Università di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE SM62

Percorso Esplorazione Geologica

Anno accademico 2022 - 2023

Geologia Marina 953SM

Parte IV

Modulo 4.6 Manifestazioni del movimento di fluidi nei sedimenti. circolazione idrotermale delle dorsali oceaniche

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Factors that determine excess pore water pressure and influence the consolidation state

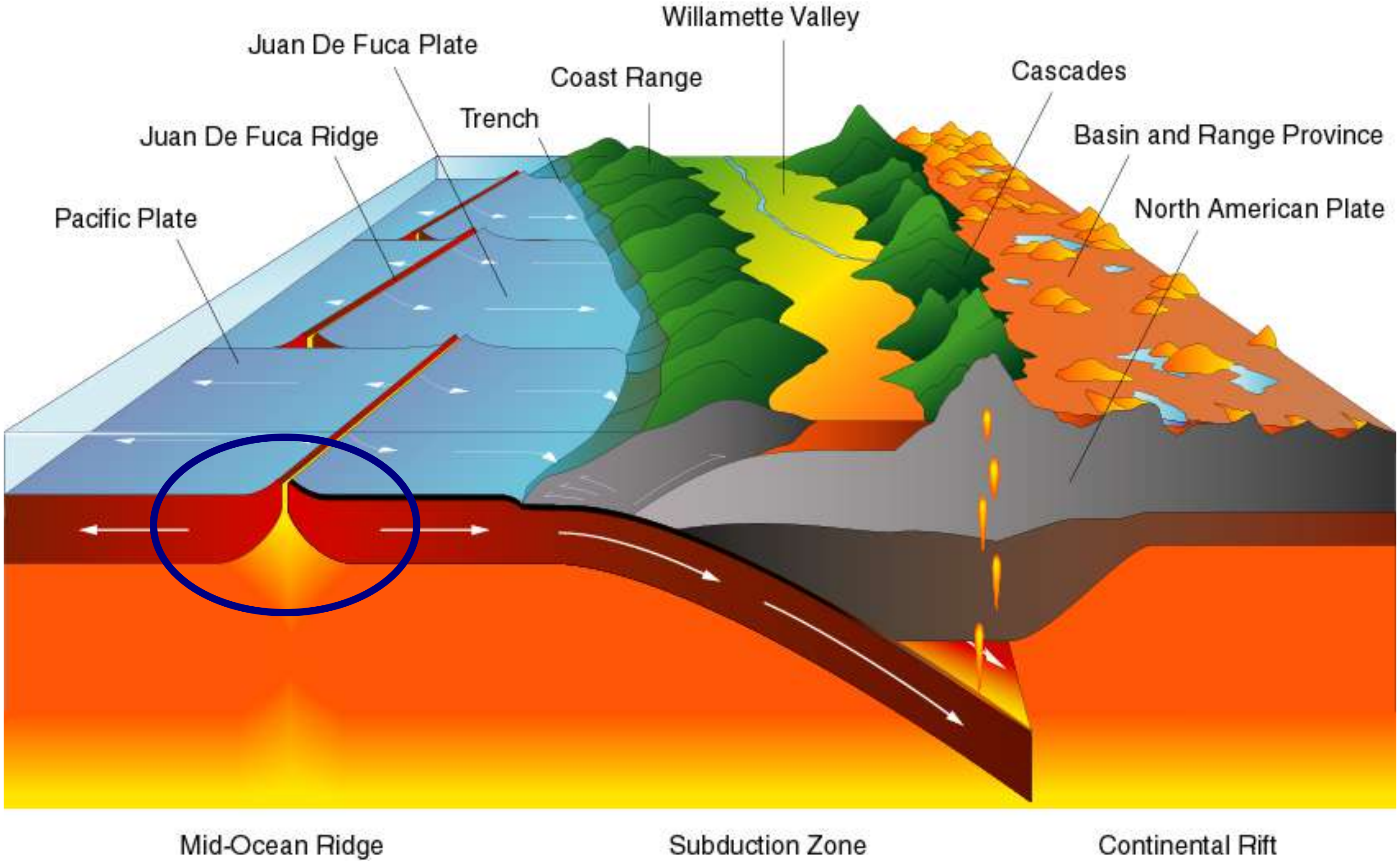
The most common factors are:

- **Stress-related factors**
  - Rapid sedimentation rate
  - Tectonic stress
- **Fluid volume increase mechanisms**
  - Temperature increase
  - Mineral transformation
  - Hydrocarbon Generation
- **Fluid movement mechanisms**
  - Osmosis
  - Hydraulic head
  - Hydrocarbon buoyancy

(**Swarbrick and Osborne, 1998**. Bryant et al., 1974; Sangrey, 1977; Arthur et al., 1980; Demaison & Moore, 1980; Bryant et al.,1981).

Temperature increase

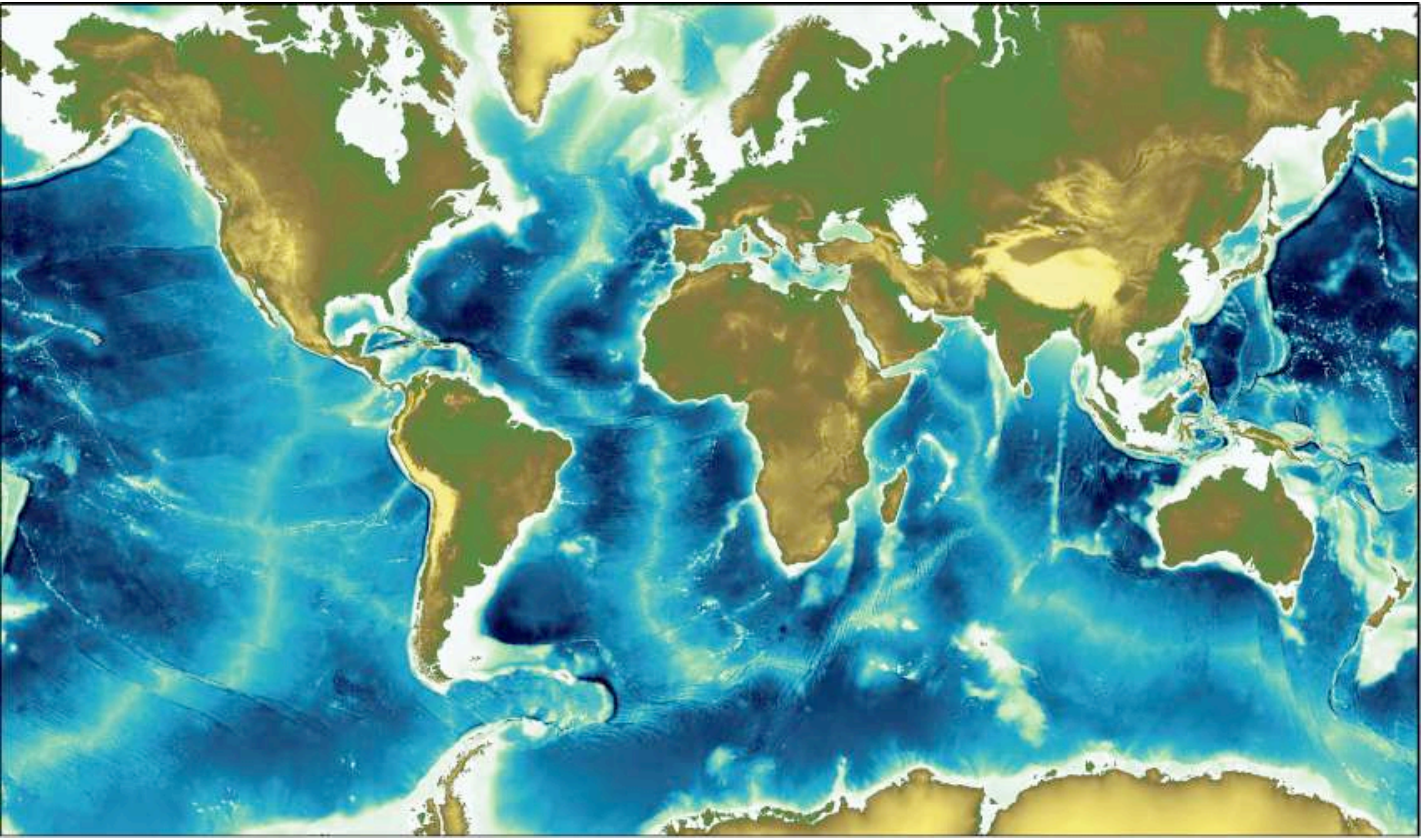
Heat transfer at mid-ocean ridges



Mid ocean ridges (spreading centres) are present in all oceans. The spreading rate is fast in the Pacific, and slow in the Atlantic

Temperature increase

Heat transfer at mid-ocean ridges



Compressibility of water

Compressibility: is a measure of the relative volume change of a fluid or solid as a response to a pressure (or mean stress) change.

Compressibility: $$\beta = -\frac{1}{V}\frac{\partial V}{\partial p}$$ where *V* is volume and *p* is pressure

At 0 °C the compressibility is **$5.1 \cdot 10^{-5}$ bar^{-1}**
As the pressure is increased the compressibility decreases, being **$3.9 \cdot 10^{-5}$ bar^{-1}** at **0 °C** and **1000** bar.

The low compressibility of water leads to them often being assumed as **incompressible**. The low compressibility of water means that even in the deep oceans at 4000 m depth, where pressures are $4 \cdot 10^7$ Pa, there is only a 1.8% decrease in volume.

