Exploring the deep oceanic lithosphere on land: a (too short) field trip in the Oman ophiolite.

“Far are the shades of Arabia, …”

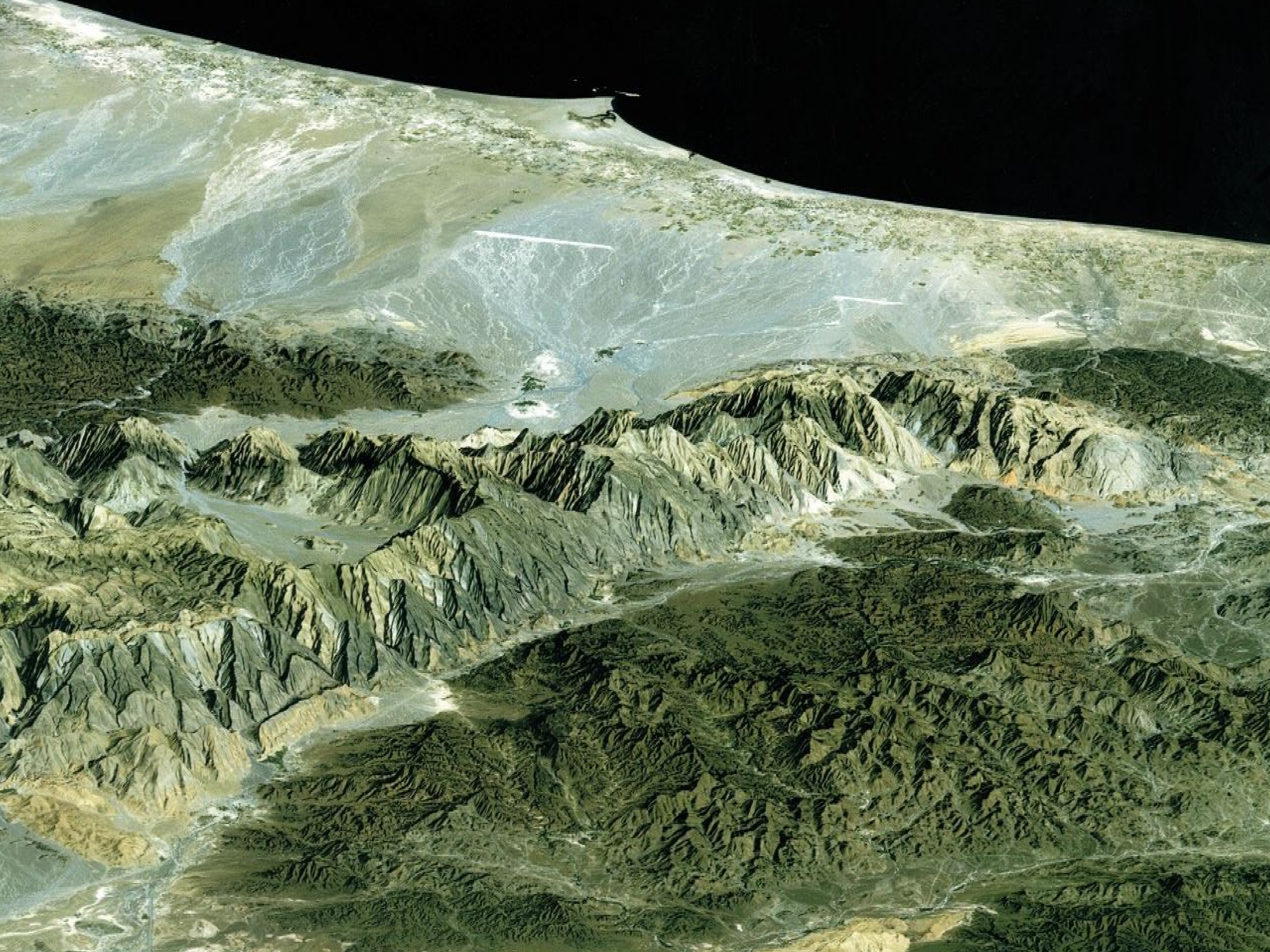
Walter de la Mare

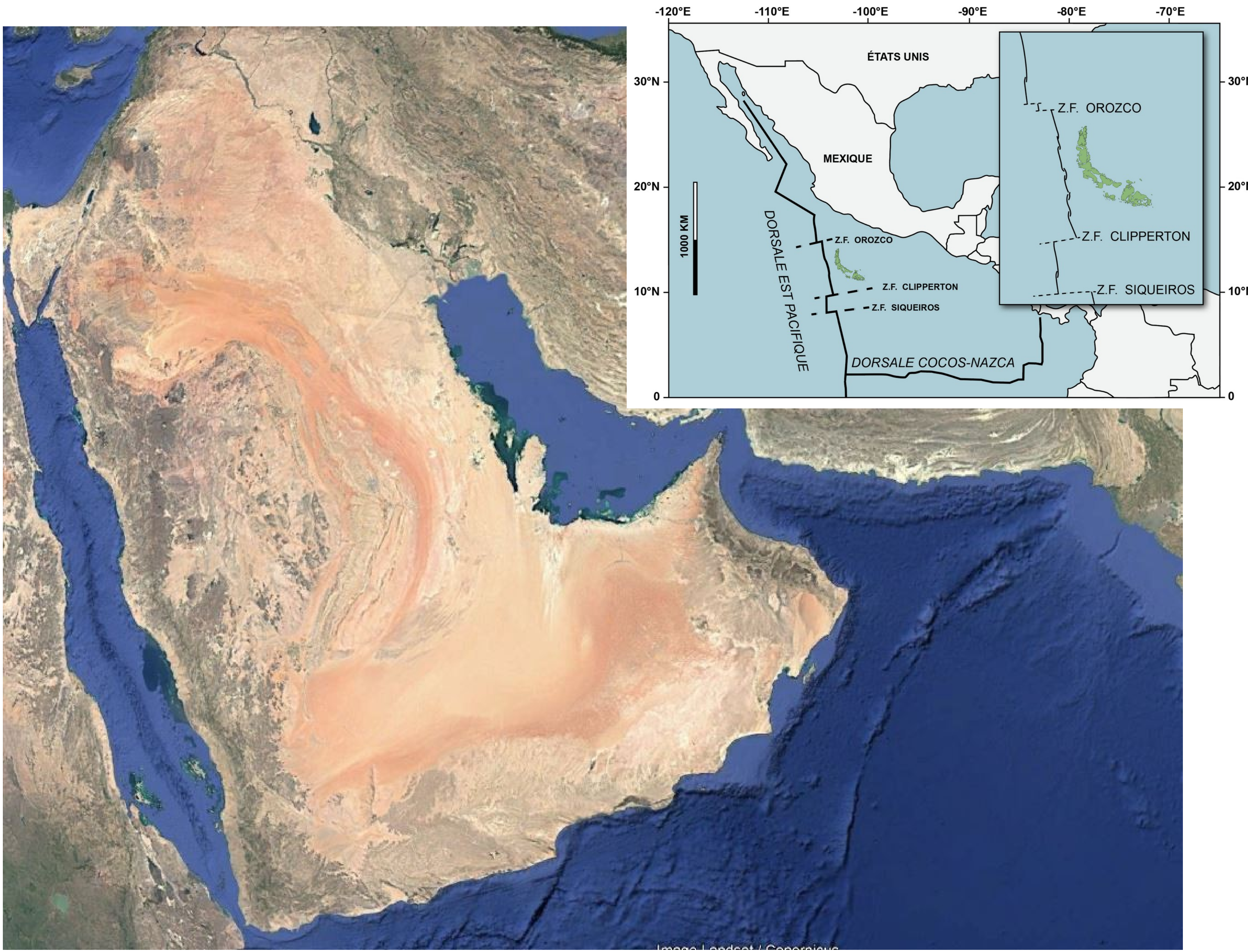
Masirah line
Owen TF
Semail ophiolite front thrust
Dibba fault
Zagros fold belt
Makran subduction prism

Gentle thrusting of a ~5 km-thick rigid lithospheric nappe on the continental margin.

Limited (but still discussed) overprint of obduction tectonics.

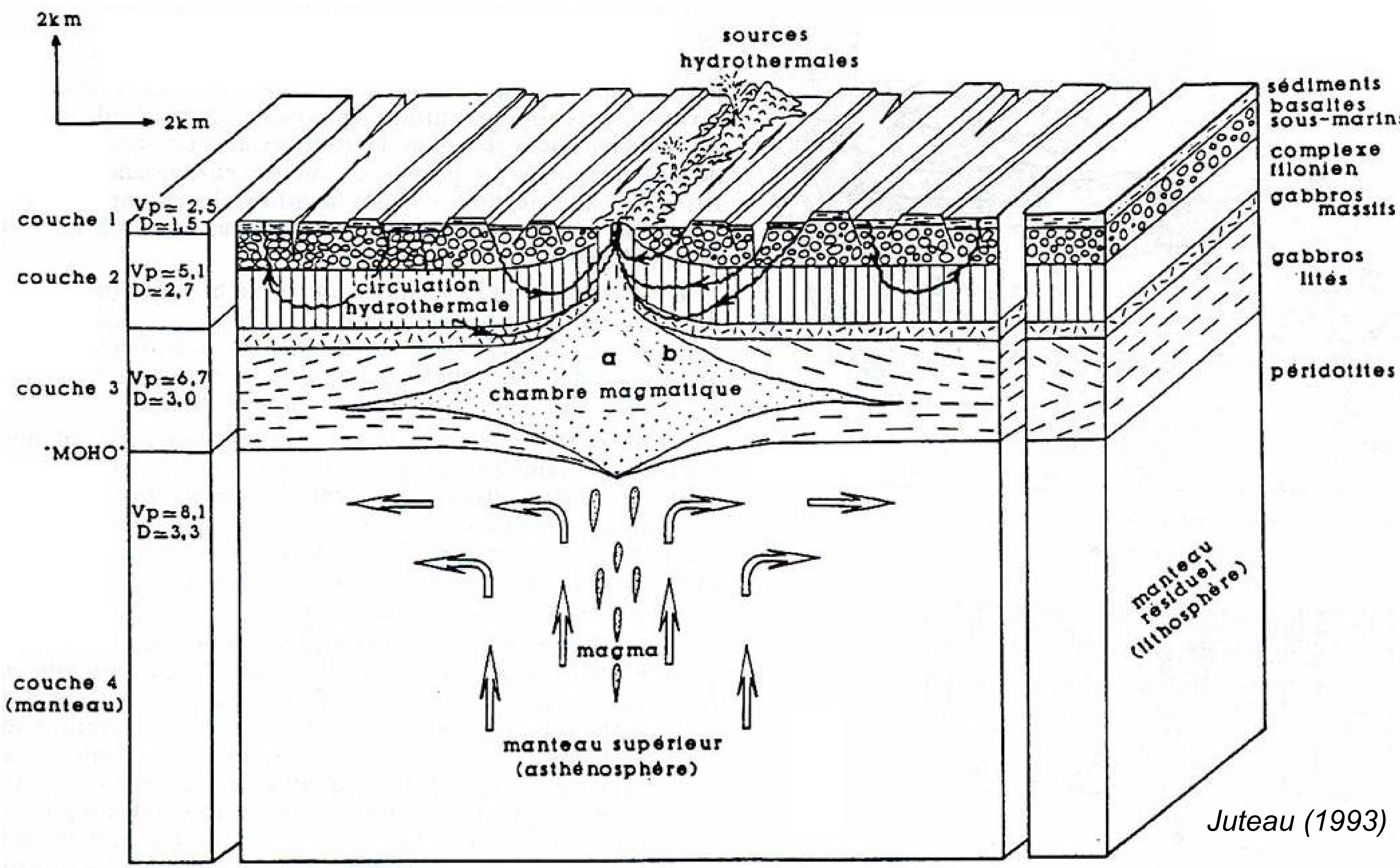
Access to a full section through the oceanic crust down to the shallow mantle.



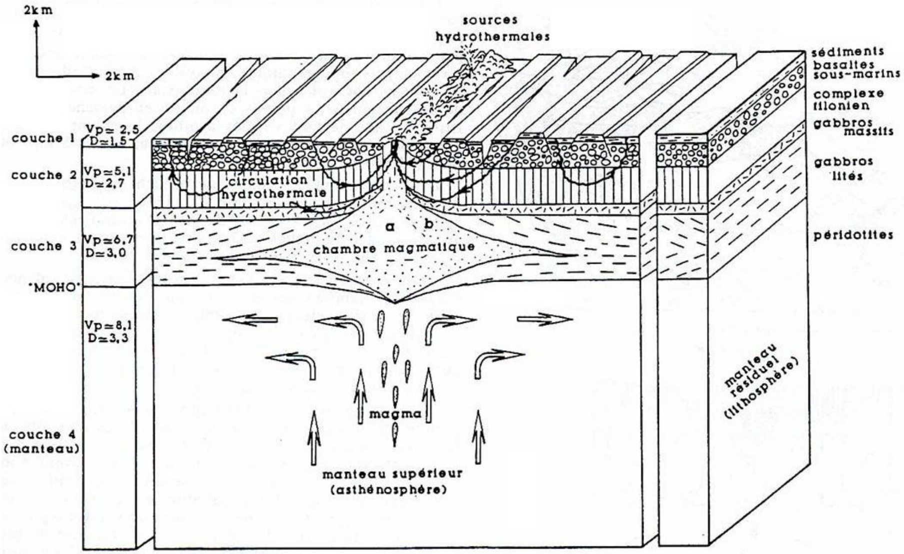


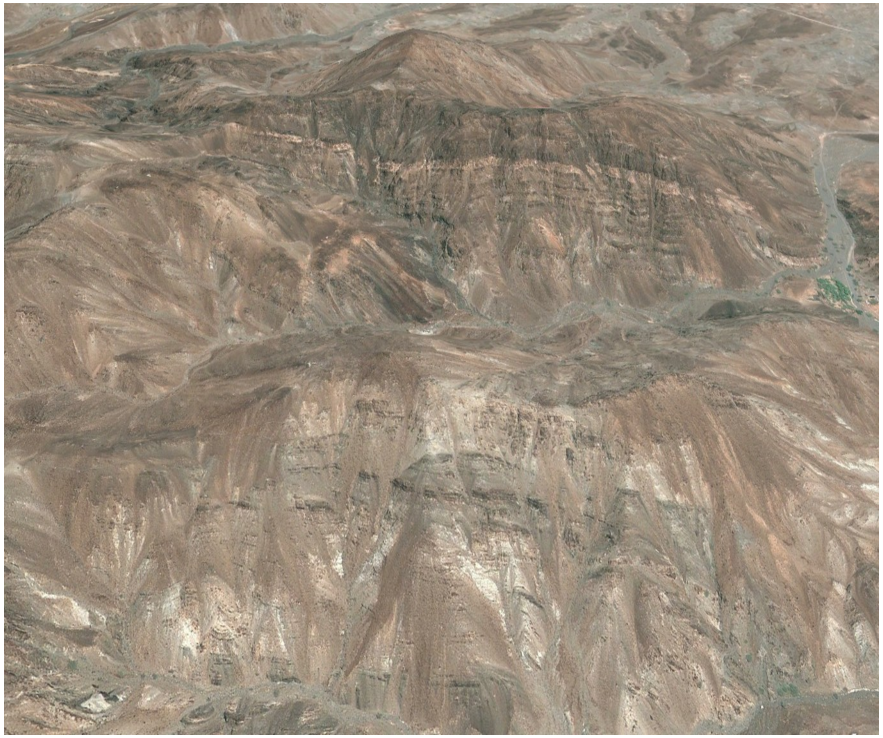
-120°E
-110°E
-100°E
-90°E
-80°E
-70°E
30°N
20°N
10°N
0
ÉTATS UNIS
MEXIQUE
1000 KM
DORSALE EST PACIFIQUE
Z.F. OROZCO
Z.F. CLIPPERTON
Z.F. SIQUEIROS
DORSALE COCOS-NAZCA

