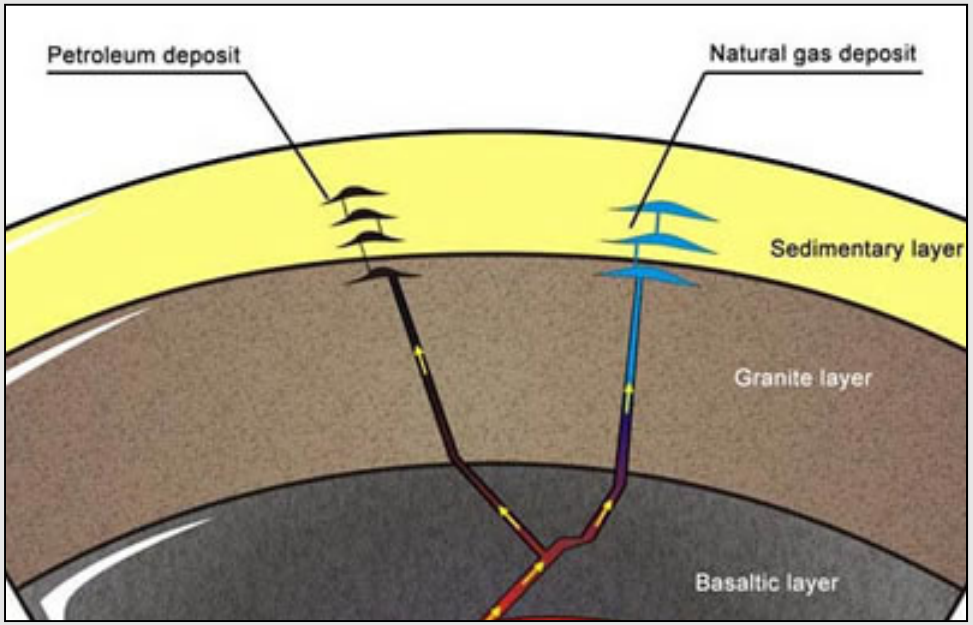
continental lower crust

temperature, K, U, Th,
proportion of metasediments
residues of melt extraction?



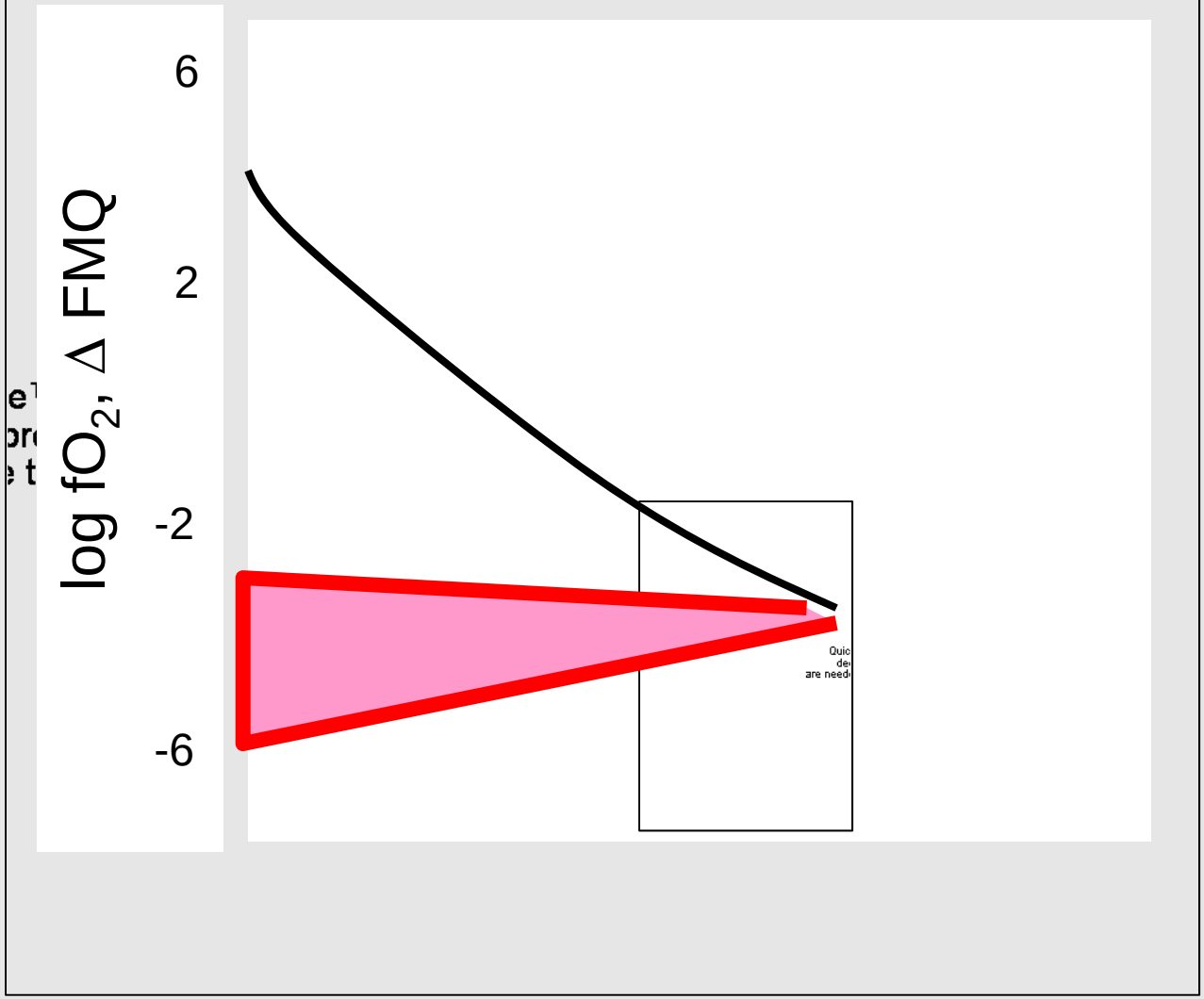
Hydrocarbons in Deep Earth? Alexander Goncharov, Geophysical Laboratory, Deep Carbon Institute, CIW