Fine and Millero, 1973

Temperature increase

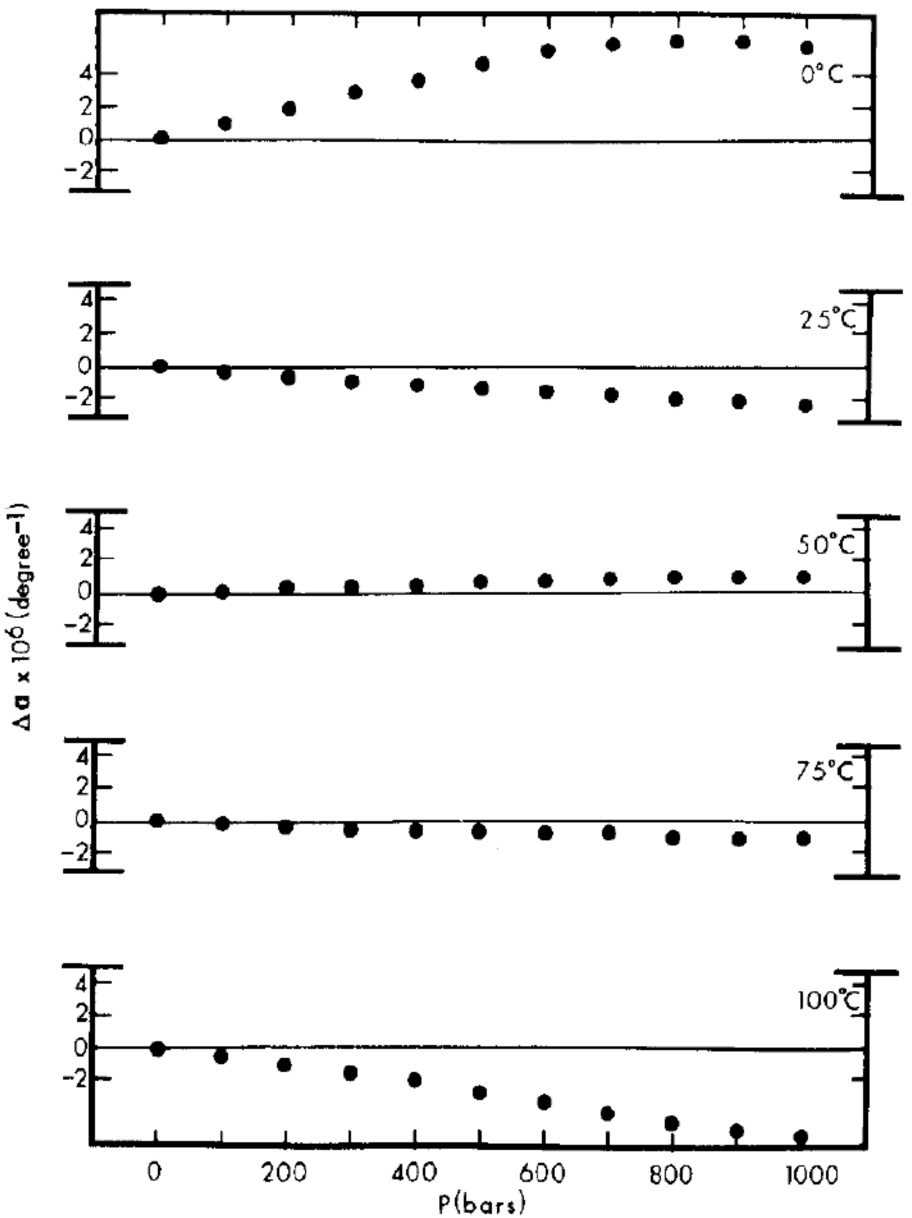
Aquathermal Expansion of water

Thermal expansion:

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)$$

where V is volume and T is temperature

Typical value $5 \cdot 10^{-4}$ °C^{-1}



Fine and Millero, 1973

Temperature increase

If a body of water is **SEALED** in a vessel, the pressure will increase rapidly if temperature rises above +4ºC.

E.g. Pressure increase of 55MPa from heating sealed water from 54 to 93ºC (caused by a volume increase of 1.65%!)

The problem is that in nature, **absolute sealing of water in geological formations is practically impossible**. In addition, the reduction of viscosity of water during heating, facilitates its escape through pores and fractures even at low permeability.

Numerical modelling shows little overpressure in muds with extremely low permeability ($3 \cdot 10^{-14}$ mD)

Only cementation can provide a seal that is nearly absolute.

Swarbrick, and Osborne, 1998

Temperature increase

Sub-surface boiling and supercritical water

In deep sedimentary basins with total depths beyond 10 km, it is conceivable that pore waters can locally (and perhaps temporarily) achieve temperatures of **400 °C** or more.
(assume an average geothermal gradient of 40ºC km^{-1})

When the pressure is too great for water to boil **(>221 bar** for pure water, and **>300 bar** for normal seawater), it attains the supercritical phase, which is neither steam nor liquid, but something in between.
(assume an hydrostatic gradient of 100 bar km^{-1})

Near the critical point on the boiling curve, the density of water changes rapidly, and is intermediate between that of liquid water (1 g cm^{-3}) and low-pressure water vapour (<0.001 g cm^{-3}).

At typical supercritical conditions, the density is approximately **0.3 g cm^{-3}**

Hovland et al., 2006

Temperature increase

Sub-surface boiling and supercritical water

Hydrogen bonding is reduced in supercritical water (non-polar fluid)

Supercritcal water can be regarded as a non-polar fluid that is able to **dissolve organic liquids (oils)**, but **unable to dissolve common sea salts.**

Supercritcal water is also highly **corrosive to silicate rocks**, a property that is of particular importance when studying deep hydrothermal systems and alteration of rocks and sediments.

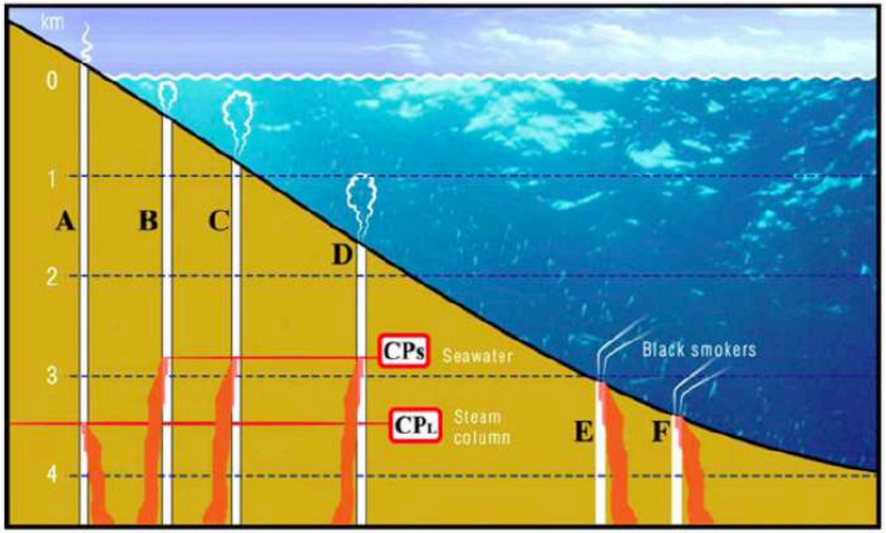
Martin Hovland proposes that many deeply rooted piercement structures, like mud volcano, mud diapirs, asphalt volcanoes, can be triggered by supercritical water movement in rocks.

Hovland et al., 2006

Temperature increase

Geological conditions for supercritical water flow:

1) A deep sedimentary basin >10 km deep.
2) An underlying crust, which is either relatively thin (hot), or which contains fault intersections with high heat-flow.
3) Excess water either within the crust or the sediments, which becomes exposed to the anomalous heat sources (at fault intersections).
4) Local anomalously high or increasing temperature gradients with depth.



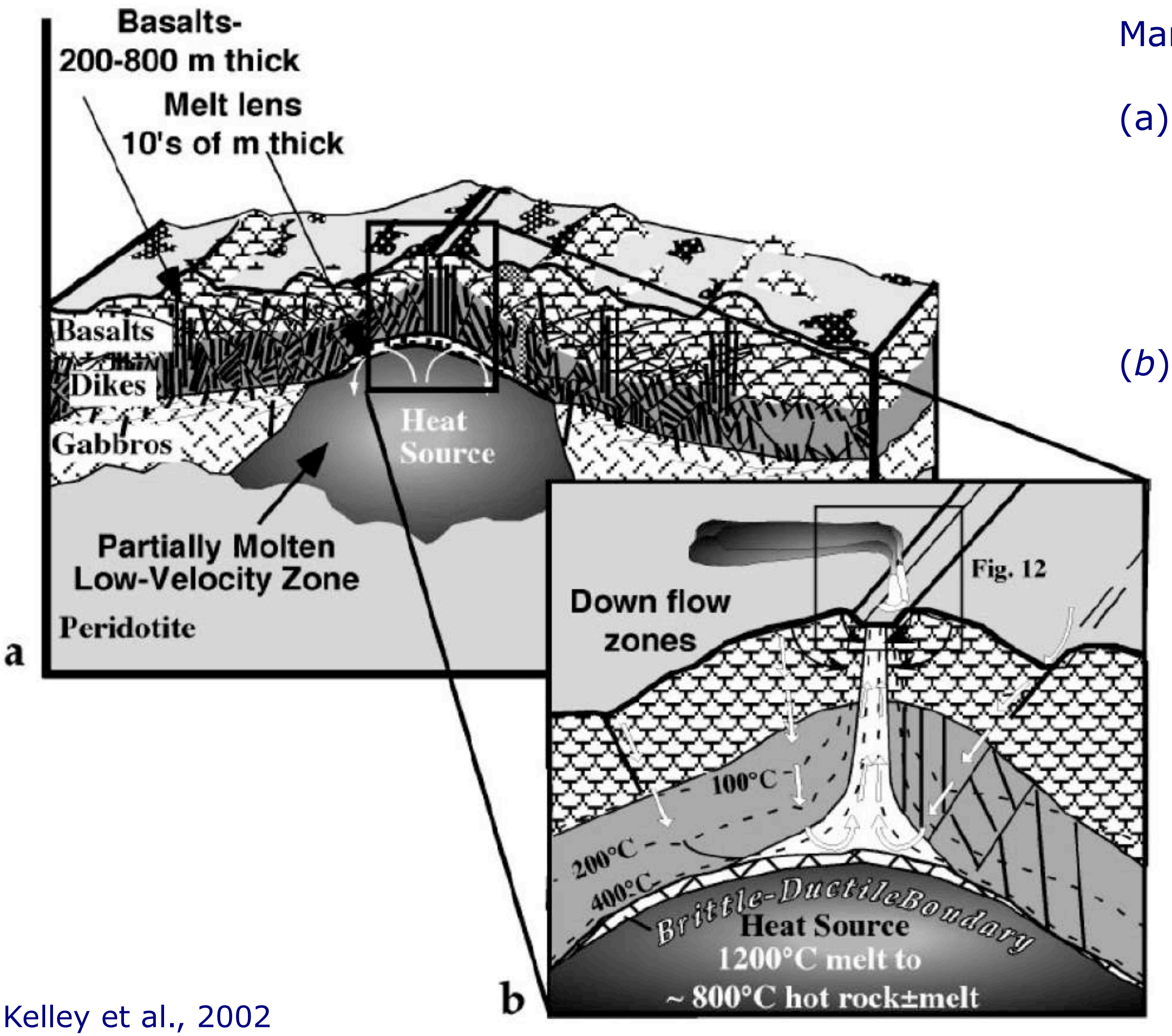
CP = Critical Point

Column A shows the association between boiling fresh water and depth on land. The steam column forms above a deep-lying heat source (>374ºC) and the CP occurs deeper than 3 km, because the density of the steam column is low.
In the ocean, beneath a cold seawater column, above a deep-lying heat source (>405ºC), the CP lies at around 2800m (pressure of about 300 bar). Colums B, C, D have a CP lying at this depth, even though the seafloor depth varies.
The two hot vents E, F have CPs at different depths, as they are both deeper than 2800m and the CP is defined by temperature (cooling by seawater) rather than by depth. These 'black smokers' invariably construct sulphide and silicate chimney structures formed by mineral precipitation as supercritical fluids are instantly cooled by seawater.