The deeper, the harder to figure out what happens there …

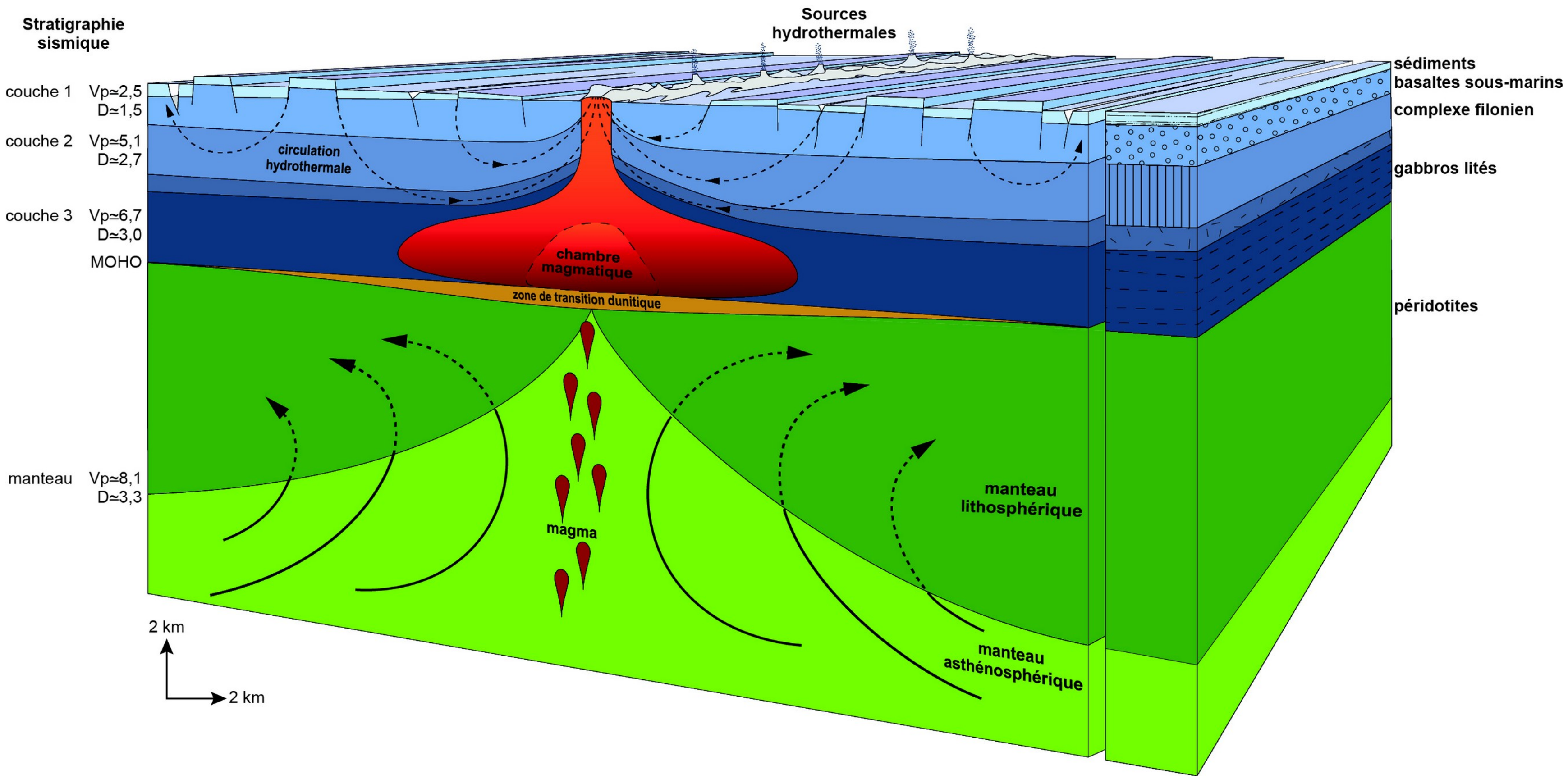


Juteau (1993)


2km
2km
sources
hydrothermales
sédiments
basaltes
sous-marins
complexe
filonien
gabbros
massifs
gabbros
lités
péridotites
manteau
résiduel
(lithosphère)
couche 1
Vp= 2,5
D=1,5
couche 2
Vp=5,1
D=2,7
couche 3
Vp=6,7
D=3,0
"MOHO"
Vp=8,1
D=3,3
couche 4
(manteau)
circulation
hydrothermale
a
b
chambre magmatique
magma
manteau supérieur
(asthénosphère)

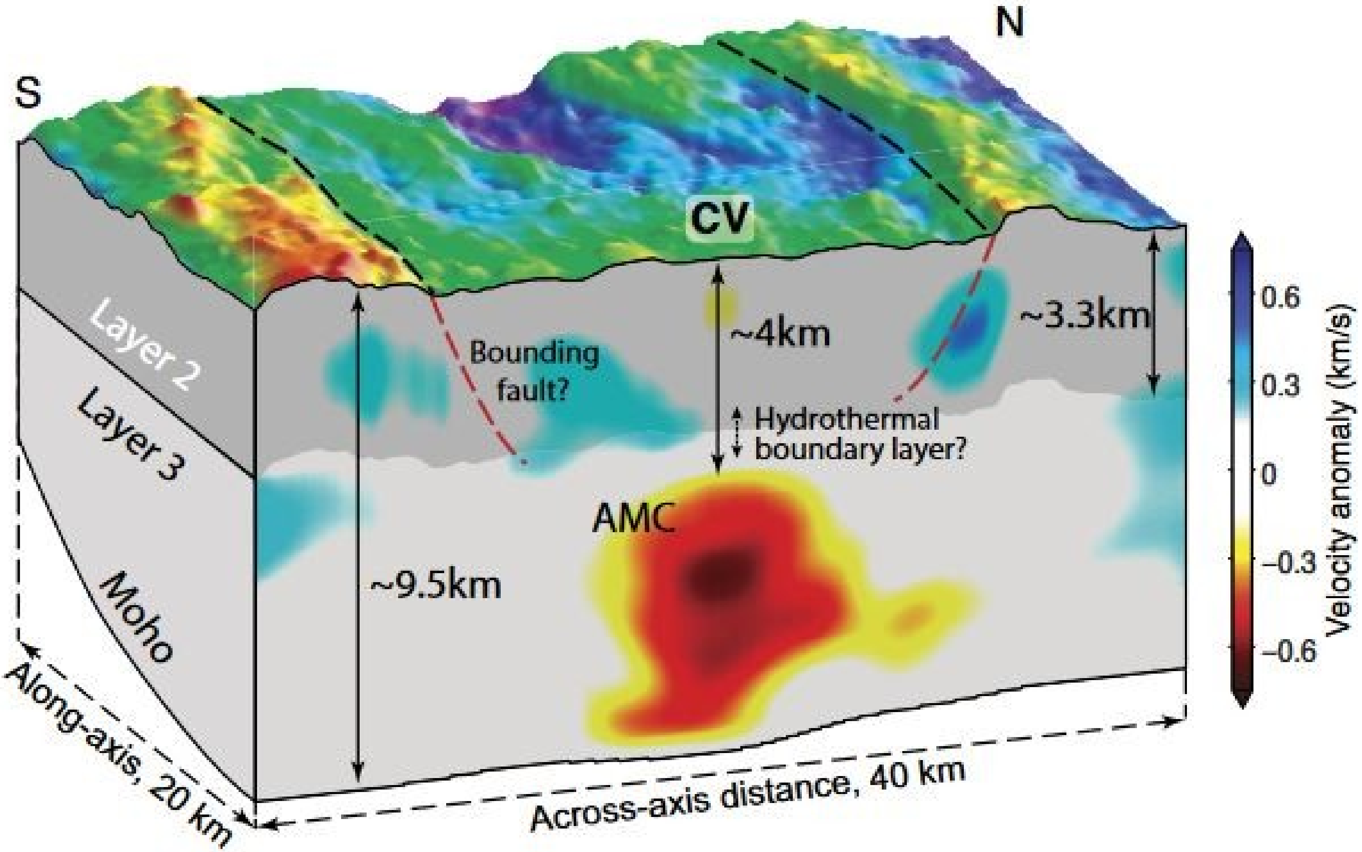


Today: melt migration in the mantle and construction of the lower crust.

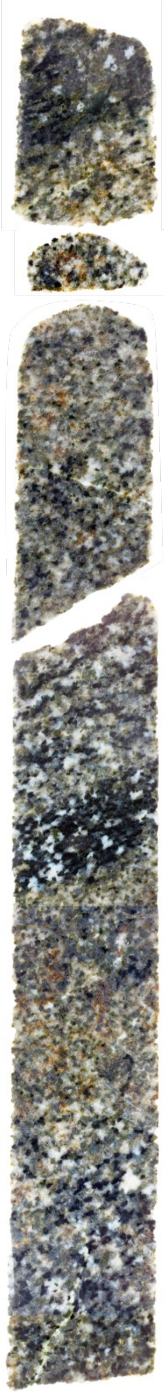



sherpa

Progresses in the determination of the general shape of axial magma chambers but the detailed structures are not resolved by seismic tomography.



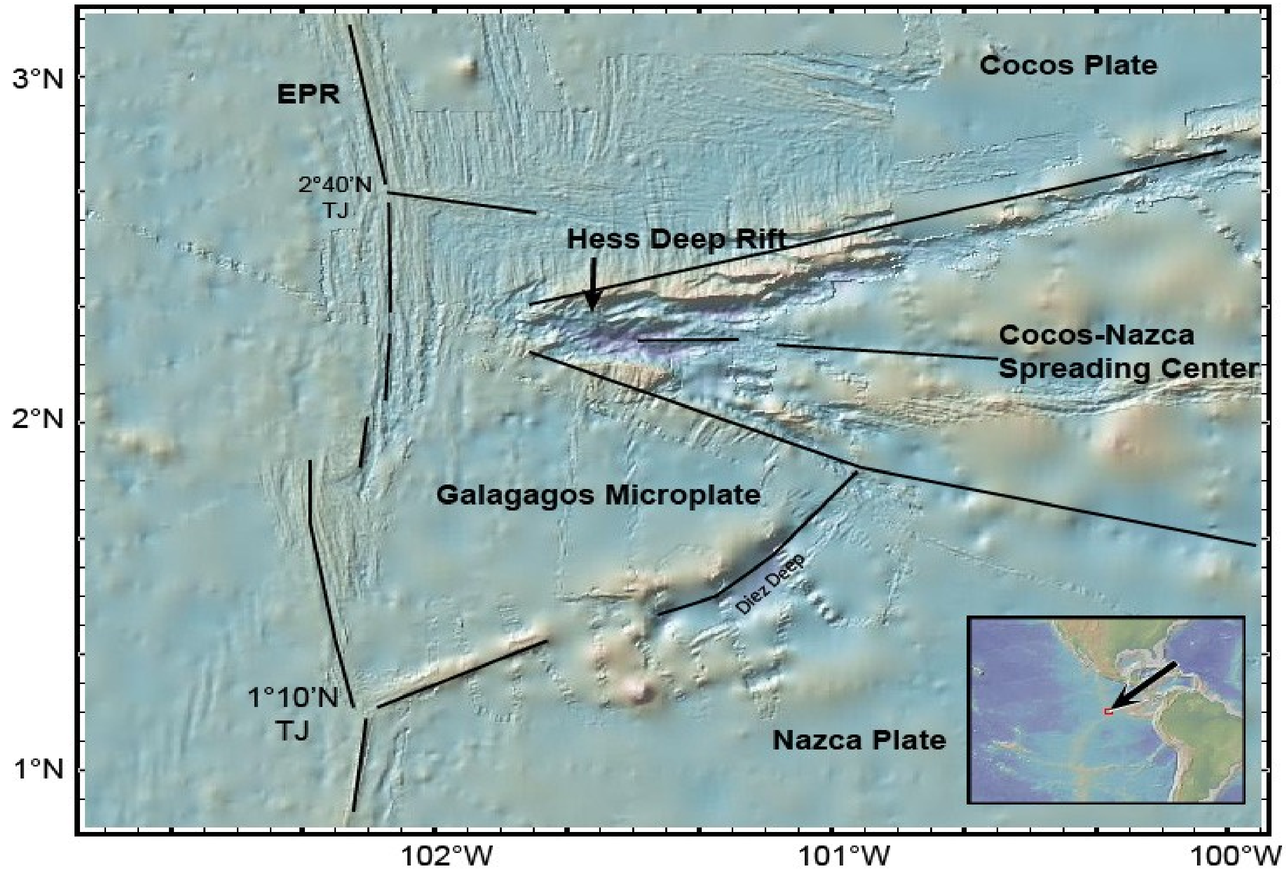
Classical interpretation of igneous layering: periodic replenishment of a magma chamber followed by fractional crystallization, crystal sorting and accumulation.



First layered cumulates sampled along a present-day mid-ocean ridge.

IODP Expedition 345 (2012- 2013).

Validation of the hypothesis inspired by observations in ophiolites.



Interlayered troctolites and gabbros drilled at Hess Deep, off the East Pacific Rise.

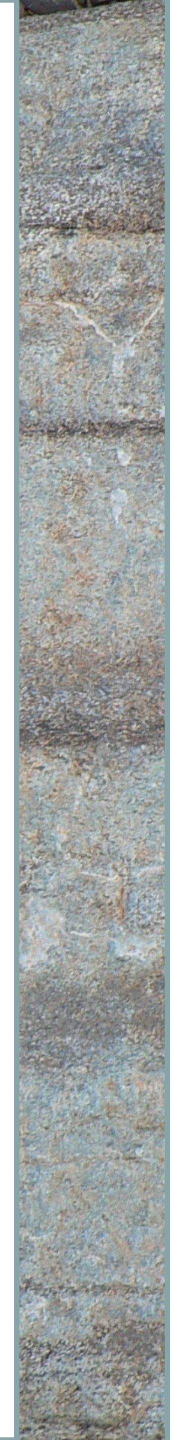
Cycles of replenishment followed by crystal settling ?

Hess Deep

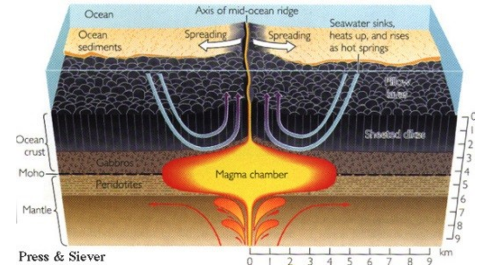
2 cm

Oman

Cores from different sections would lead to different stories…

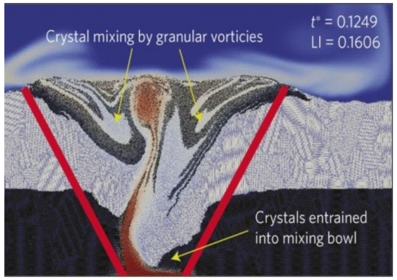


Classical interpretation…



<u>Wise hypothesis</u> : periodic replenishment in an orderly magma chamber.

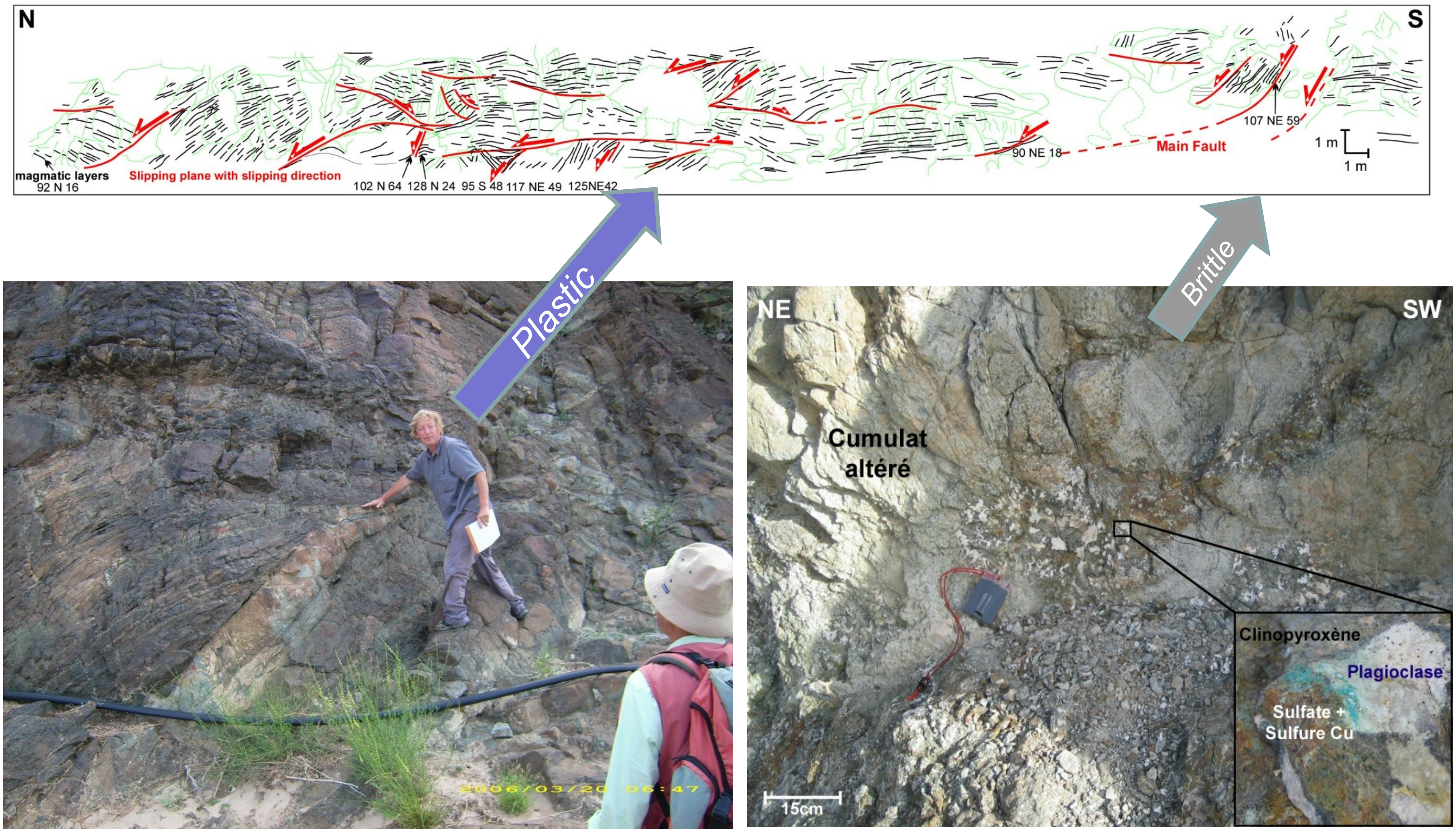
Crazy interpretation…



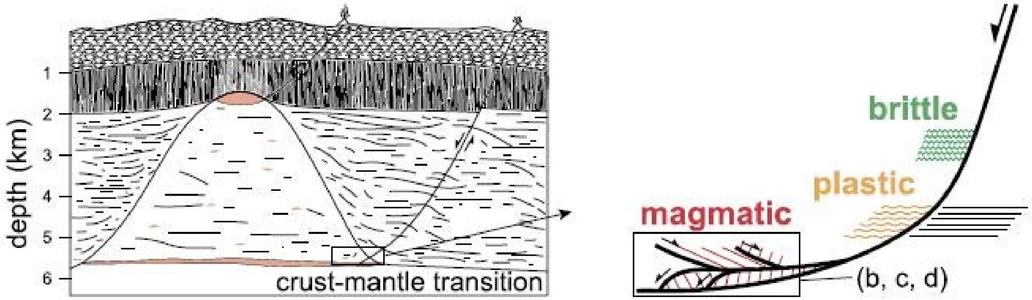
<u>Provocative hypothesis</u> : complex processes in a messy magma chamber.