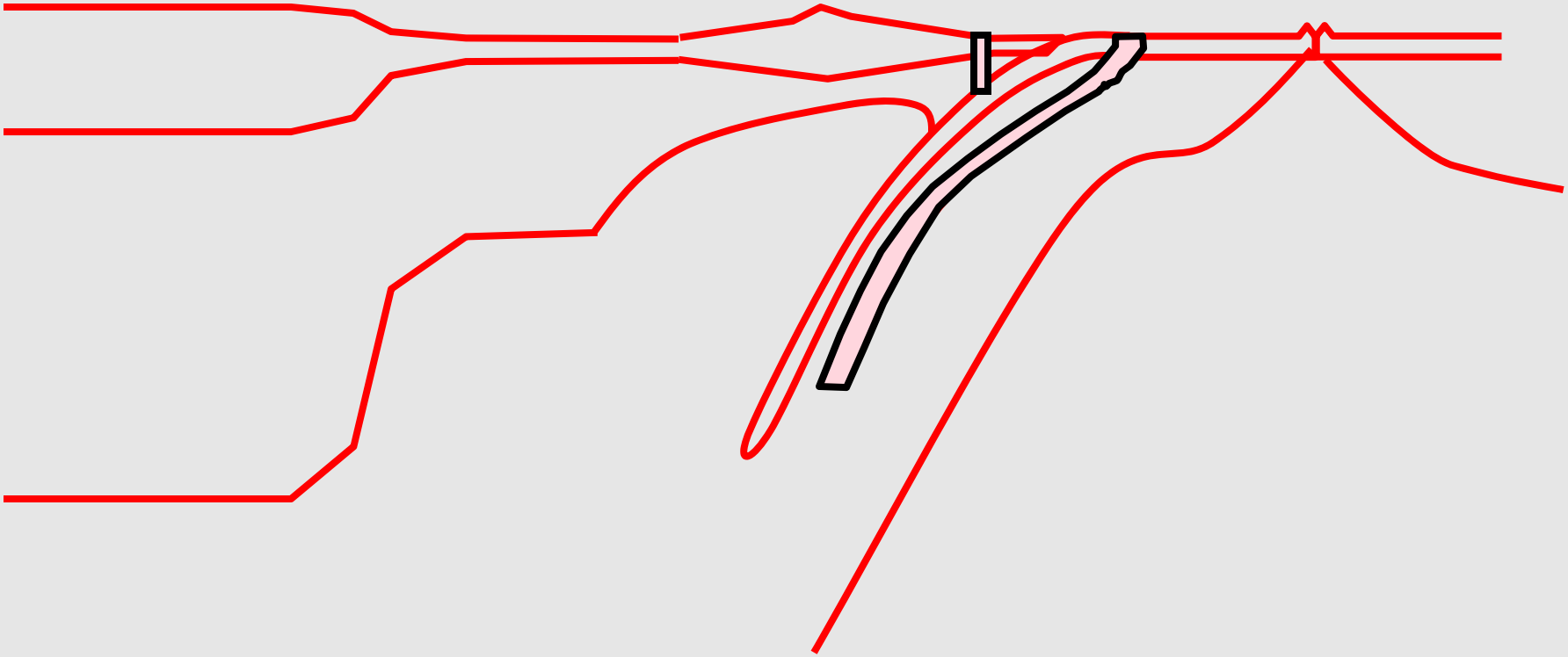
QuickTime™ and a
decompressor
are needed to see this picture.