Hovland et al., 2006

Temperature increase

Heat transfer at mid-ocean ridges



Kelley et al., 2002

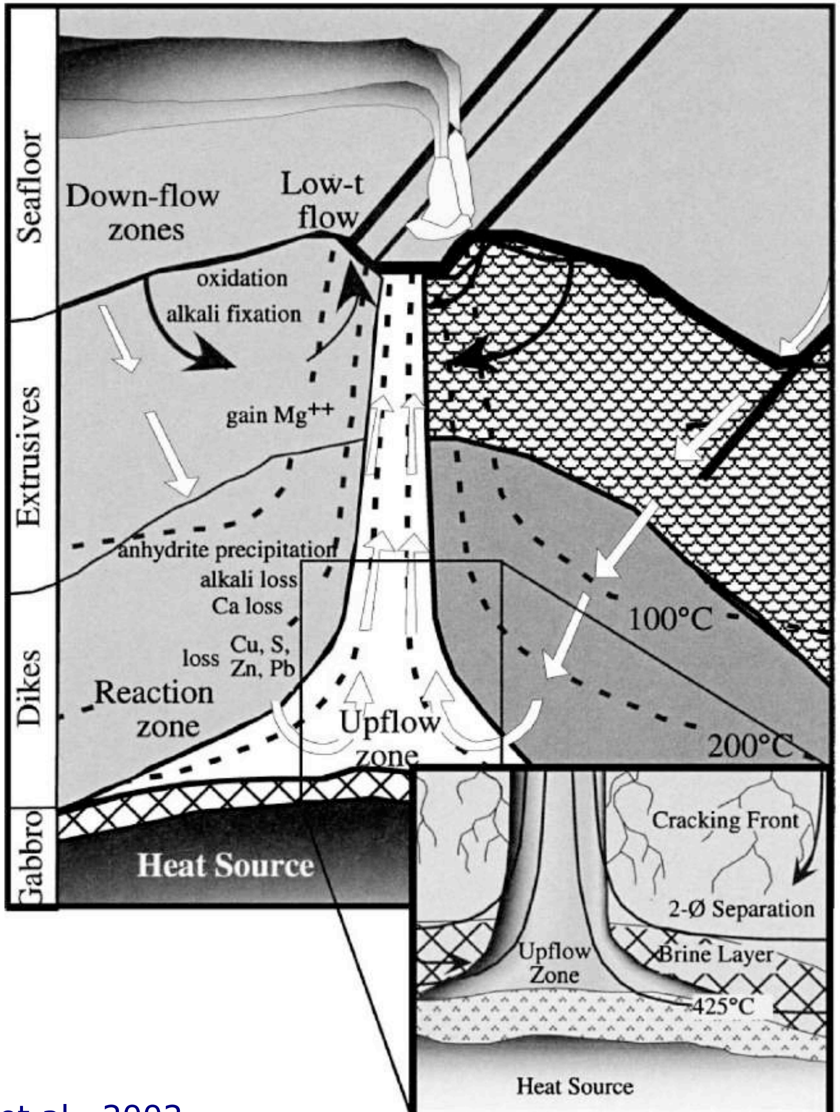
Mantle-crust relationships beneath ridge crests.

(a) Crustal magma chambers, fed from melt percolating through the underlying mantle section, typically form at depths of **1–4 km below the seafloor.**

(*b*) Steep thermal gradients resulting from **intrusion of 1200 degrees basaltic melt** into cool, water-saturated and porous crustal rocks drive hydrothermal circulation beneath the spreading centers. High temperature limbs of the resultant hydrothermal cells focus metal-rich, acidic fluids onto the seafloor, which form sulfide deposits upon mixing with cold, oxygenated seawater.

Temperature increase

Heat transfer at mid-ocean ridges



Kelley et al., 2002

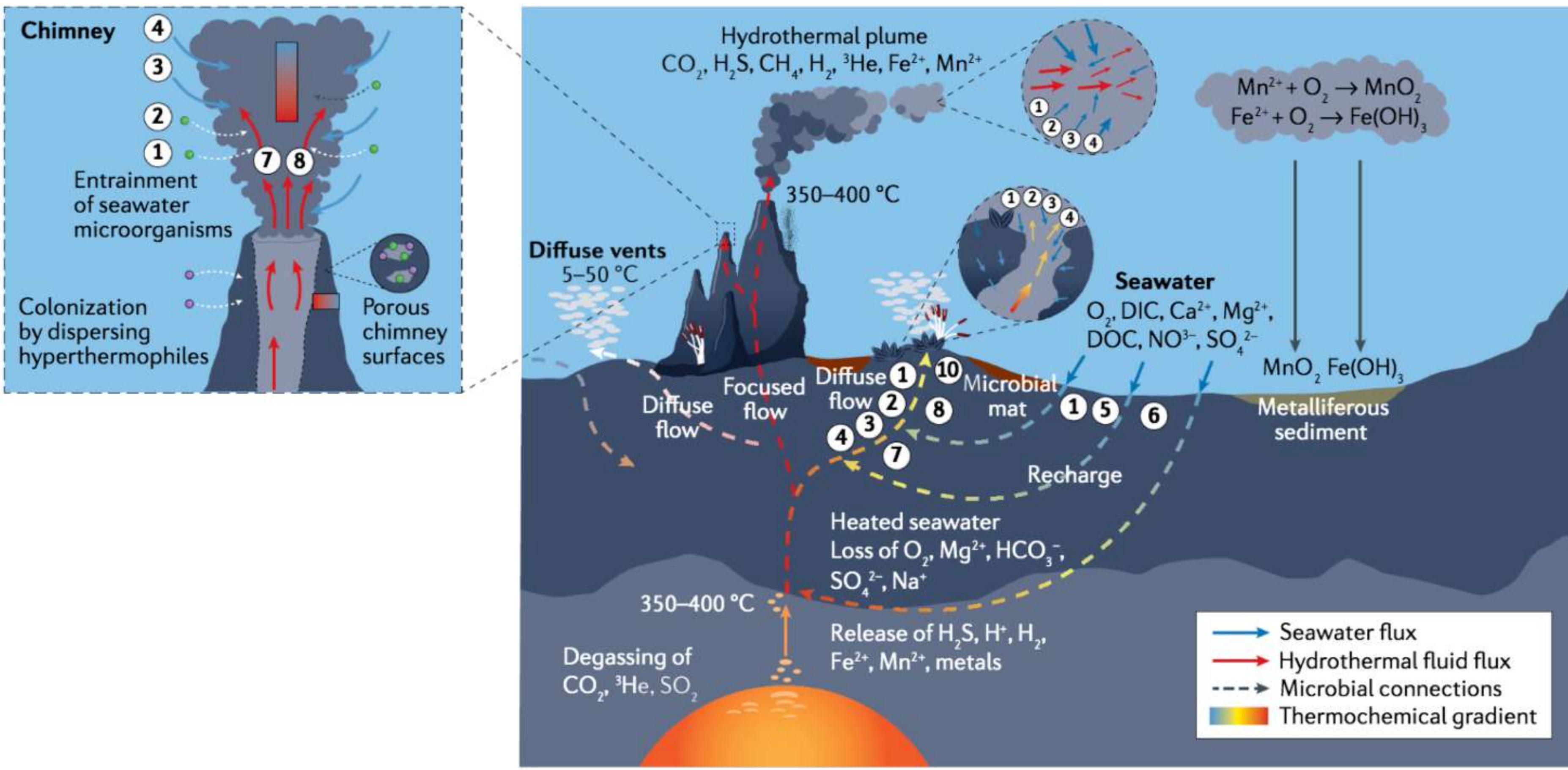
Schematic showing chemical reactions and mineral precipitation associated with down-welling recharge systems, low-temperature shallow circulation, and deep penetration by hydrothermal fluids into the reaction zone.
At the base of many mid-ocean ridge hot springs, the seawater-derived fluids undergo either boiling or condensation.
If condensation occurs for prolonged time periods, a brine layer may develop deep within the crust. These fluids may be expelled during waning of high-temperature hydrothermal flow.

Fluid penetration is believed to occur during downward migration of small fracture networks and cooling of the crust along a cracking front, which allows fluids to have continual access to hot, fresh rock.

Recent review paper:

Früh-Green, G.L., Kelley, D.S., Lilley, M.D. *et al.* Diversity of magmatism, hydrothermal processes and microbial interactions at mid-ocean ridges. *Nat Rev Earth Environ* (2022). https://doi.org/10.1038/s43017-022-00364-y

b Black smoker flow paths, fluid–rock interaction and ecosystems



Main types of submarine hydrothermalism and associated mineralization processes presently recognized within the oceanic crust:

a) Hydrothermal systems of high temperature and formation of massive sulphides
b) Low temperature systems with serpentinization of ultramafic rocks and genesis of abiogenic methane
c) Hydrothermal-hydrocarbon systems associated with intrusive sills in deep oceanic basins
d) Remnant hydrothermalism and Fe-Mn crust formation