Igneous discordance → synmagmatic faulting…

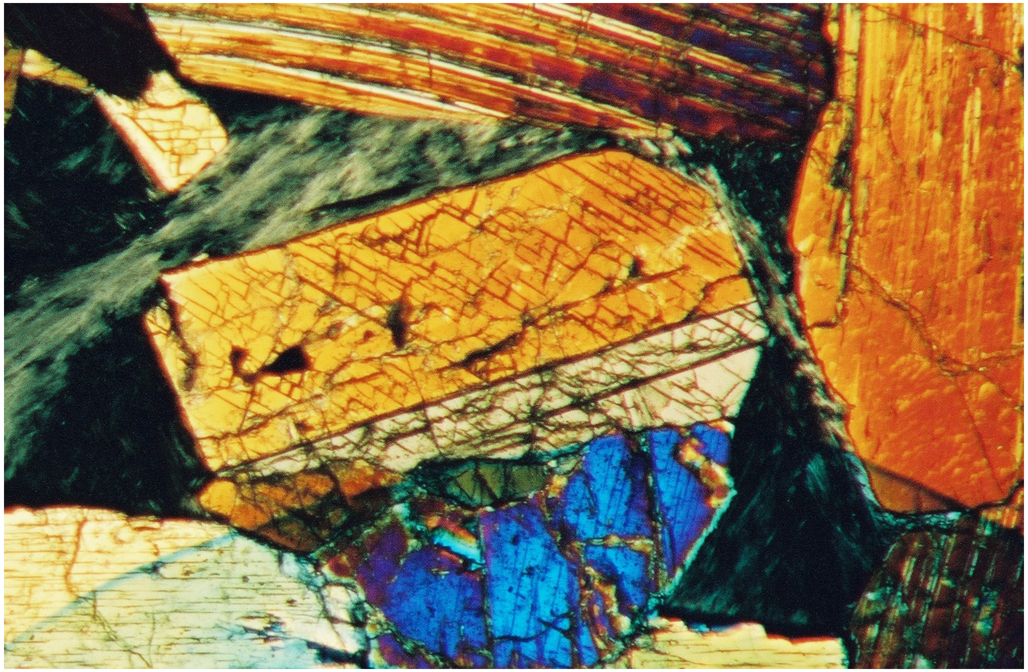
Toward the paleo-ridge axis



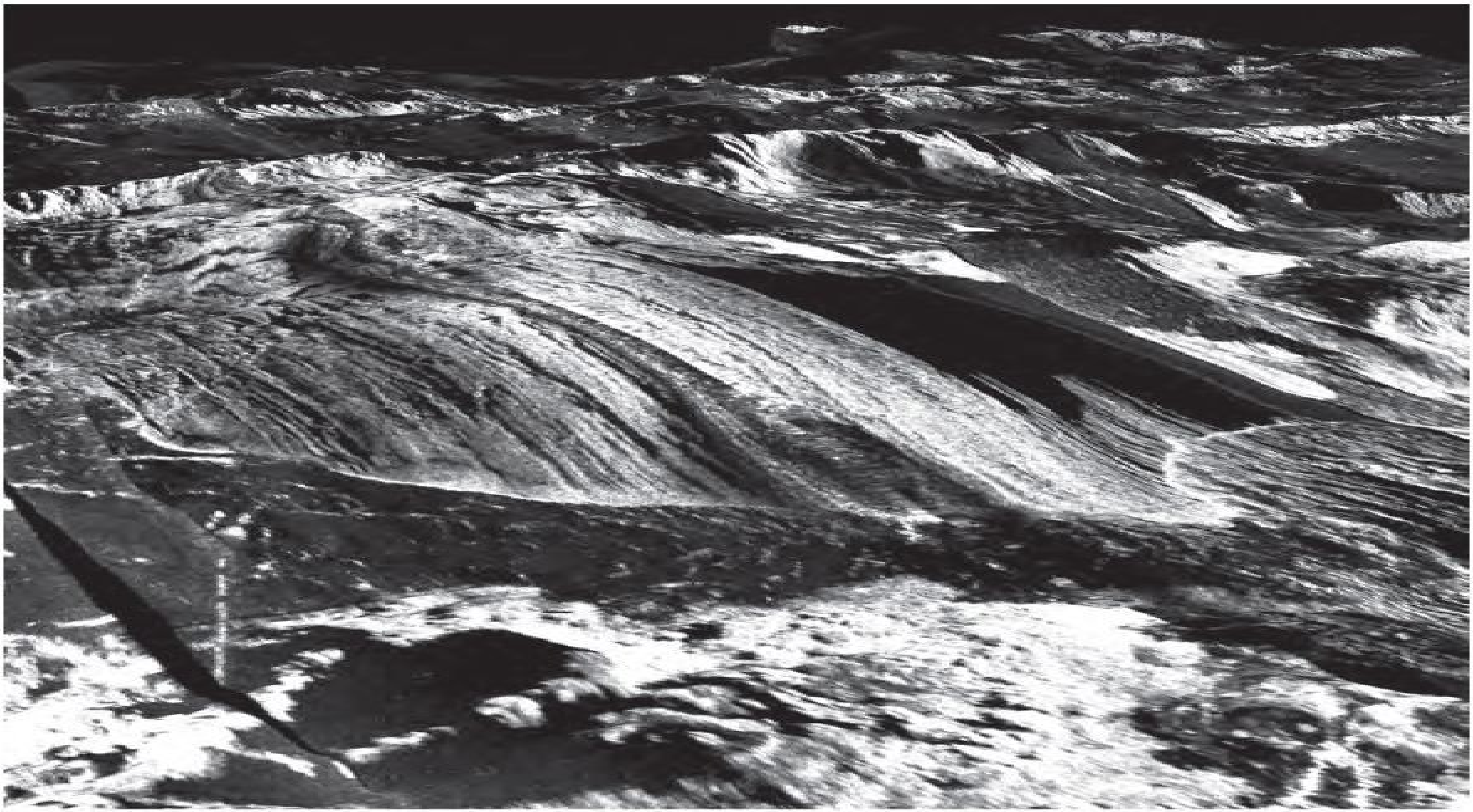
Magmatism, tectonics and hydrothermalism can work together at the same place and at the same time to build an oceanic crust with a complex architecture and to trigger exchanges between the deep and shallow Earth.



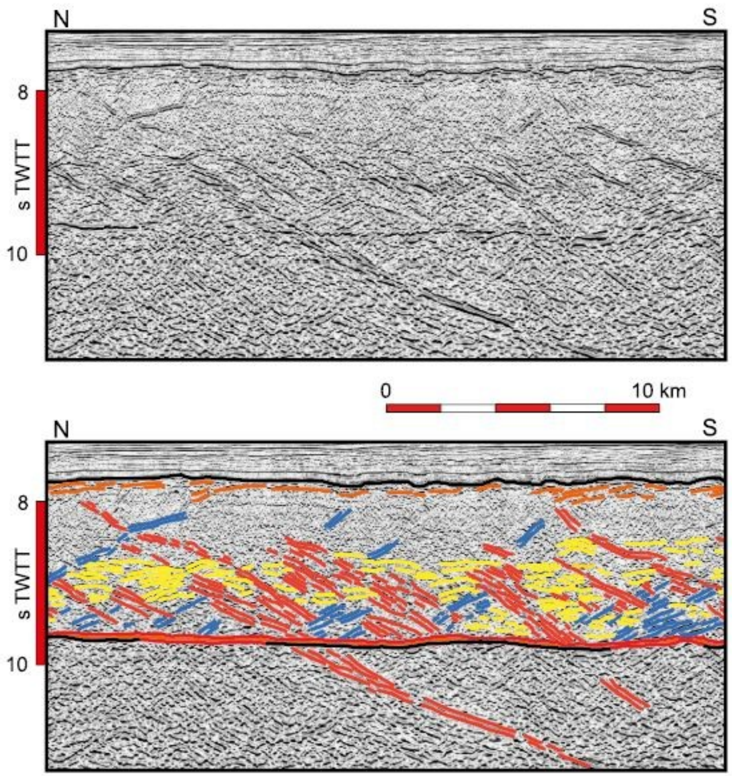
Hydrothermal pyroxene crystallizing at very high temperature (~800°C) at the expense of serpentinized mantle peridotite at Moho level.



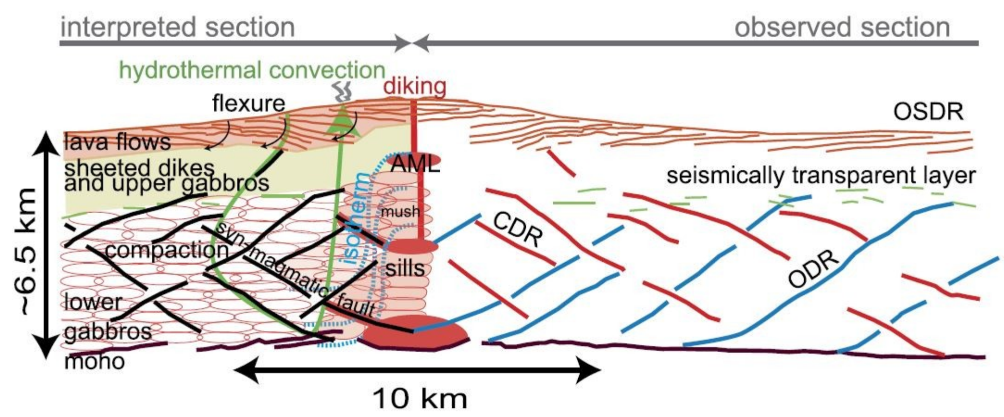
Deep seated faults are documented along slow spreading ridges.
So called «oceanic core complexes are supposed to be specific to slow, magma poor, ridges but...



… might occur at fast spreading ridges too, hidden below a thick pile of basalt.

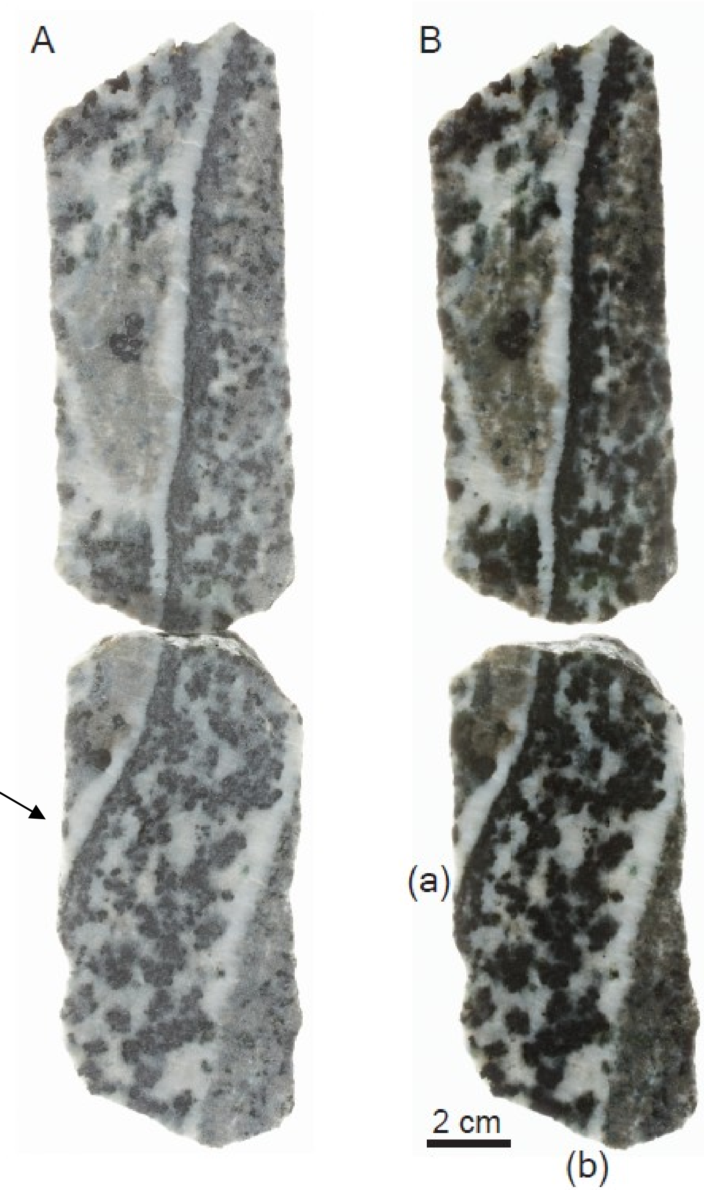


Re-interpretation of seismic reflectors at fast spreading ridges in terms of synmagmatic « hidden » faults.



Oman ophiolite

Observations in Oman help to interpret strange structures in cores from present-day ridges in terms of synmagmatic tectonics.