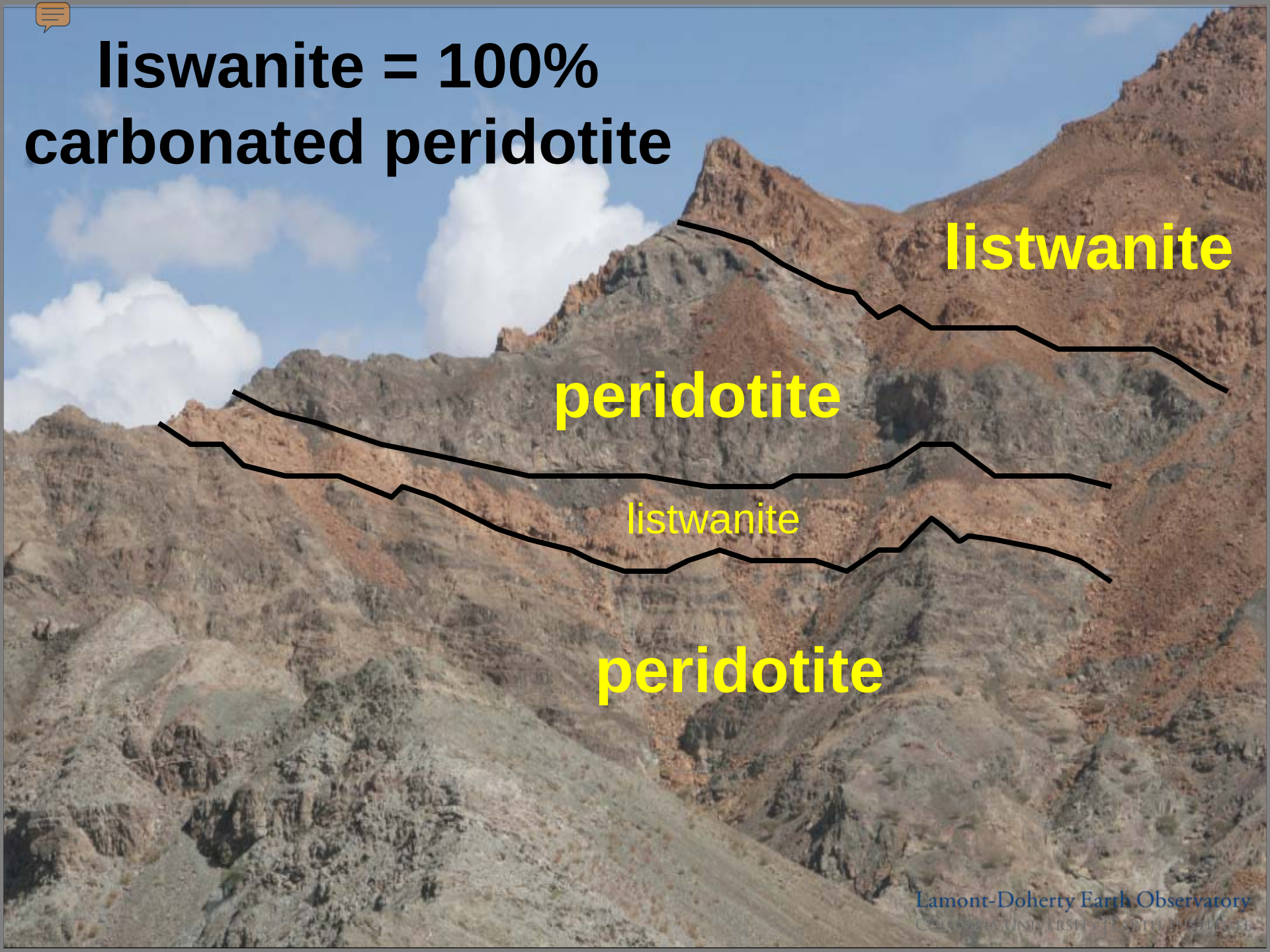


Hydrocarbons in Deep Earth?
Alexander Goncharov, 2008

Gold & Soter, Sci Am 1980


log fO_2, Δ FMQ
6
2
-2
-6




liswanite = 100%
carbonated peridotite
listwanite
peridotite
listwanite
peridotite
Lamont-Doherty Earth Observatory

"No, I can't make it next Friday. How about a week Tuesday?