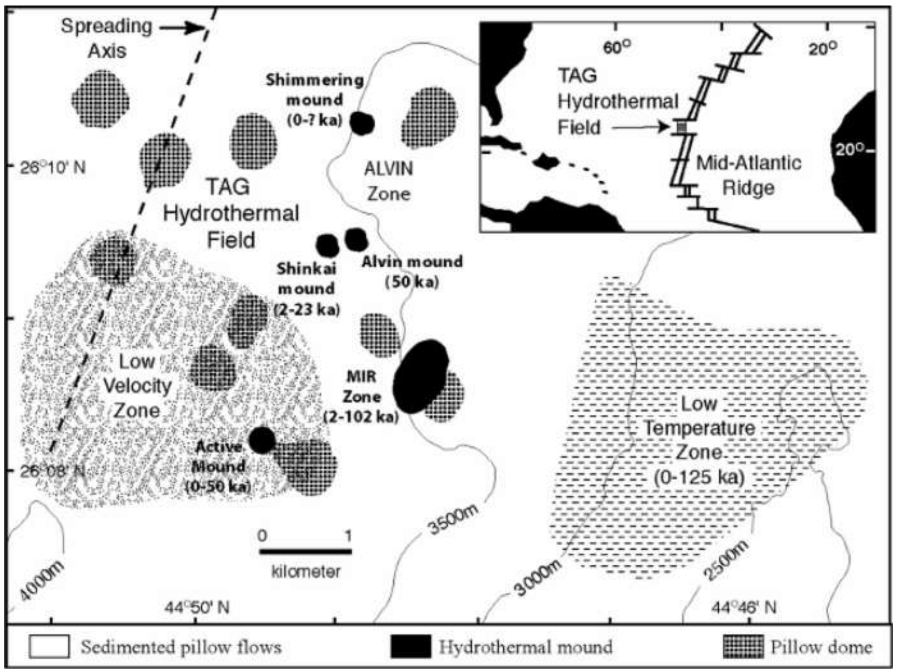
Luis Somoza, IGME

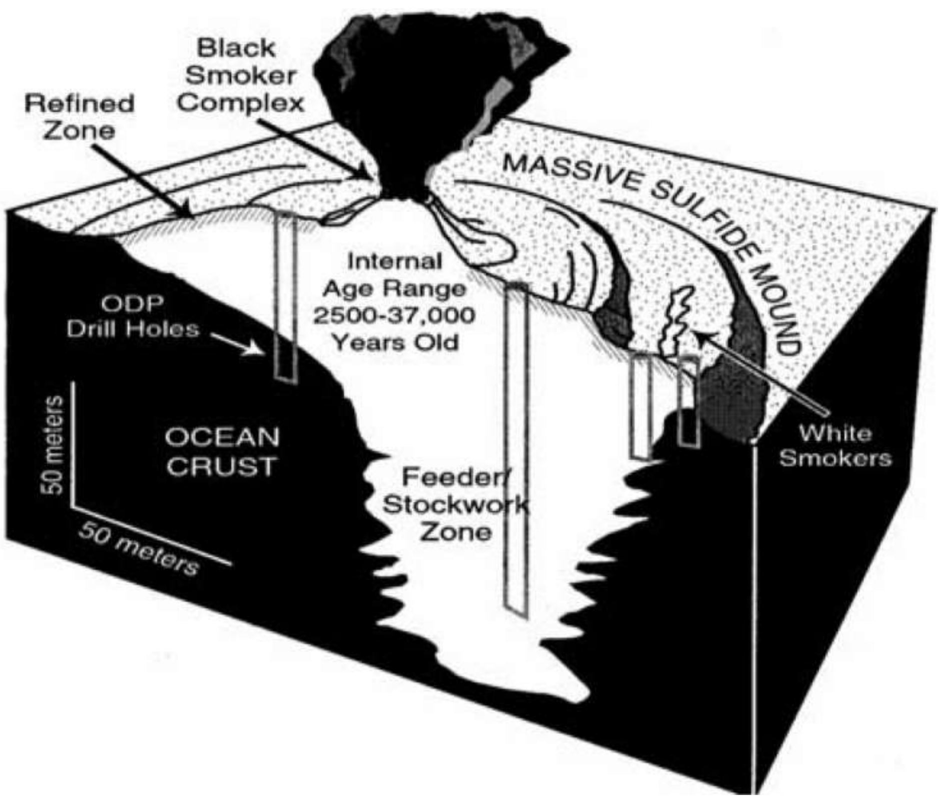
a) Hydrothermal systems of high temperature and formation of massive sulphides

High temperature hydrothermal systems generated along the Mid-Ocean Ridges (MOR) include massive sulphides, metalliferous muds, Fe-Mn crusts and stratabounds. The interest of all these mineral deposits lies in the high contents they present in rare and strategic metals (Au, Ag, Co, Ni, Cu, Zn, Ge, Ga, Te, Li, Mo, In) for technological development (Rona, 2008).

Frequently the formation of these deposits is induced or controlled by microorganisms that catalyze the concentration of certain metals and rare earth elements (Wang and Muller, 2009; Emerson et al., 2010; González et al., 2020).
In the Atlantic Ocean, extensive hydrothermal fields such as *TAG*, *Logatchev* or *Rainbow* have been discovered, among others (Scott, 1997; Charlou et al., 2000; Hannington et al., 2004; Rona, 2008; Wheeler et al., 2013; Cherkashov, 2017; Somoza et al., 2020).

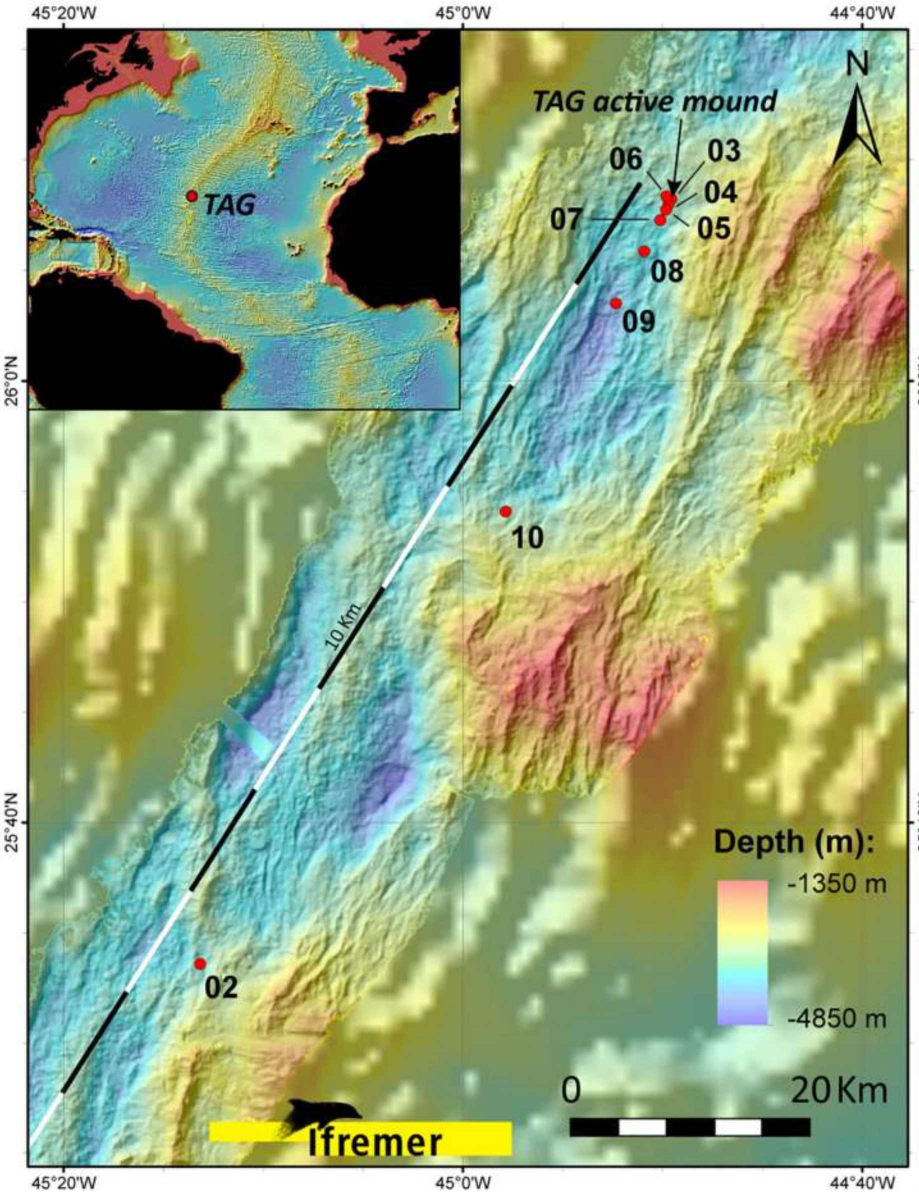
NOAA - TAG Trans-Atlantic Geotraverse project in 1985 (Rona et al., 1986).

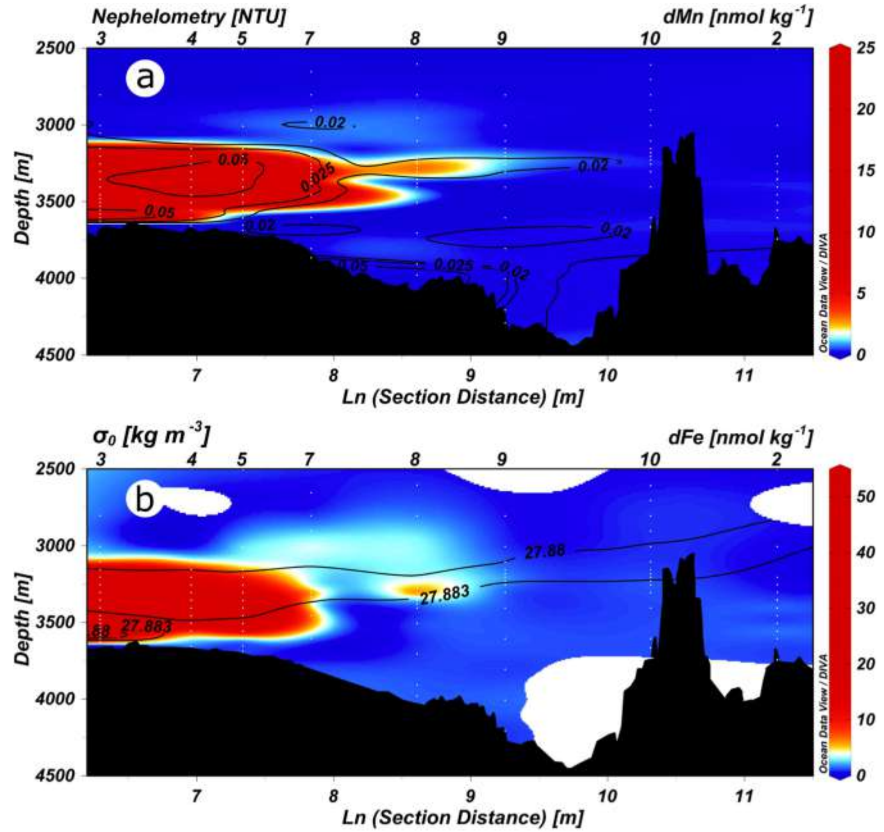




Rona, 2005.