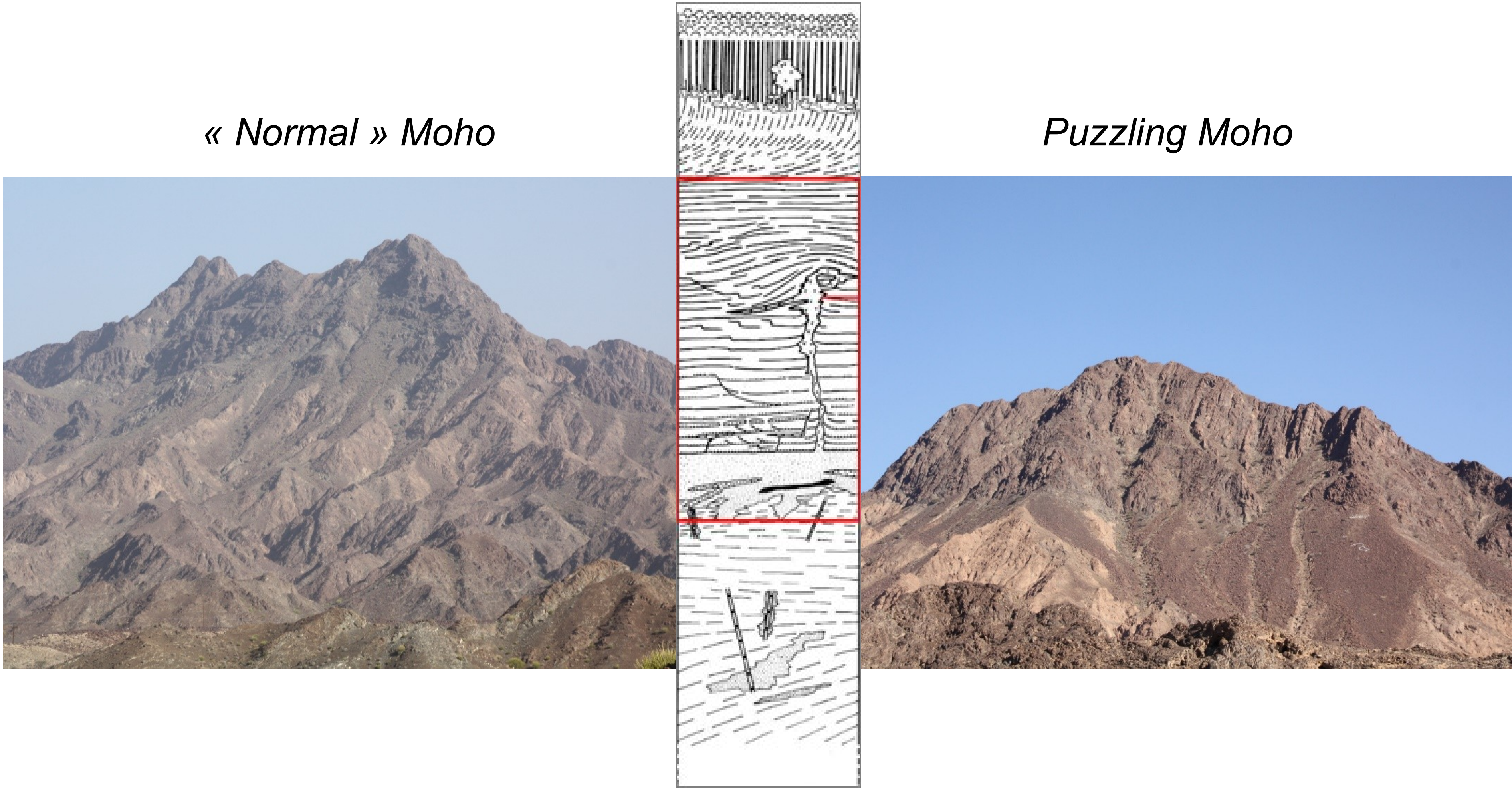


Hess Deep - East Pacific Rise
IODP Expedition 345

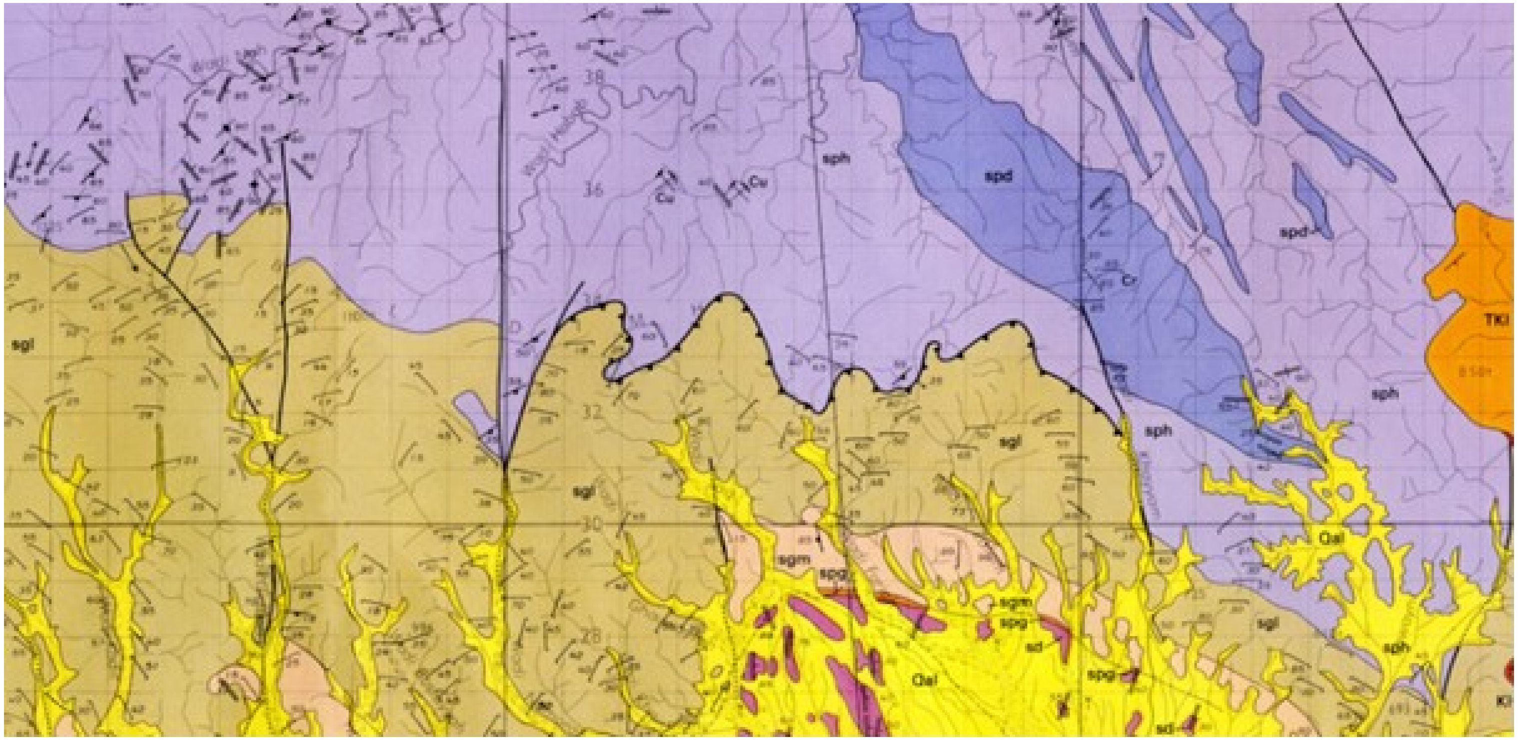
Is the classical « representative » geological section through the Oman ophiolite really representative of its structural diversity ?

« Normal » Moho

Puzzling Moho



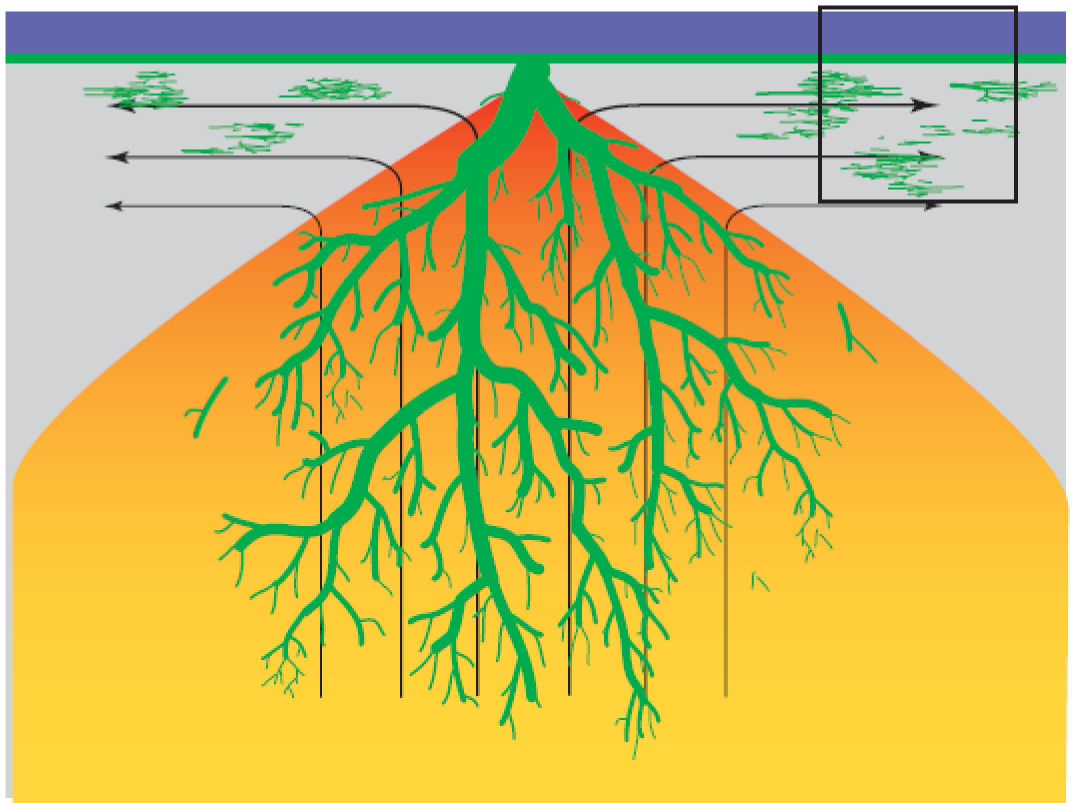
Faulted or not faulted?
That is the (…conflictual…) question!



Detail of the map from the JGR 1981 special issue on the Oman ophiolite.

Mapping the melt plumbing system in the mantle … still a dream!

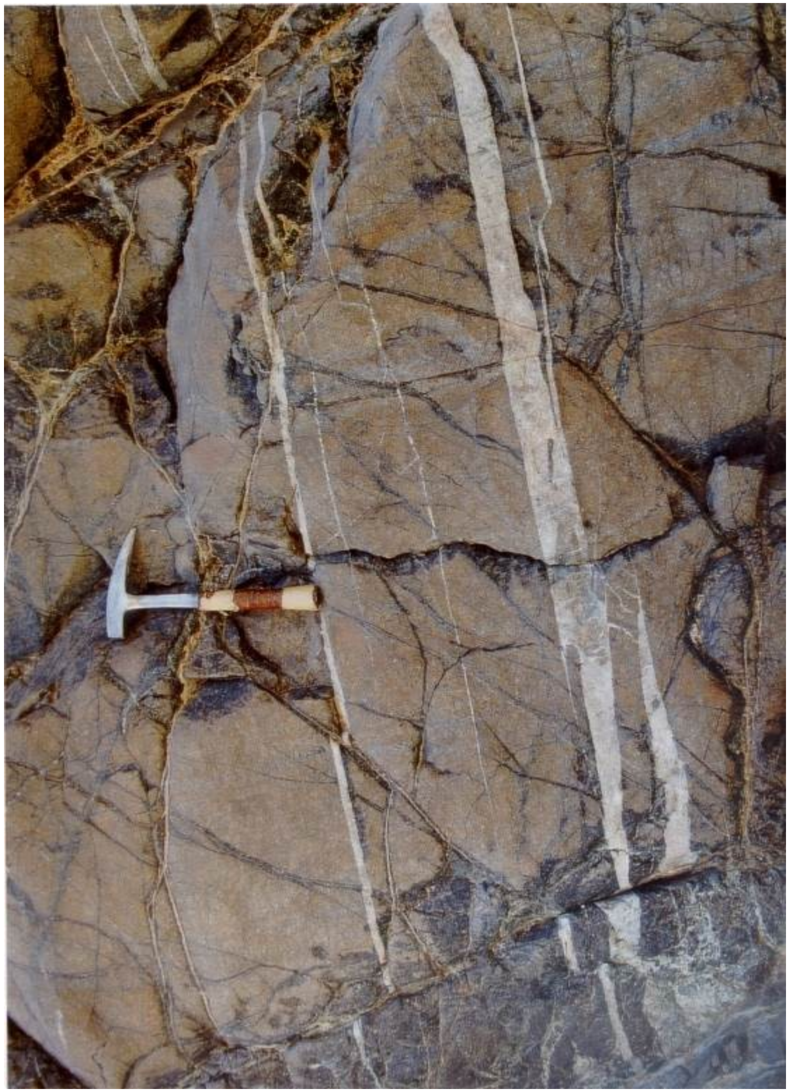
Geophysics is still too short sighted to image the shape of the melting region and, a fortiori, the small scale melt migration structures.



Melt migration is much more than « just » mechanics.

It is a fundamental petrogenetic process governing how incremental melt fractions mix to produce MORB.

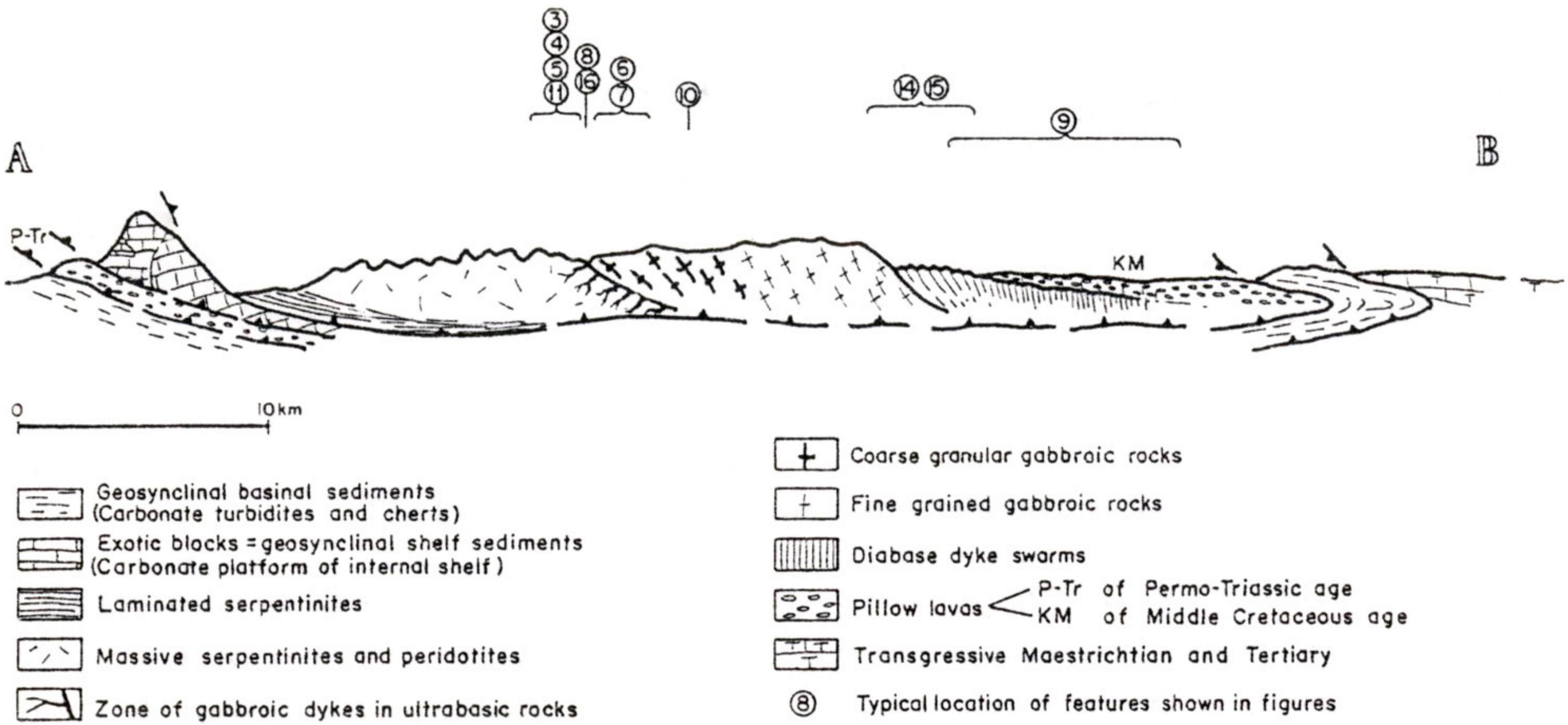
Which structures attributable to melt migration in the mantle are preserved in the Oman ophiolite (and all other ones…)?



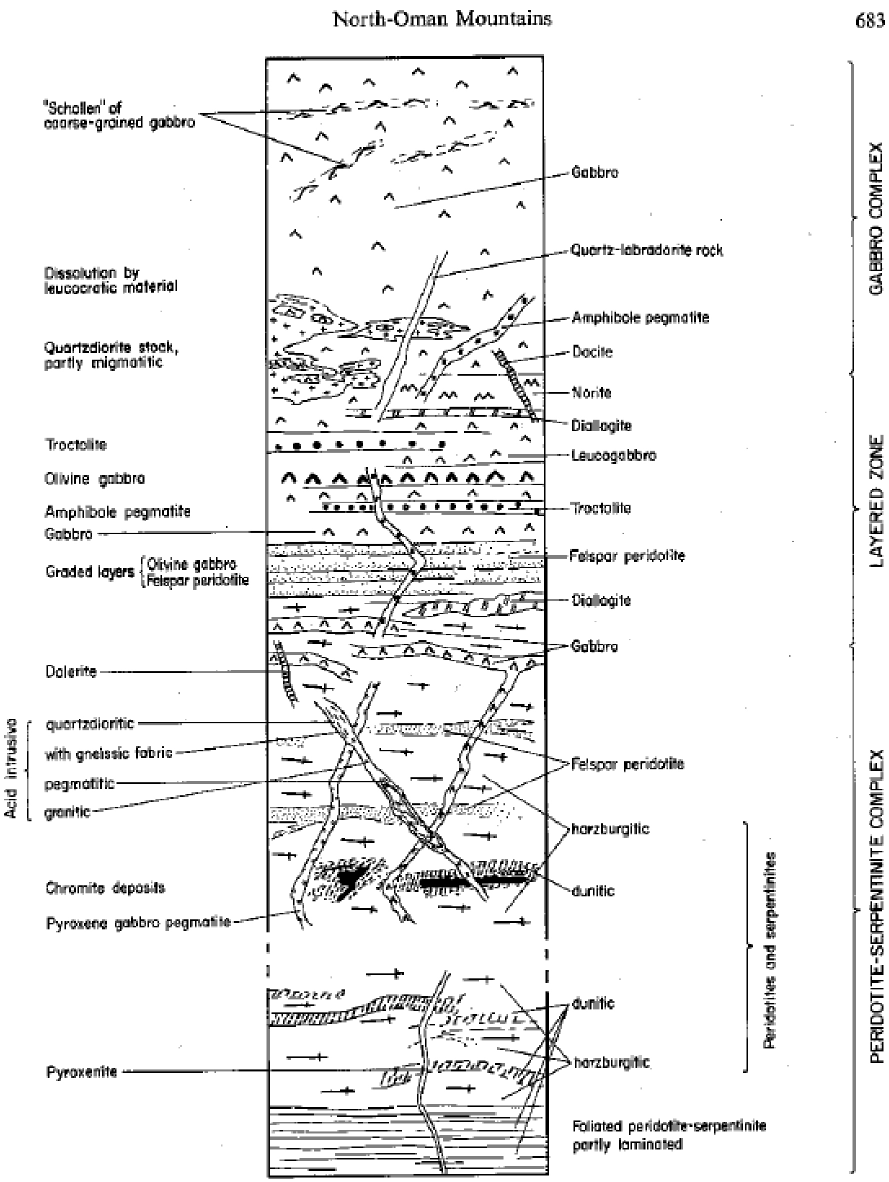
" Dykes of gabbro are common in the serpentine. No definite sequence could be determined."

Lees (1928)

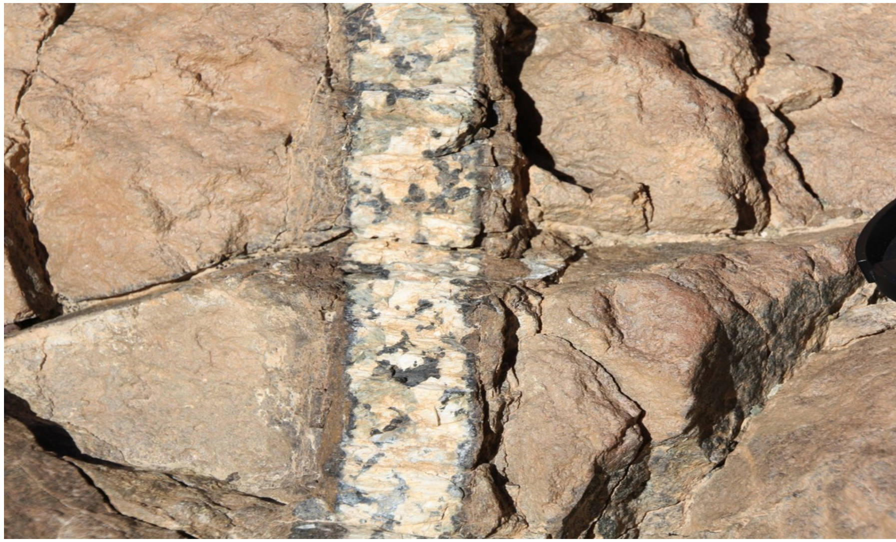
Ophiolites in the Oman Mountains Geosyncline



Reinhardt (1969)



Allemann and Peters (1972)



Dykes come from the depths!
Concept of ''feeding dykes''.