Iron and Manganese Dispersal From the TAG Hydrothermal Plume (Mid-Atlantic Ridge)





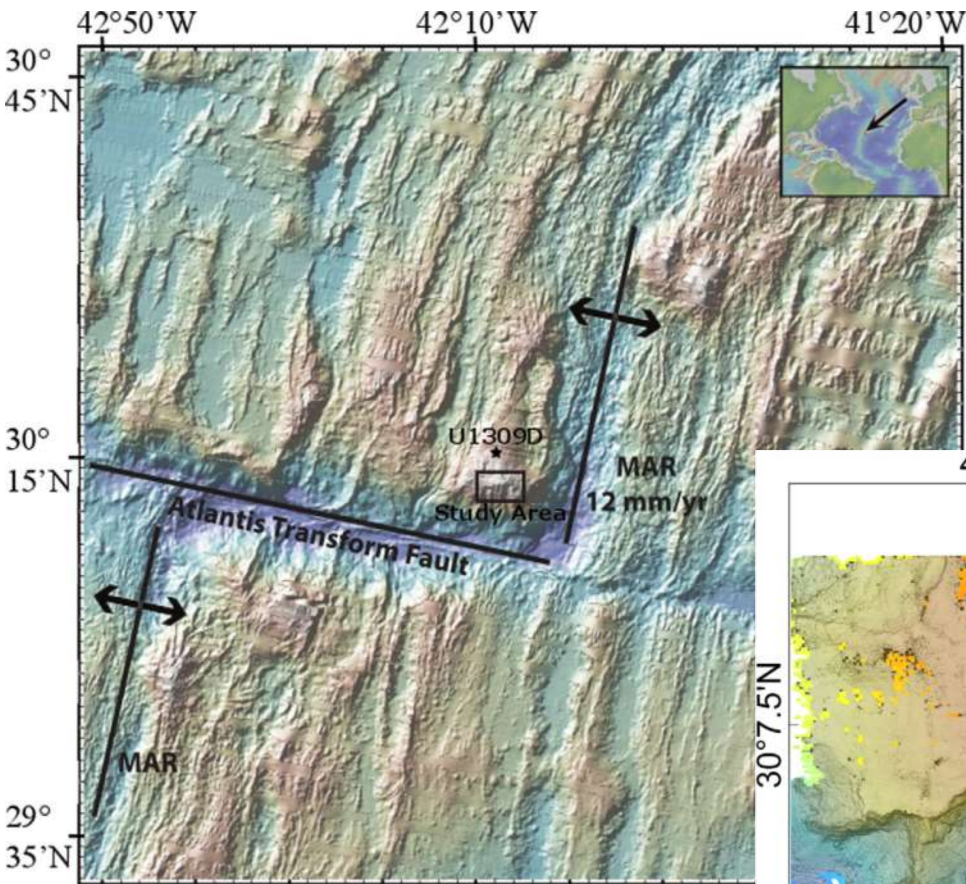
González-Santana &al., 2020 Processes Driving Iron and Manganese Dispersal From the TAG Hydrothermal Plume (Mid-Atlantic Ridge): Results From a GEOTRACES Process Study. Front. Mar. Sci. 7:568. doi: 10.3389/fmars.2020.00568

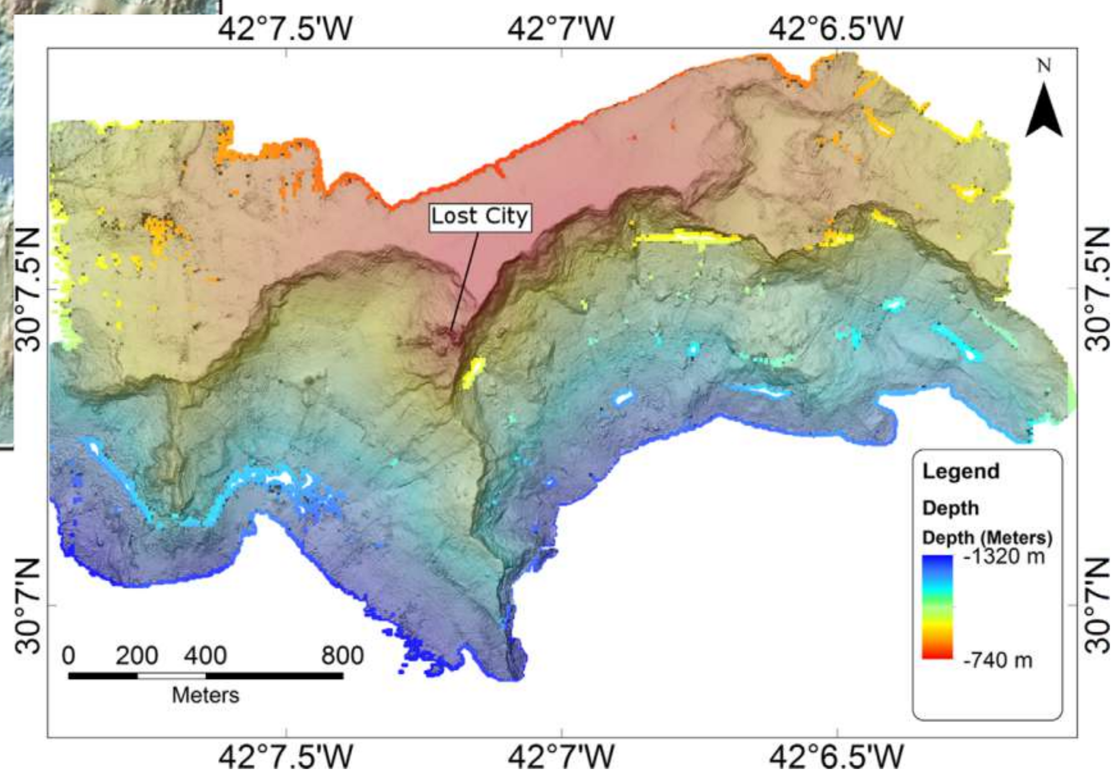
b) Low temperature systems with serpentinization of ultramafic rocks and genesis of abiogenic methane

The development of these types of hydrothermal systems has been observed in relation to transform faults off-axis, such as the *Lost City* complex (31ºN).

It is characterized by the presence of carbonate derived from abiogenic methane produced during the serpentinization processes of mafic and ultramafic rocks of the oceanic lithosphere forming mounds and chimneys (Charlou et al., 1998). The serpentinization processes in peridotitic rocks produce large amounts of H2 that can theoretically react with CO2 or CO to form hydrocarbons through Fisher-Tropsch Type synthesis, with massive production of CH4 without prior biological mediation (Apps and van de Kamp, 1993).
The importance of this process is that a similar mechanism of methane genesis without the intervention of any kind of life, including microbial life, has been invoked to explain the amounts of CH4 detected on Mars.

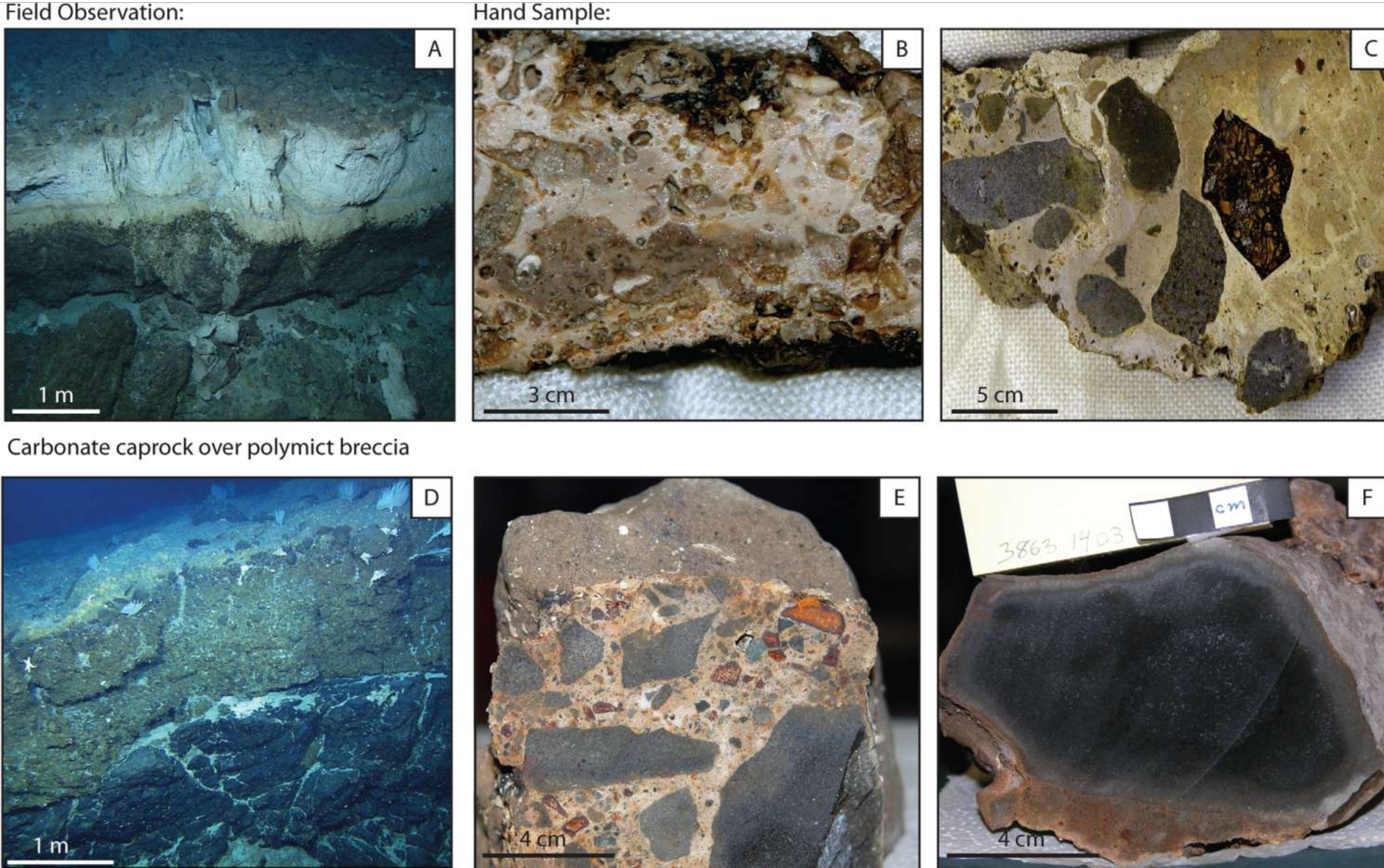
Lost City complex (31ºN).





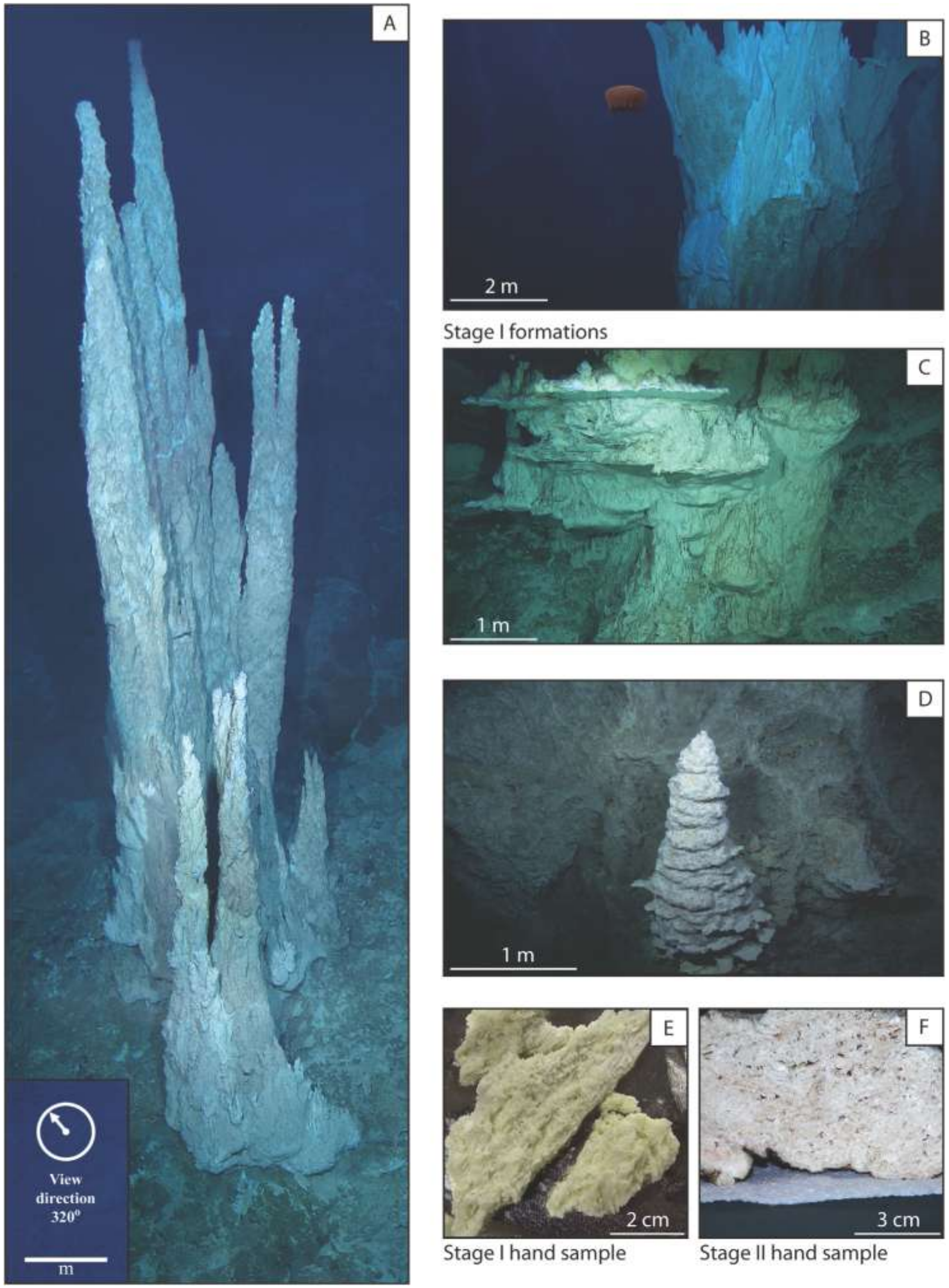
Denny et al., 2015

Lost City complex (31ºN).

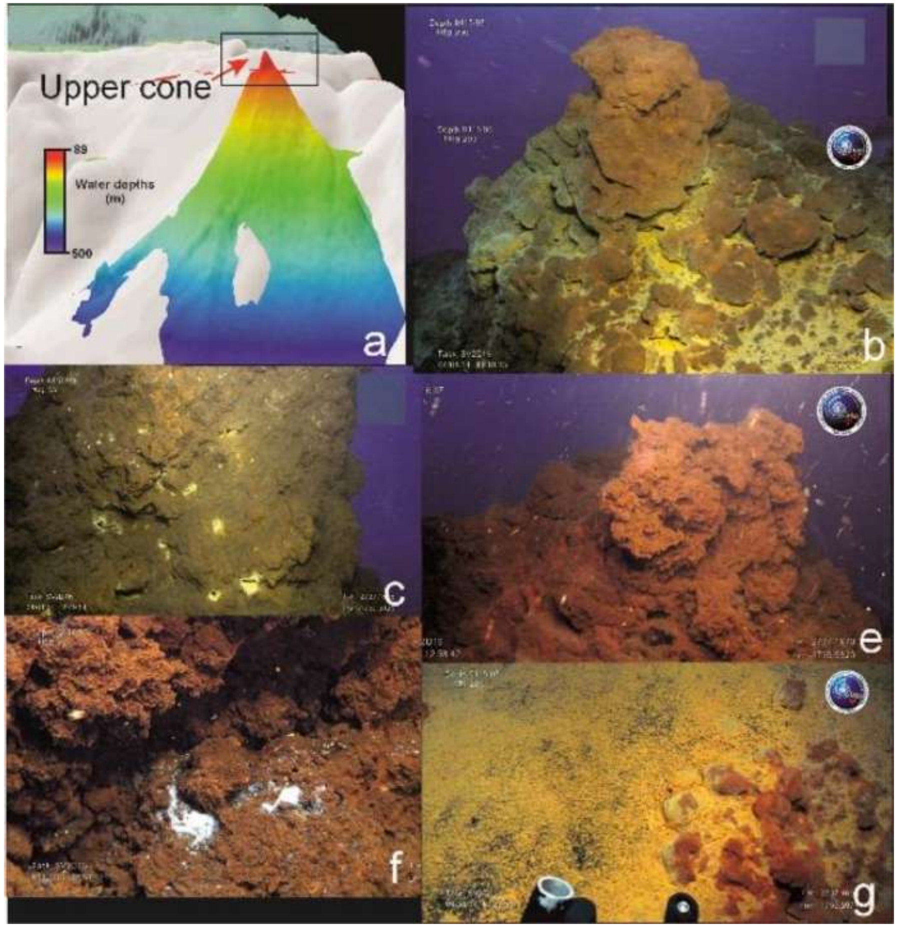


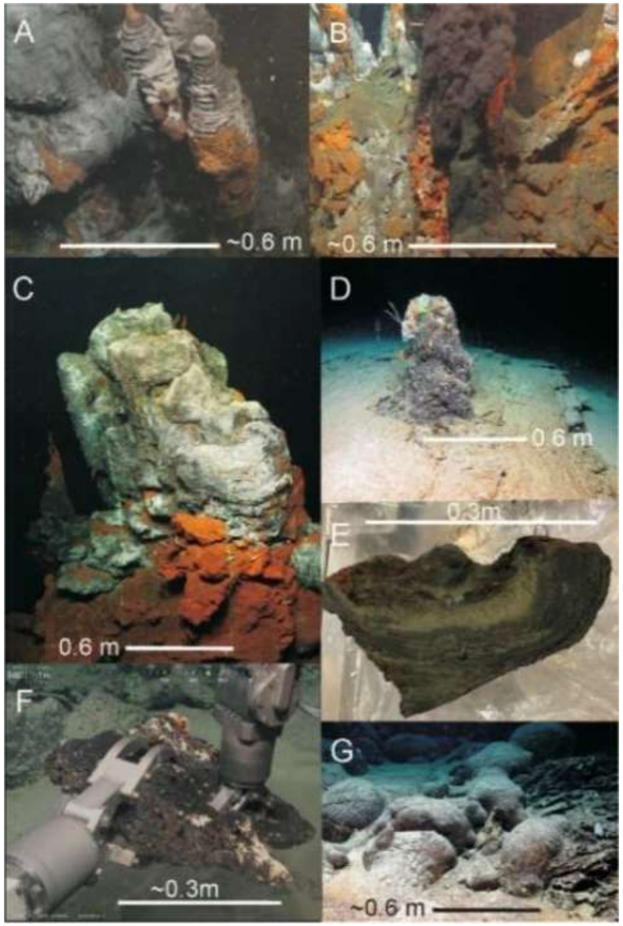
Lost City complex (31ºN).