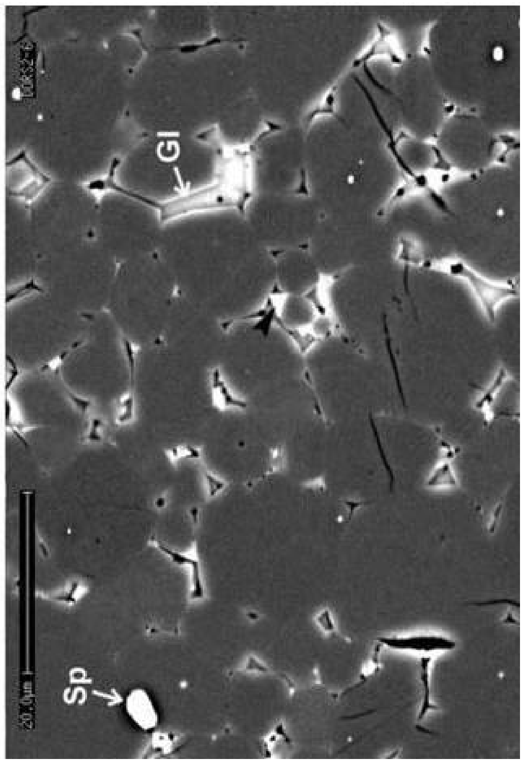
Dyking is a brittle process.

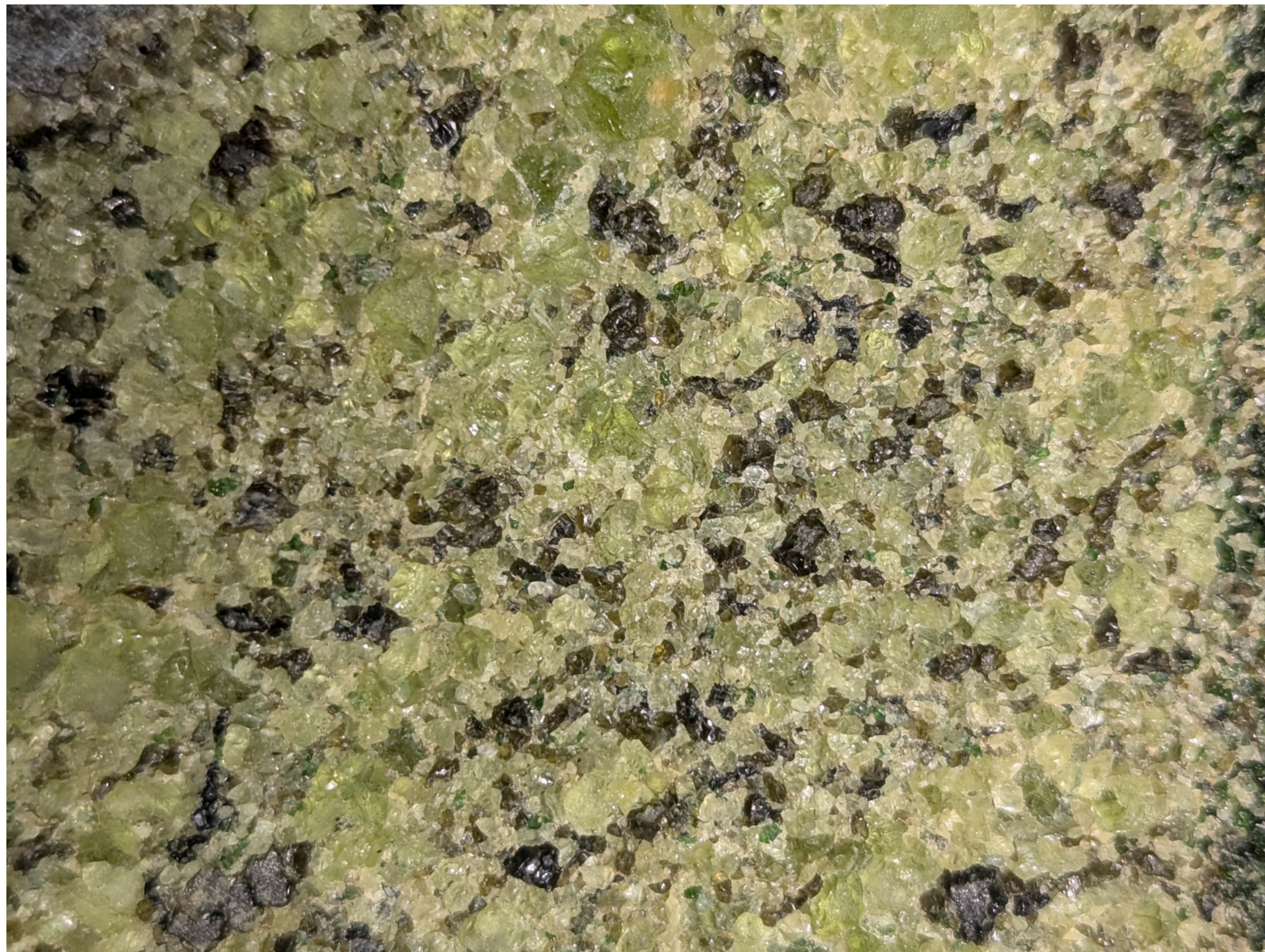
Is it representative of melt migration in the asthenosphere?

Partial melting occurs at the junction of different minerals.

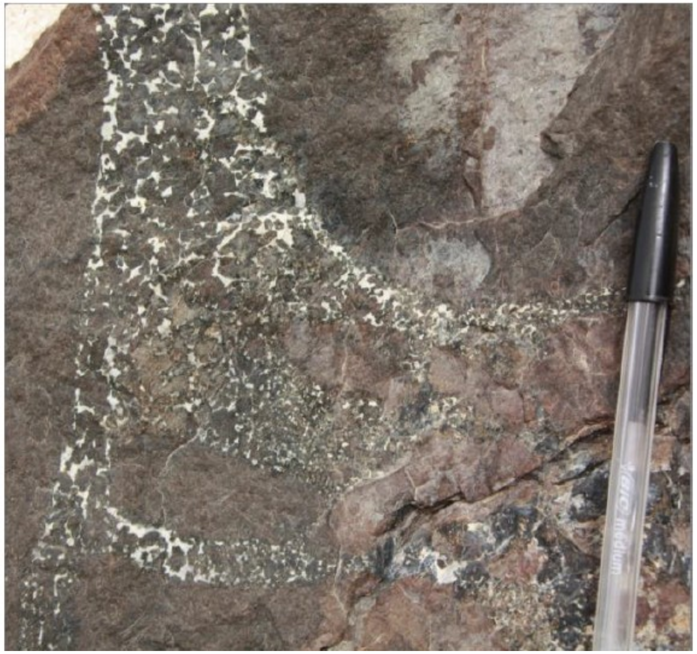
→*Melt is initially scattered as an intertitial phase in the solid matrix.*

→ *The first stage of melt migration involves, a priori, porous flow along grain boundaries.*





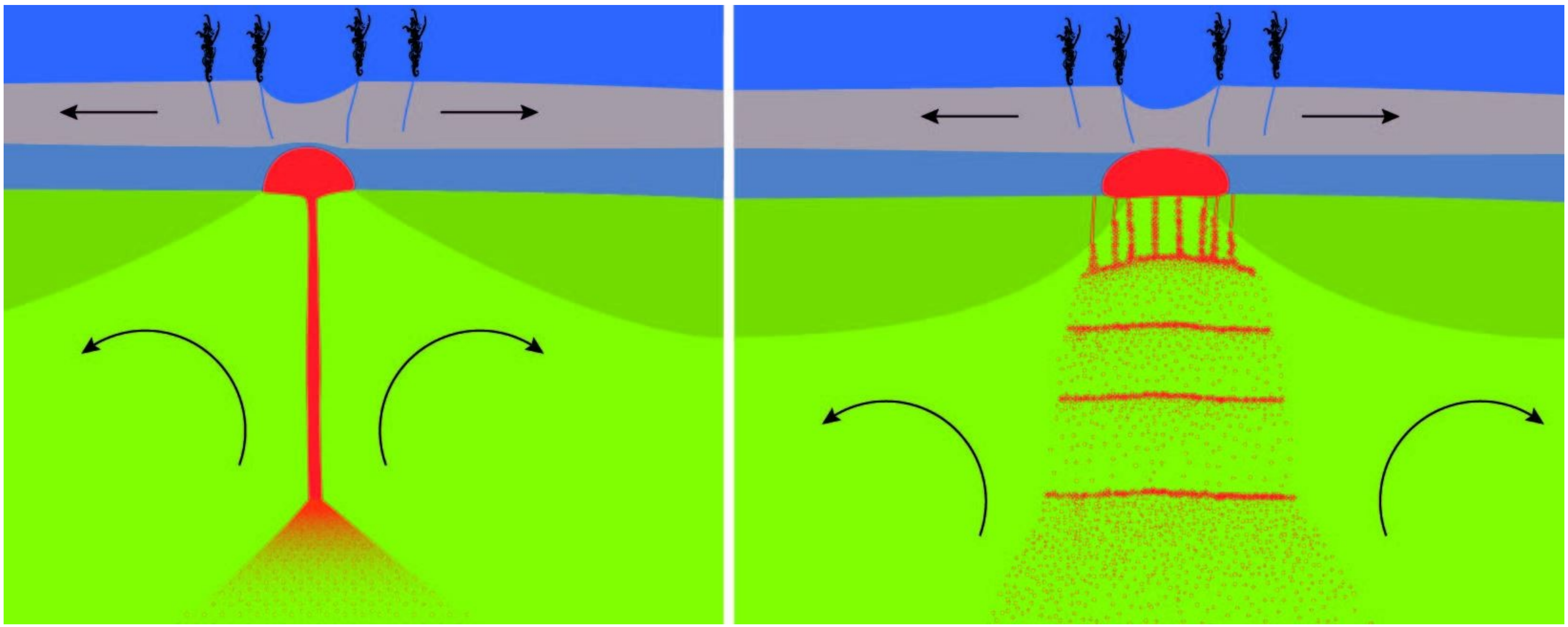
Relics of melt migration along grain boundaries, « porous flow structures », are observed too but are much less abundant than dykes.



What is the main mode of melt transport in the mantle beneath oceanic ridges?

Where and at which temperature does dyking overcome porous flow?

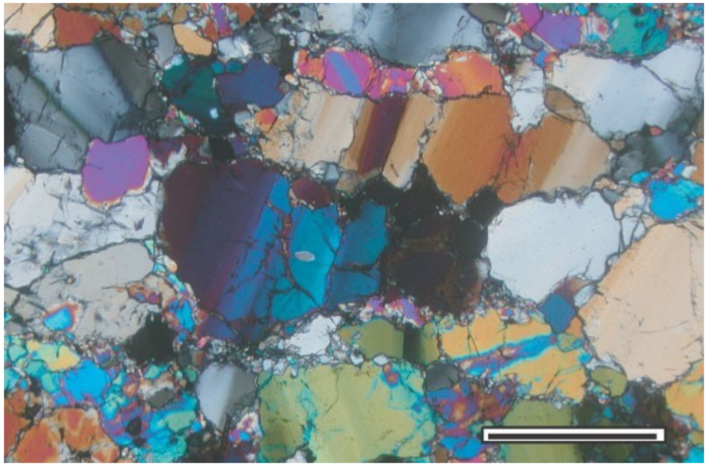
The question of the « brittle/ductile » transition for melt migration is a major, still debated issue.

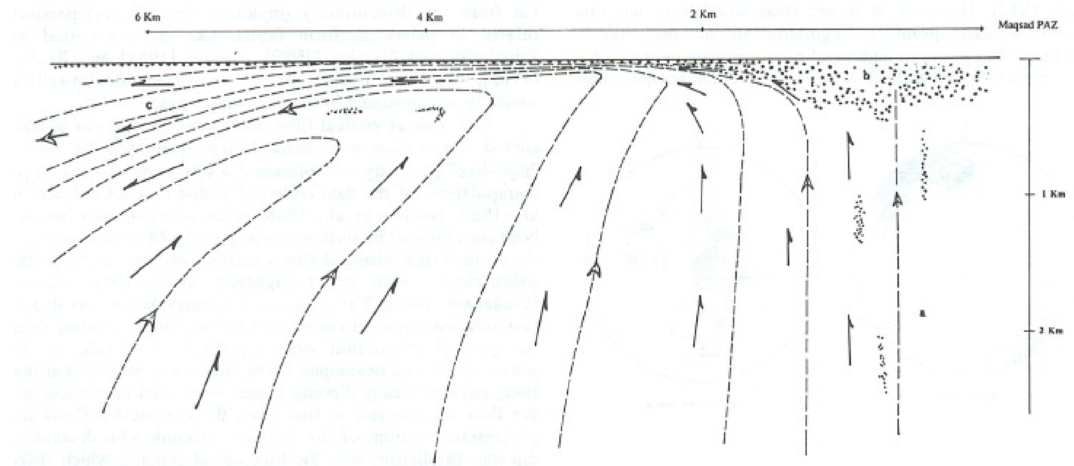


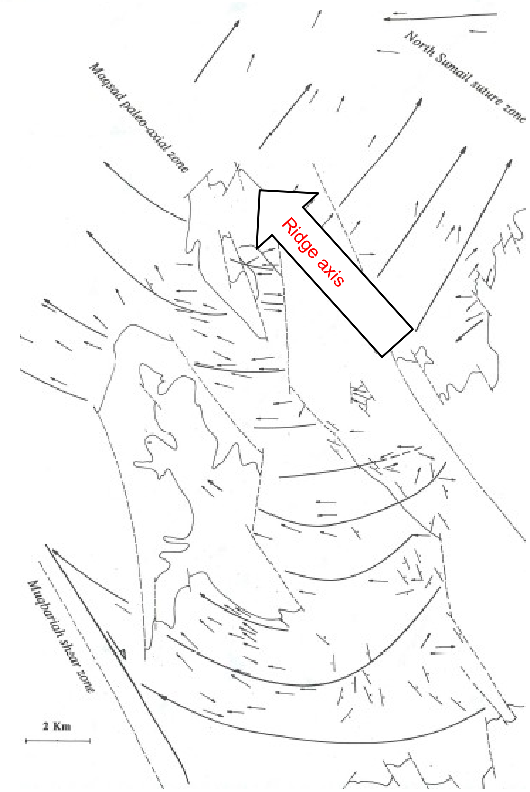
Dyking starts at great depth.

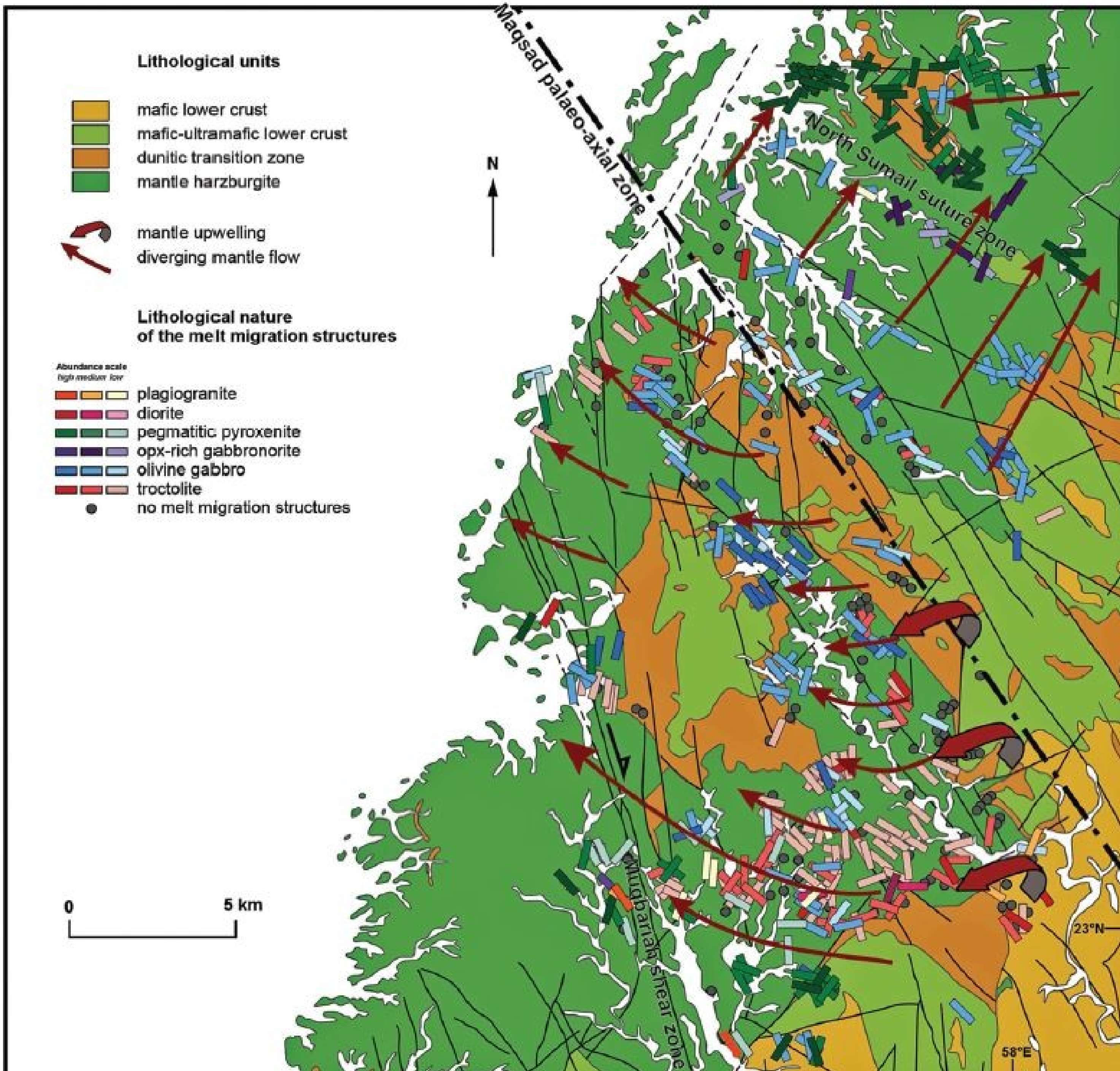
Dyking is restricted to shallow depths.