Examples of active and extinct hydrothermal carbonate



Denny et al., 2015



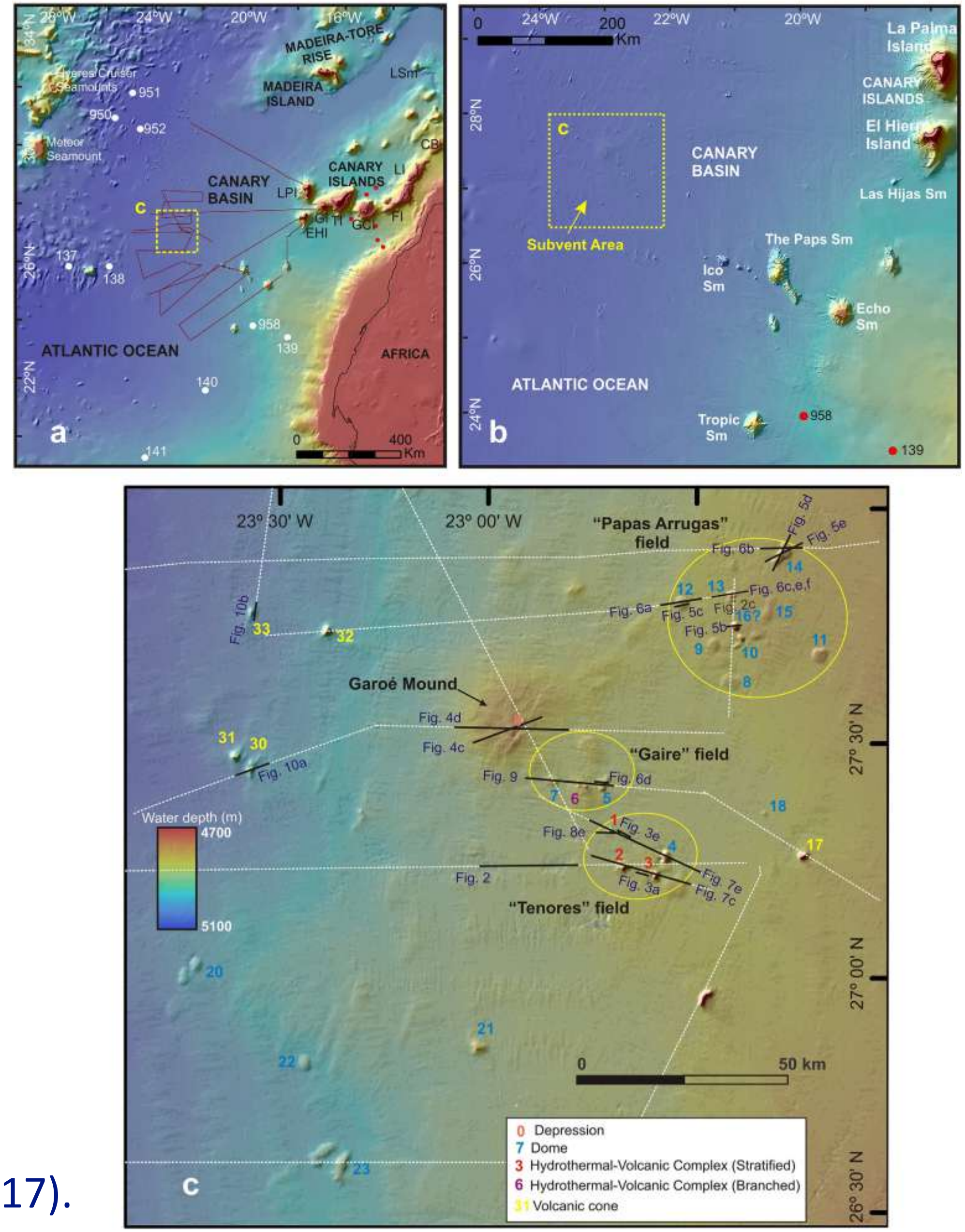


Left panel: Low-temperature hydrothermal fields developed after the eruption of the Tagoro volcano (South of El Hierro Island) in 2011-2012 (González et al., 2020); Right panel: Hydrothermal fields of high-temperature (A, B, C y E; massive sulphides and active chimneys) and low-temperature (D and F: carbonate chimneys) investigated in the Mid-Atlantic Ridge (G), north of the Azores Archipelago, during the EXPLOSEA-2 cruise (Somoza et al., 2020).

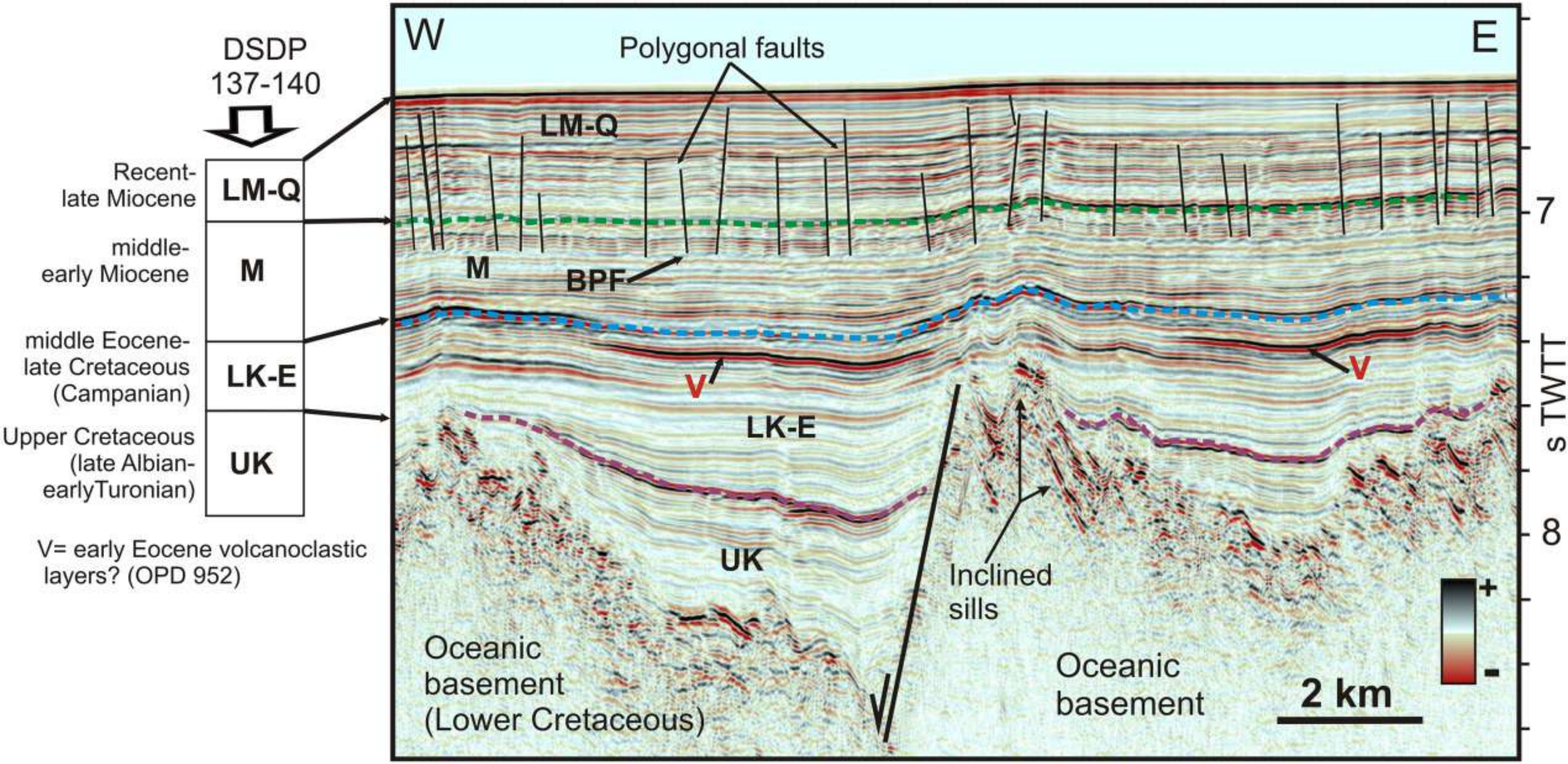
c) Hydrothermal-hydrocarbon systems associated with intrusive sills in deep oceanic basins

Hydrothermal systems can also be associated with the occurrence of extensive buried intrusive complexes accompanying volcanic activity (Berndt et al., 2001; Planke et al., 2005; Thomson, 2007).

Emplacement of these intrusions in sedimentary basins can caused strong thermal perturbations and consequently extensive hydrothermal activity forming striking hydrothermal vent complexes related to **overpressured fluids**. Magmatic intrusions can act as a heat source that promotes organic matter maturation in their host rock and can trigger CH4 and CO2-rich fluid production, releasing large amounts of carbon into the water column and the atmosphere through vent complexes (Iyer et al., 2013). In this sense it has been postulated that widespread magmatic intrusions could have had important implications for global climate triggered by a massive release of carbon-rich fluids to the surface and to the atmosphere (Dickens, 2004; Svensen et al., 2004; Jourdan et al., 2008; Reynolds et al., 2017). Exploration of several ancient systems of this type have been addressed in the North Atlantic margins, in Norway, Faroe Islands, Greenland, etc. (Magee et al., 2016 and references therein).