Mantle peridotite record solid-state asthenospheric flow geometry.

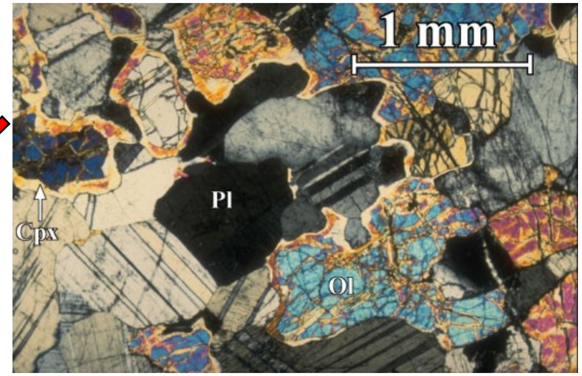




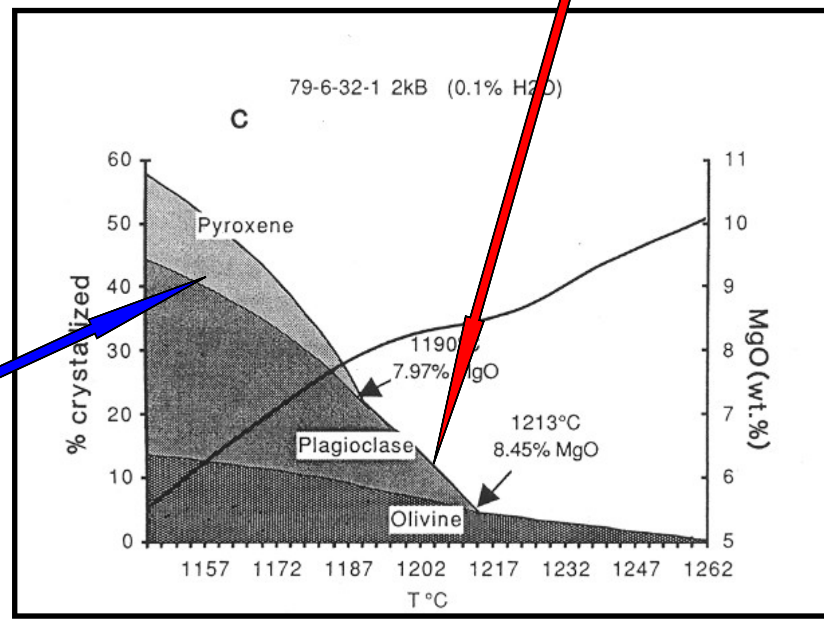



Lithological units
mafic lower crust
mafic-ultramafic lower crust
dunitic transition zone
mantle harzburgite
mantle upwelling
diverging mantle flow
Lithological nature
of the melt migration structures
plagiogranite
diorite
pegmatitic pyroxenite
opx-rich gabbronorite
olivine gabbro
troctolite
no melt migration structures
N
0
5 km
Maqsad palaeo-axial zone
North Sumail suture zone
Muqbariah shear zone
23°N
58°E

Determination of the T° of the brittle-ductile transition for MORB migration in the shallow mantle.



Troctolite



Olivine gabbro

Brittle-ductile transition for MORB migration occurs at a T° close to the Ol+Plg low pressure cotectic, near 1190°C (i.e. at the troctolite-gabbro transition).

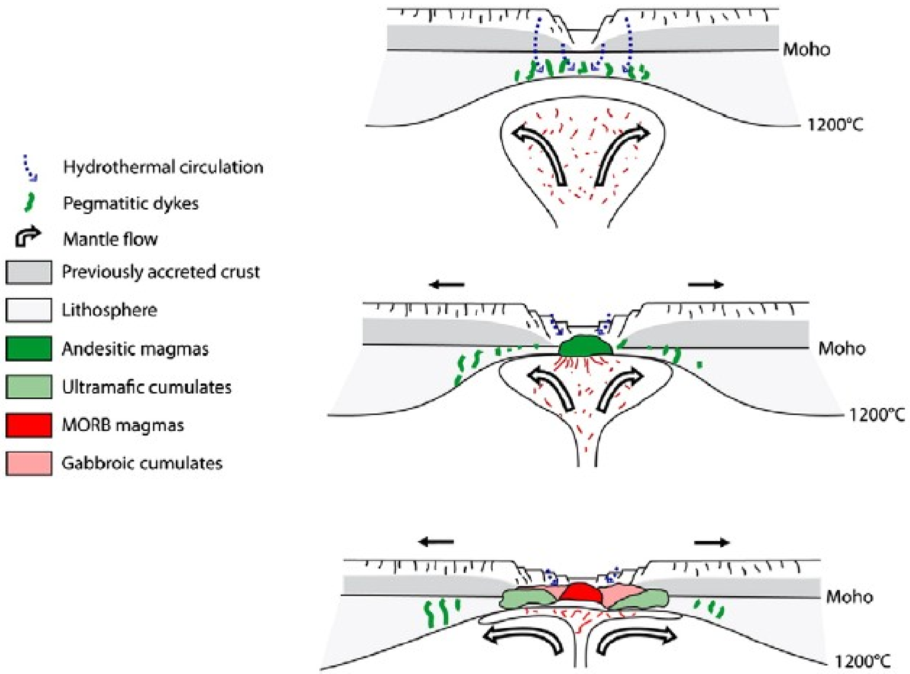
In the asthenosphere, porous flow is the main melt migration process.

Dyking occurs at high temperature but is restricted to the lithosphere.

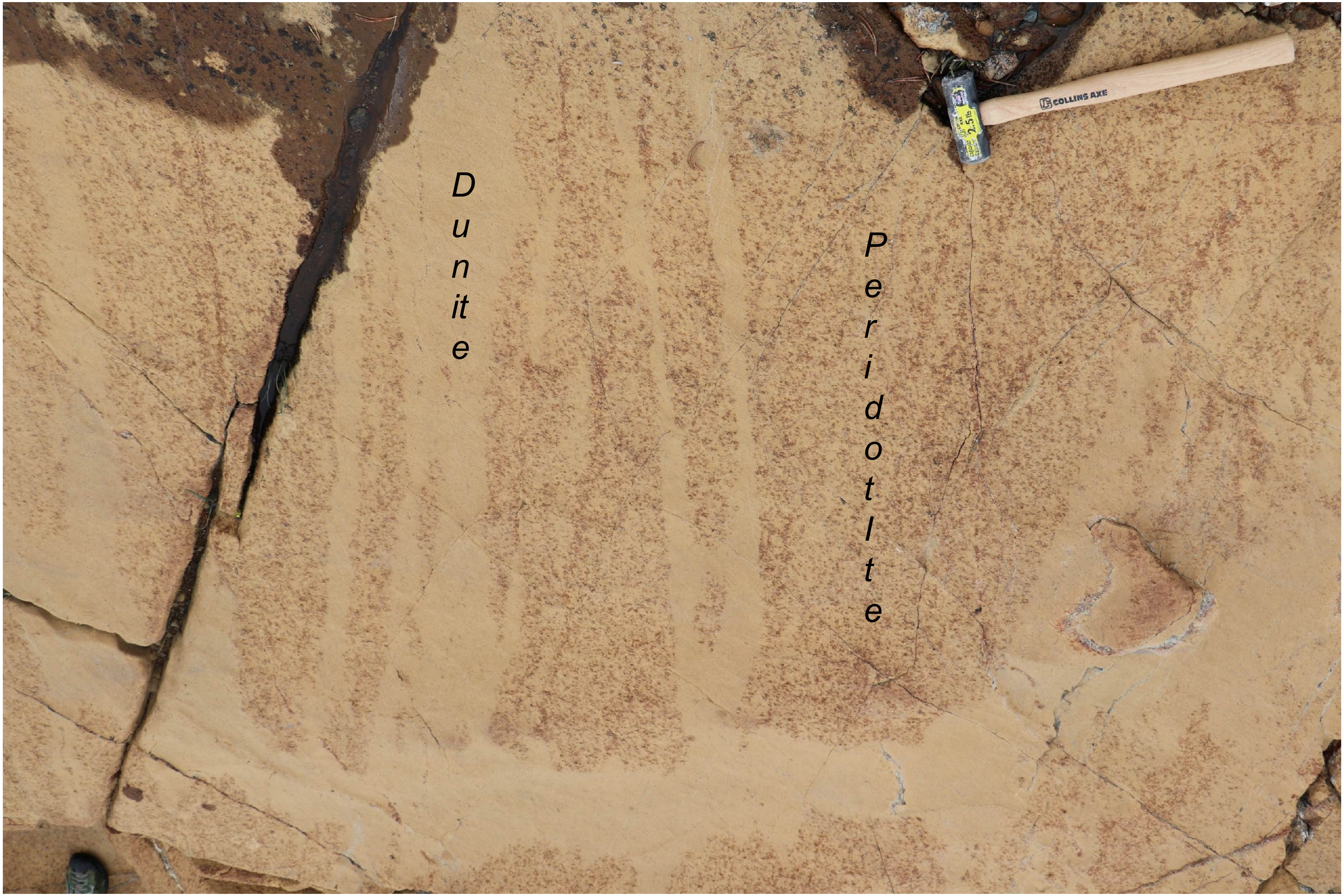
Dykes are more abundant than porous flow structures in ophiolites because:

(1) Diapirism is a periodic process and to preserve cores of diapirs frozen at Moho level below a paleo-ridge is unlikely… but occurred in Oman!

(2) Most melt crystallization occurs in the grabbro field → in dykes rather than in porous flow channels.



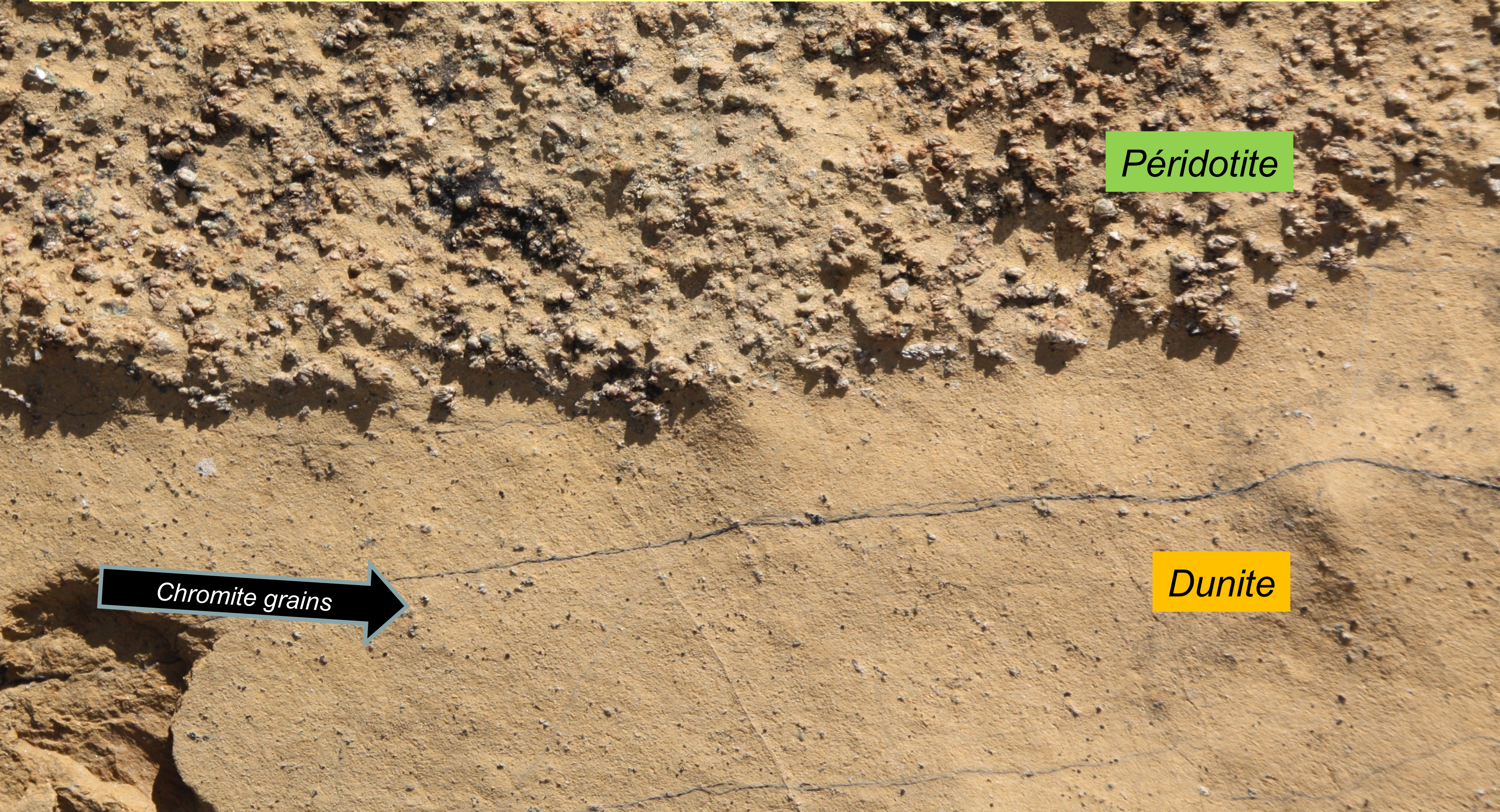
Porous flow is (highly) assisted by infiltration melting.


Dunite
PeridotIte
COLLINS AXE

$(Mg,Fe)SiO_3$ (Opx) + Melt-1 = $(Mg,Fe)_2SiO_4$ (Ol) + Melt-2

Melt-2 = Melt-1 + SiO_2 (+ minor and trace elements incompatible in olivine)

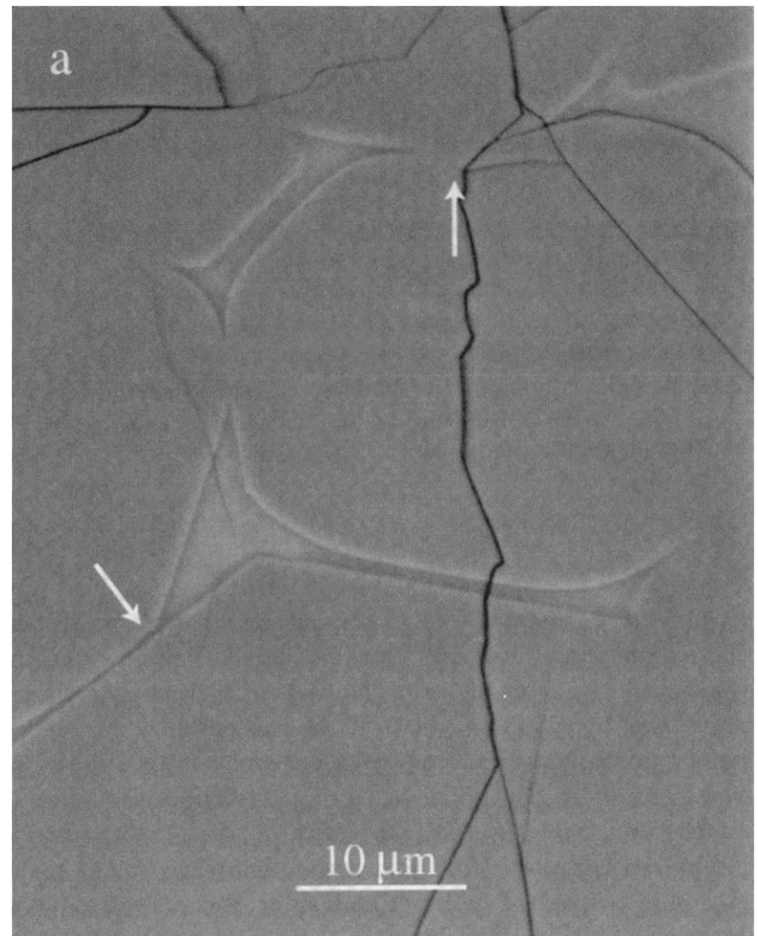
Pyroxenes are the main reservoir of incompatible elements in mantle peridotite→ the dunitification reaction leads to the re-mobilization of (almost!) all the elements from the Mendeleev table.



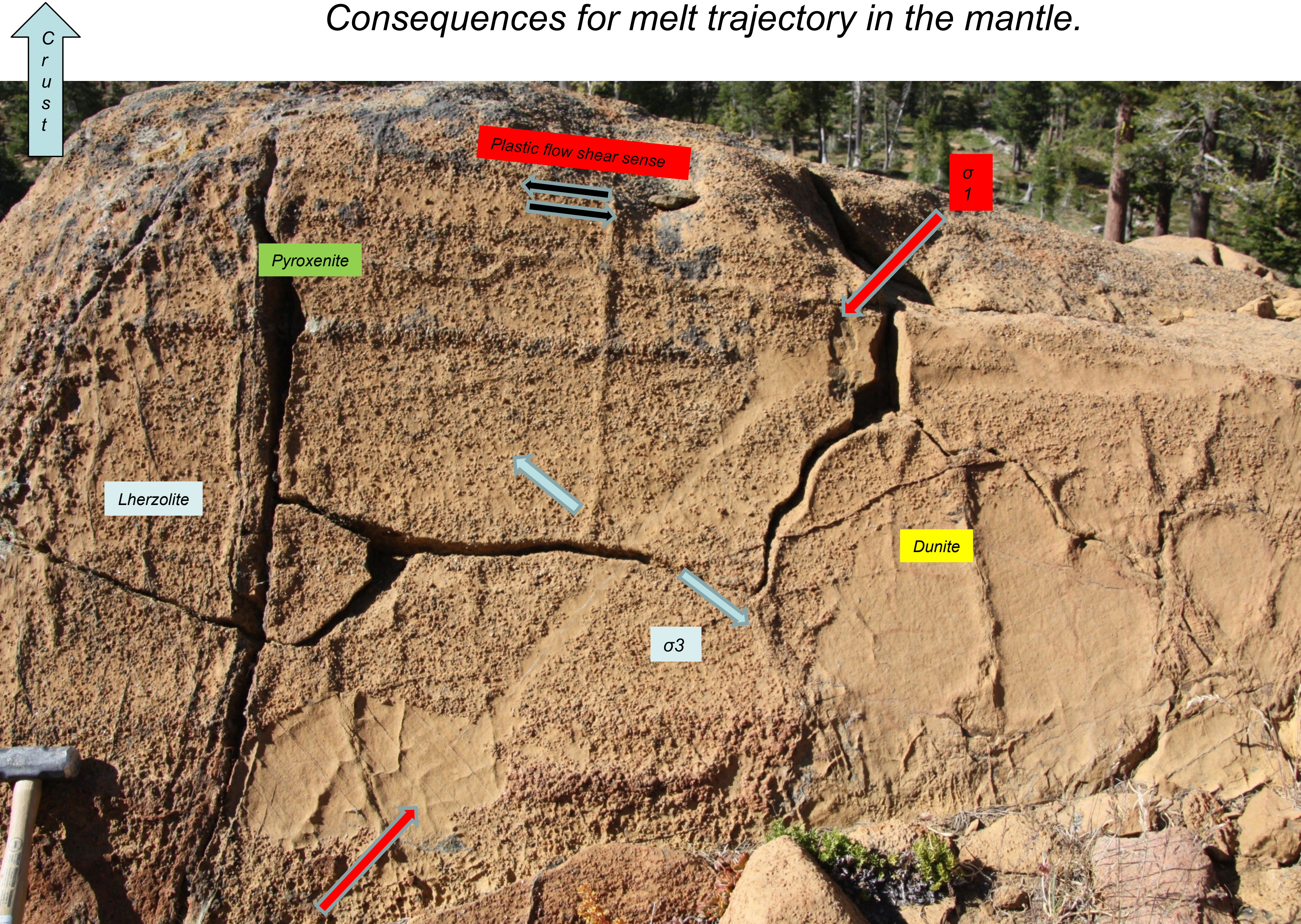
Pyroxene dissolution increases the porosity.

It also increases the permeability due to wetting properties of olivines.

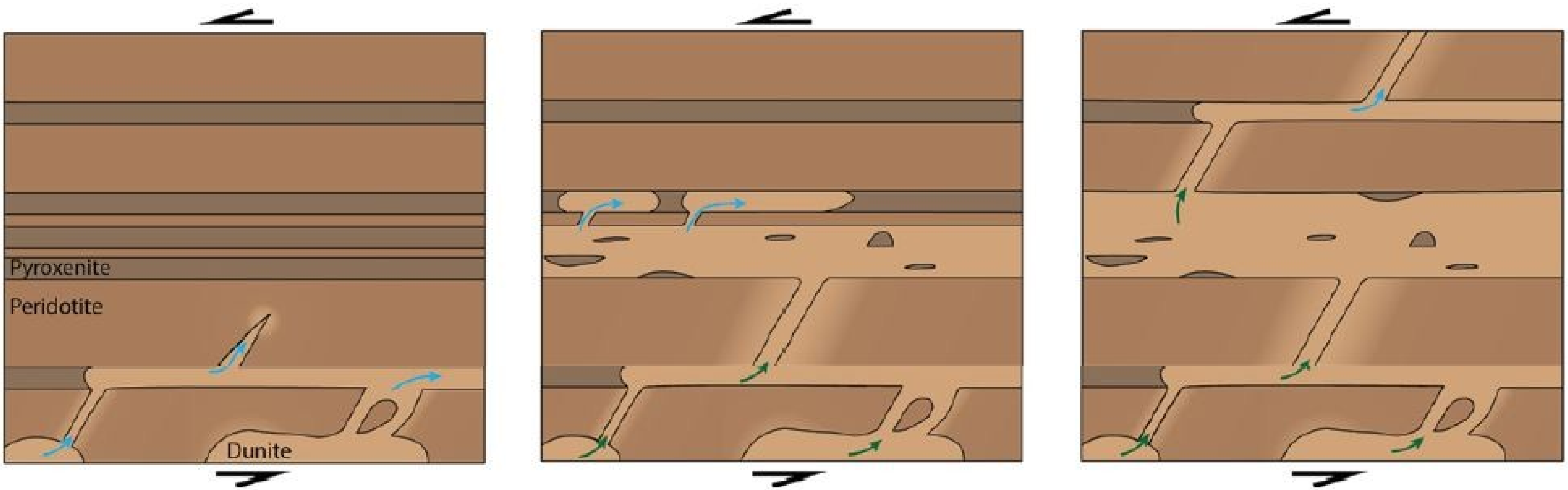
→ Dunite formation enhances the efficiency of melt migration.



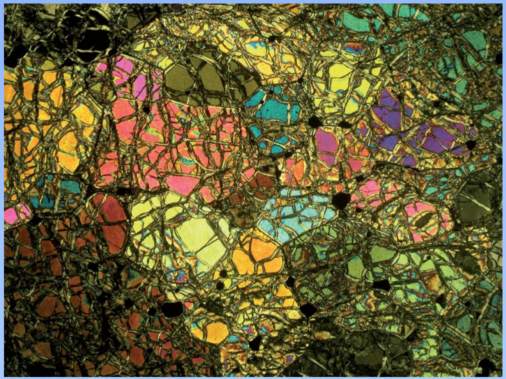
Consequences for melt trajectory in the mantle.

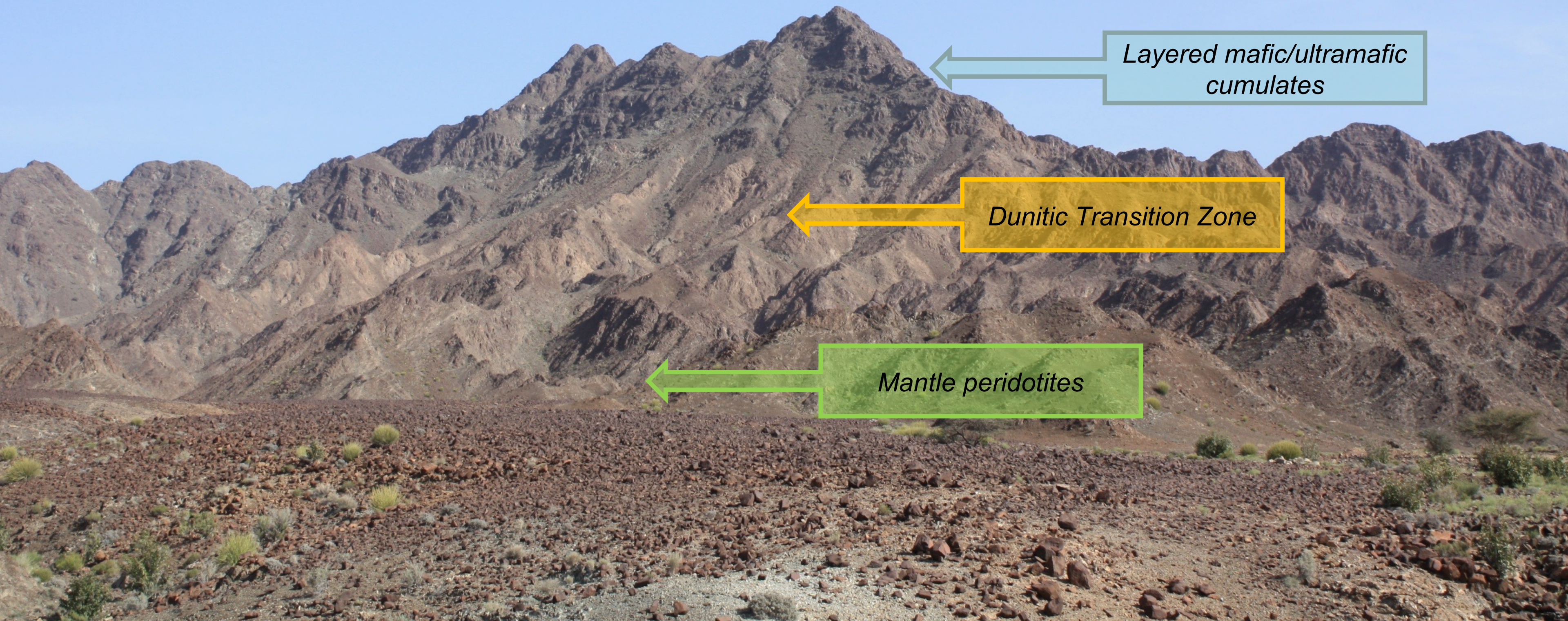


Possible melt migration pattern beneath mid-ocean ridges.

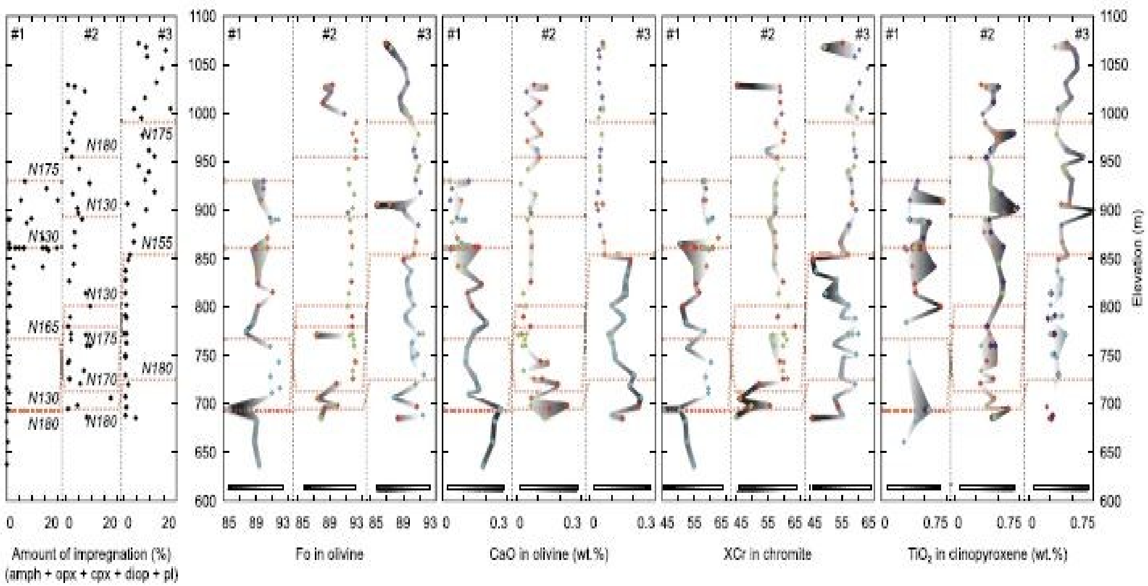


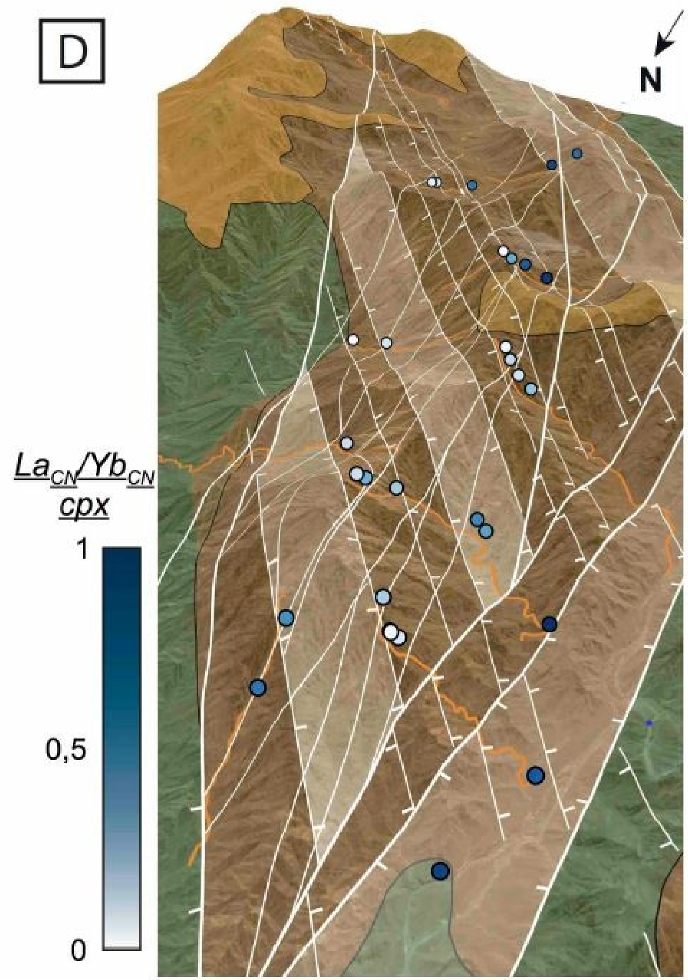
The unexpected occurrence of a mysterious dunitic transition zone, a few hundred meters thick, between the layered gabbroic crust and the residual mantle peridotite.





Geochemical cross sections interpreted in their structural context.

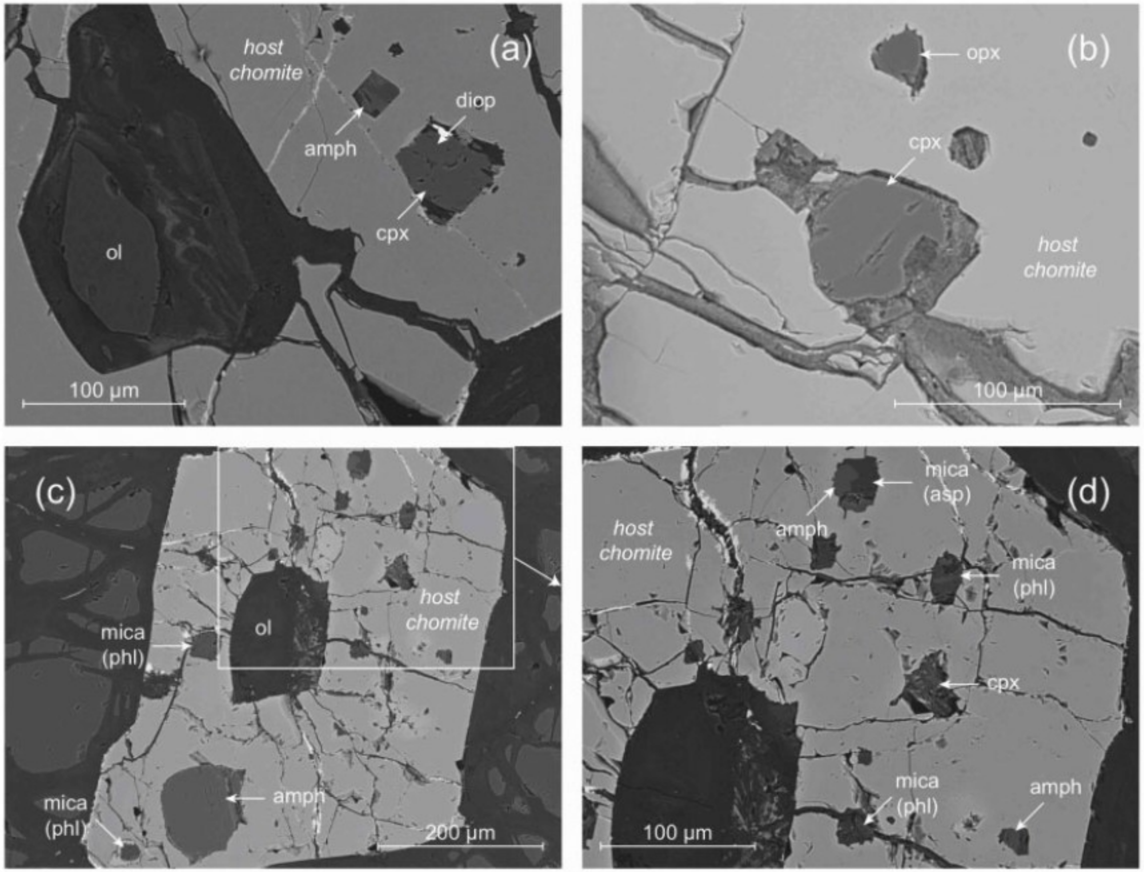




What is the petrological nature of the corrosive melt-1 ?

Present paradigm: the corrosive melt is just a common basalt produced at high pressure but no more in equilibrium with pyroxene at low pressure. It is not fully satisfactory.

Chromite grains crystallized during the genesis of dunite entrap mineral inclusions whose nature (pargasite, micas, diopside, ...) call for an « exotic » corrosive agent, rich in water and alcalic elements, hybrid between basaltic melts and hydrothermal fluids, forming thanks to synmagmatic faults.

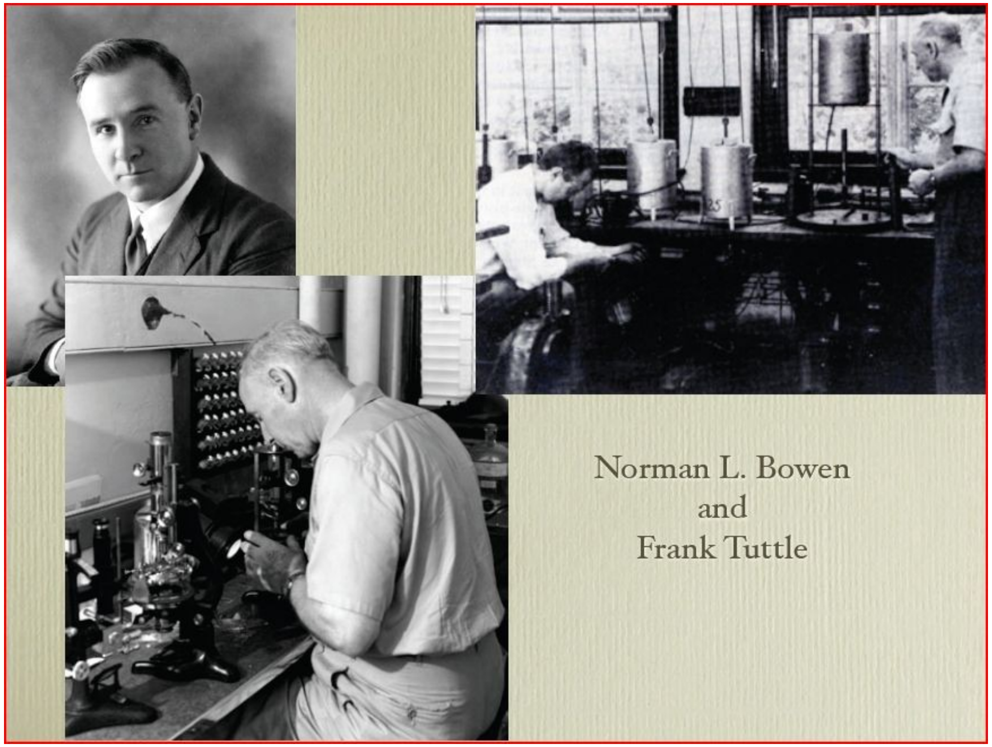


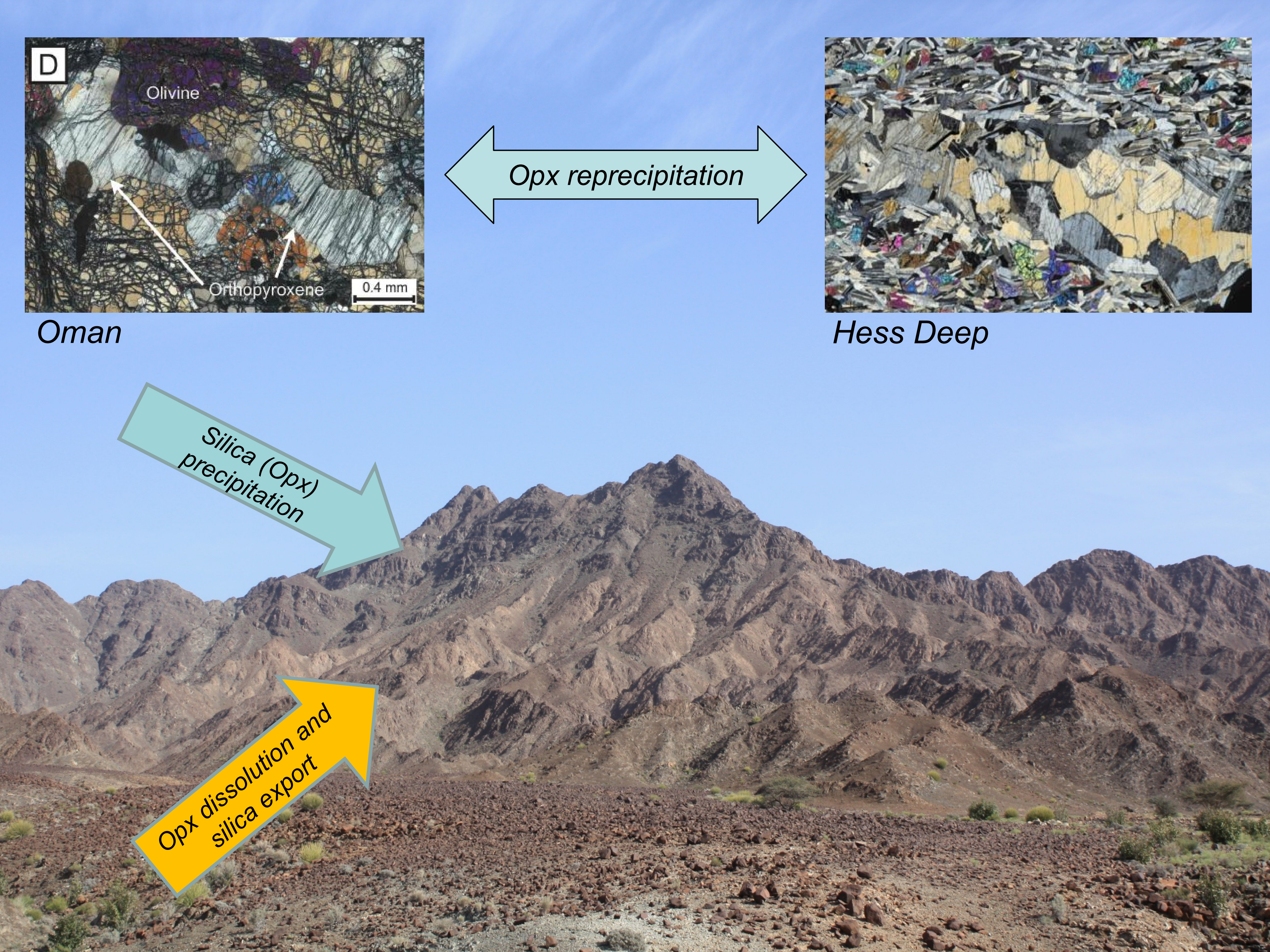
A hydrous origin of dunites was suggested a long time ago, fortuitously, on the basis of experiments … that failed!

“We pointed out that silica was abstracted from some of our charges by water vapour and that special precautions were necessary to prevent this transport of SiO2.”

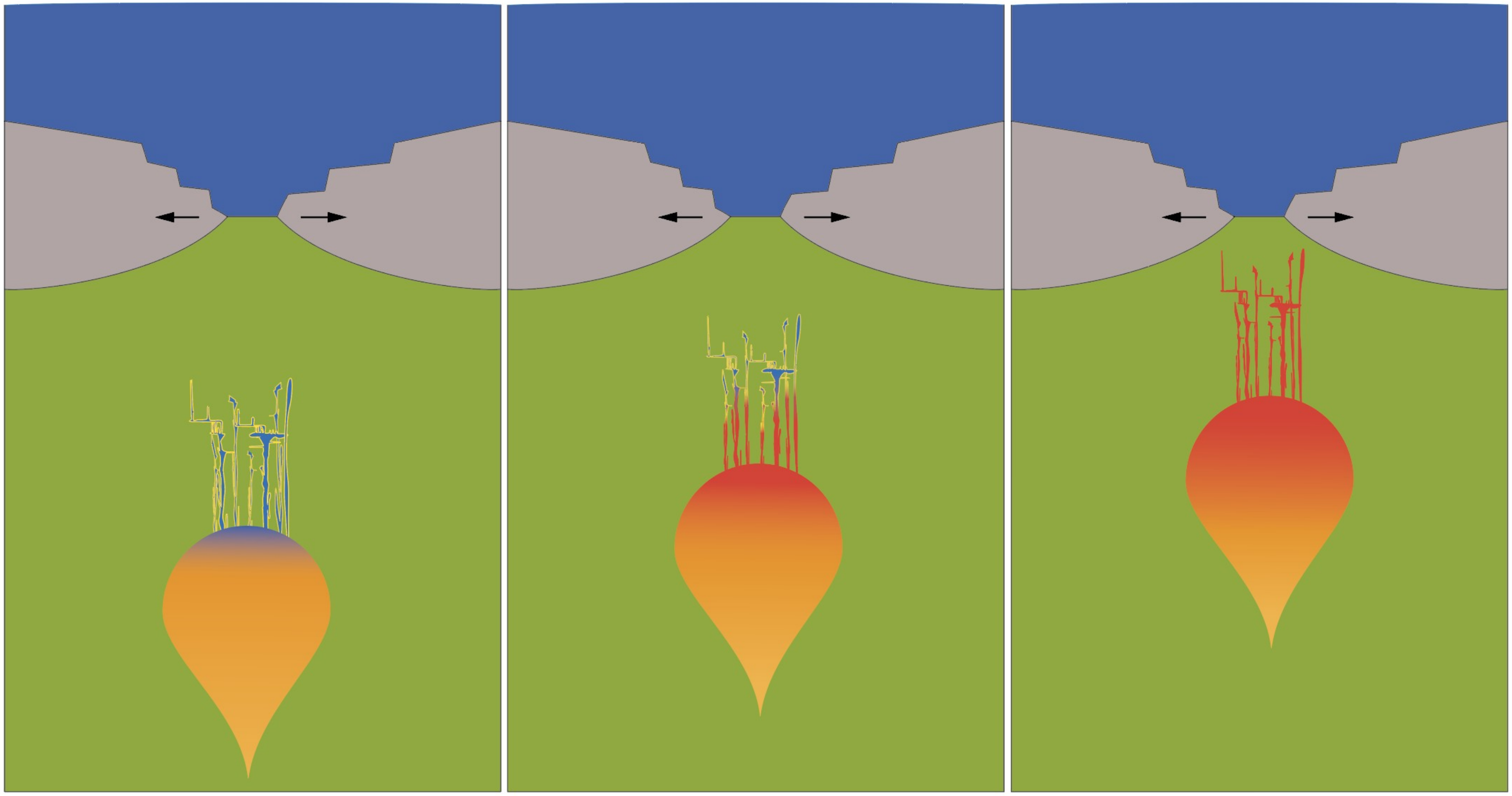
“After heating synthetic enstatite at 725°C and 22,500 lbs/in2 pressure of water vapour for two days it was found that some of the enstatite was transformed to forsterite, when no precautions were taken against removal of silica by water vapour.”

Bowen and Tuttle (1949).




D
Olivine
Orthopyroxene
0.4 mm
Oman
Opx reprecipitation
Hess Deep
Silica (Opx) precipitation
Opx dissolution and silica export

The corrosive « pioneer » melt can also comme from the depths.



Water peridotite interaction is still active in Oman … at low temperature.


Hydrogen and methane production by serpentinization.
Source of energy for our kids ?

Take home message.

The Moho at mid-ocean ridges is the place of intense interaction between magmas, hydrothermal fluids and rocks from the shallow mantle and deep crust.

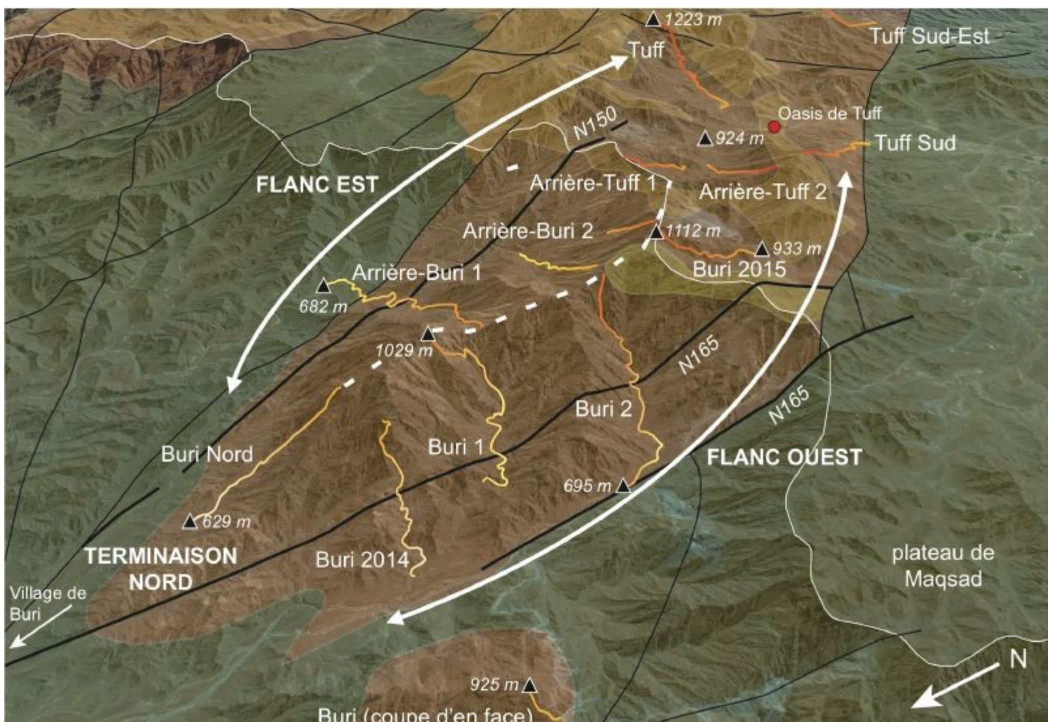
It is made possible thanks to faults acting in a wide T° and depth range, including synmagmatic faults at Moho level.

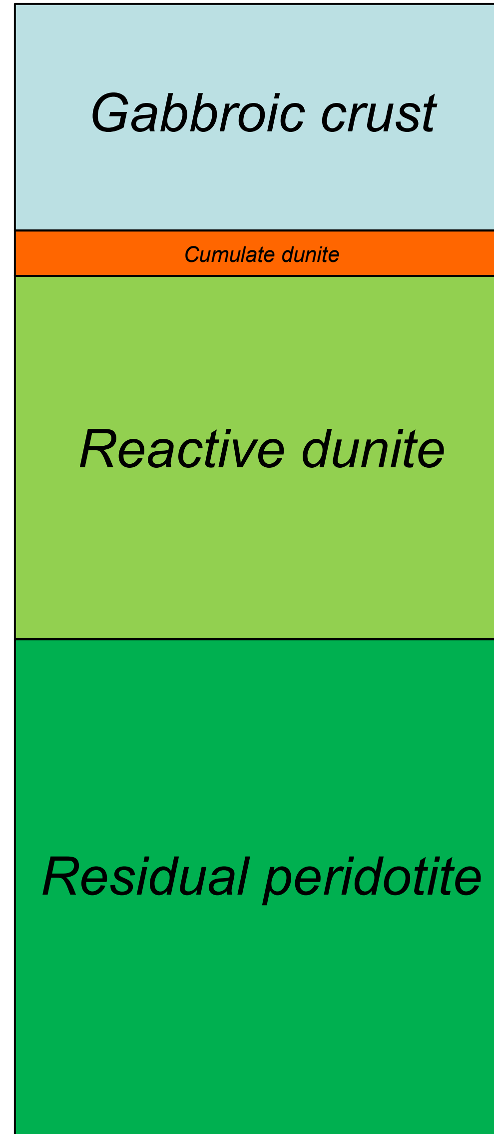
The initiation of infiltration melting is triggered by the formation of a pioneer melt hybrid between basalt and hydrothermal fluids, highly corrosive for pyroxenes.

These processes lead to the redistribution of most chemical elements and have an impact, likely major, on the global geochemical cycles.

The melt trajectory in the mantle results from a competition between the stress field and petrological reactions and is highly sensitive to the presence of lithological heterogeneities.

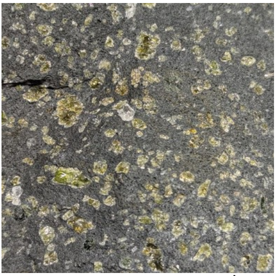
Our conclusion





Possible origins of the dunitic transition zone (DTZ)

Gabbroic layered crust
Cristallization and of a basaltic melt



Hypothesis 1

DTZ = Cumulate dunites

Petrological Moho

Mantle peridotite
Residue of partial melting

Seismic Moho

Gabbroic layered crust
Cristallization of a basaltic melt

Petrological Moho

Hypothesis 2

DTZ = Reactionnal dunites

Mantle peridotite
Residue of partial melting

Consequences

. Mg-rich magma and very hot mantle source.
. DTZ is just a zone of crystal accumulation.
. Weak geochemical impact.

Consequences

. Mg-poor magma and colder mantle source.
. Quite corrosive melt percolating in the DTZ.
. The DTZ is a reactive filter.
. Huge geochemical impact.