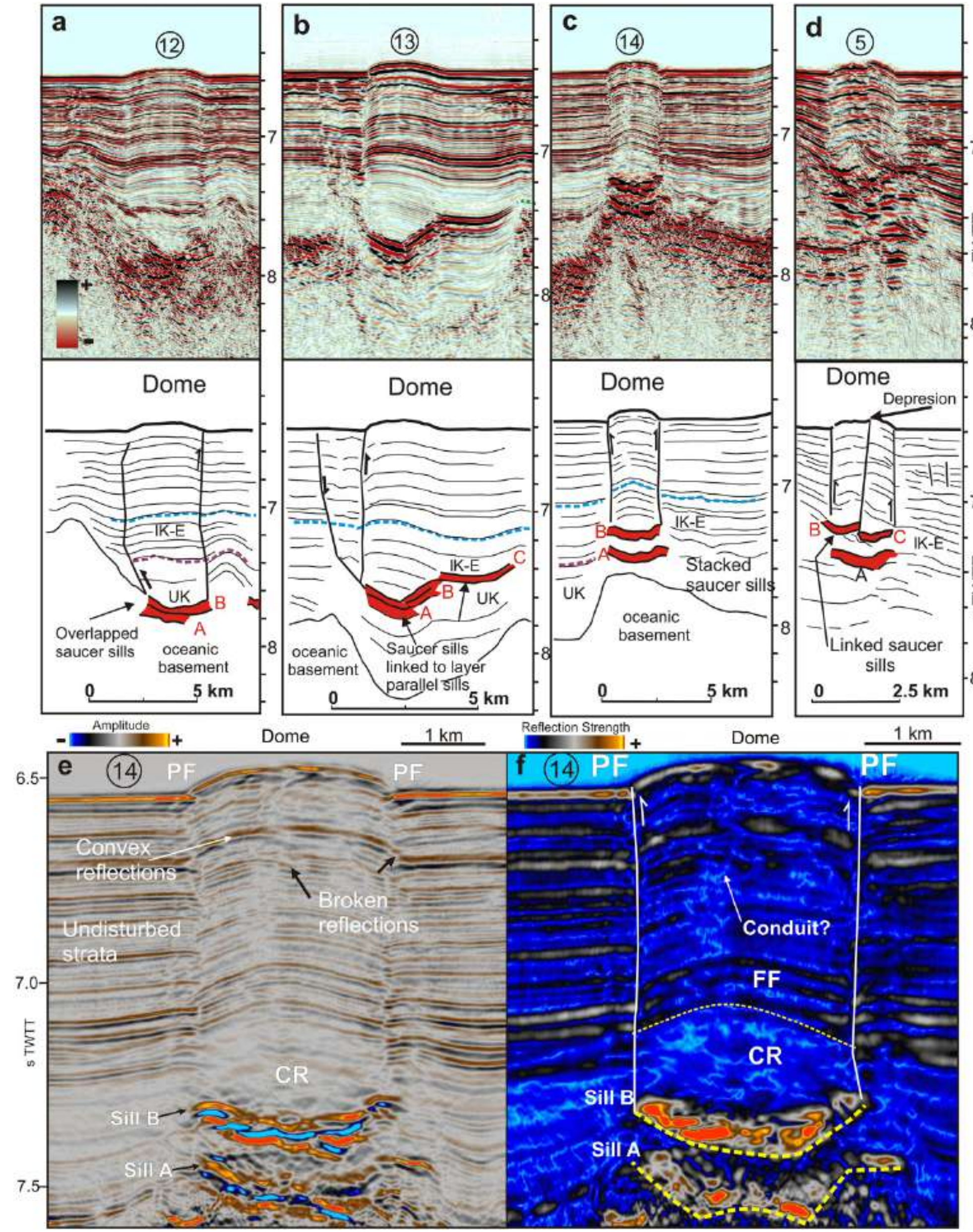


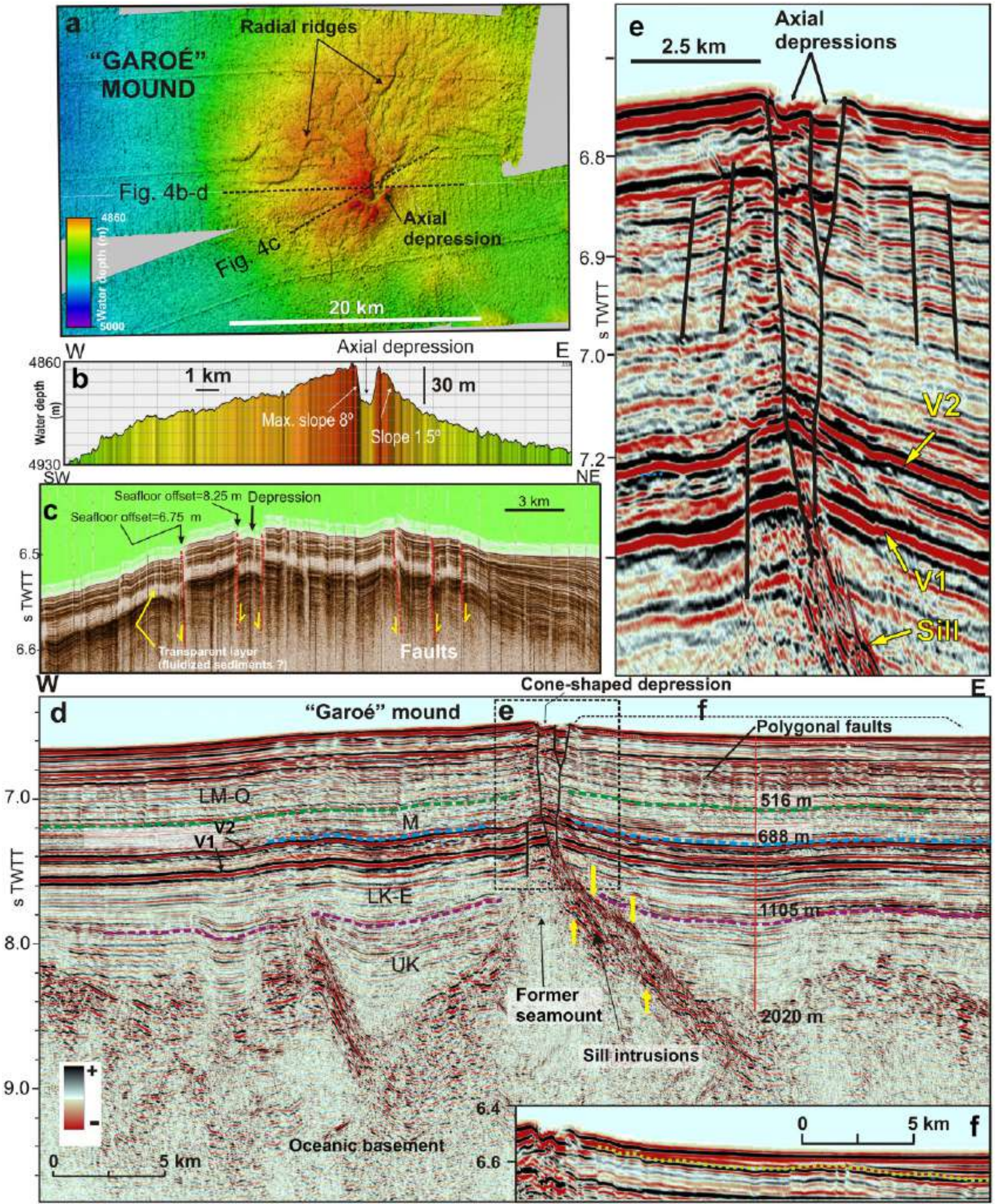
(Medialdea et al., 2017).



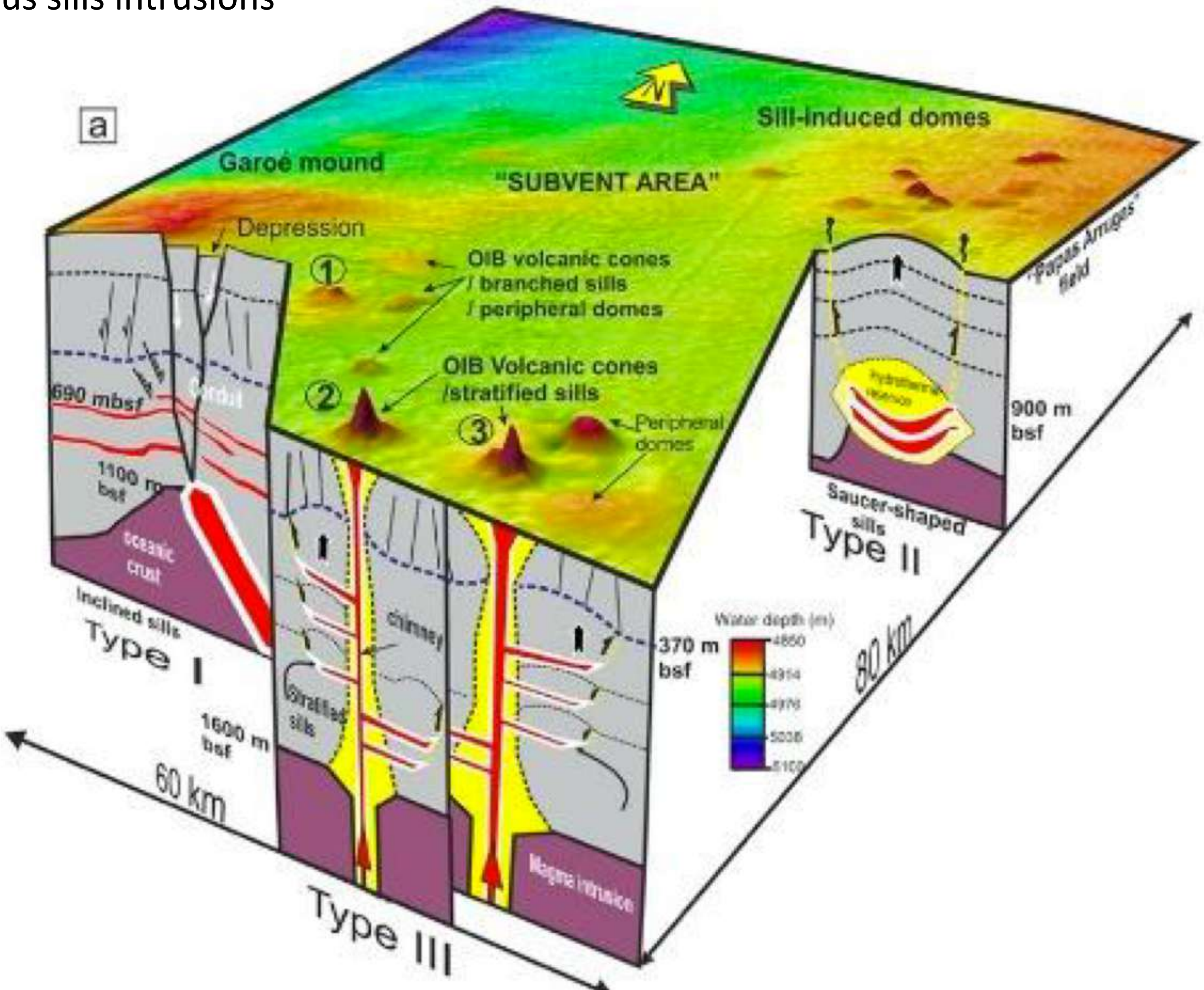
(Medialdea et al., 2017).

Seafloor mounds related to deep hydrothermal fields induced by sills discovered in the Canary Basin during previous oceanographic cruises of the research group by means of seismic and sampling (Medialdea et al., 2017).

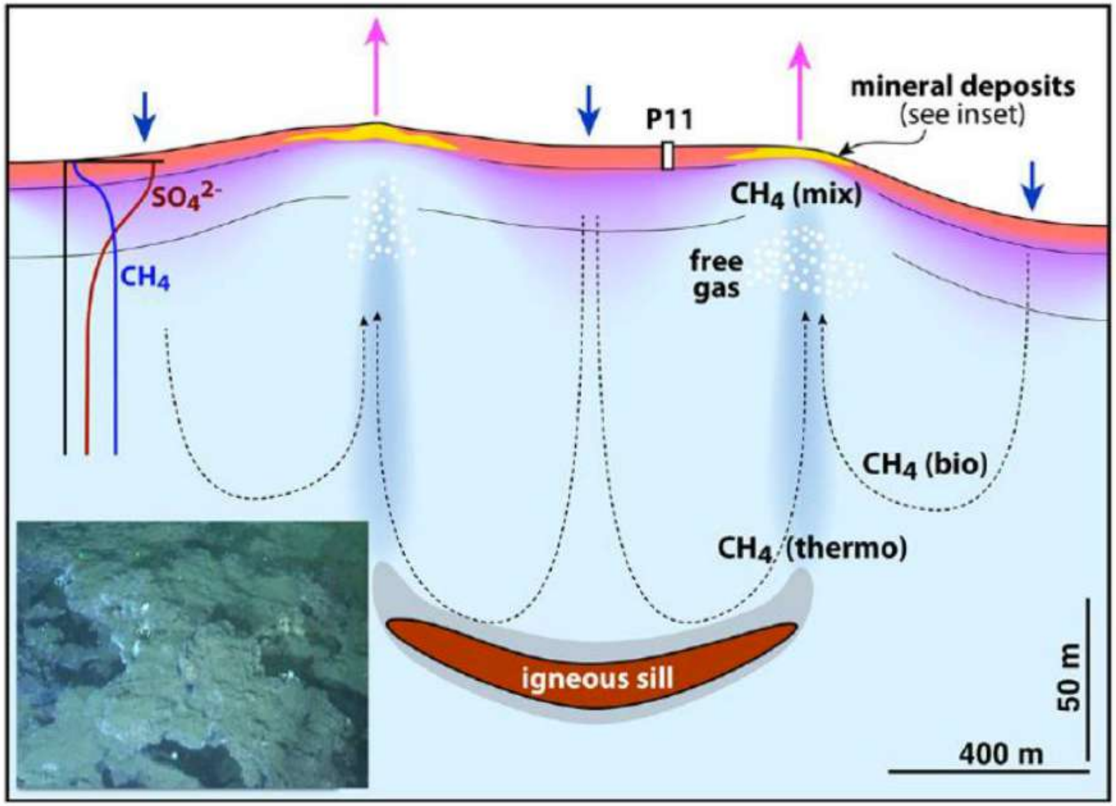



a
"GAROÉ" MOUND
Radial ridges
Fig. 4b-d
Axial depression
Fig. 4c
20 km
4860
5000
Water depth (m)
W
E
Axial depression
b
1 km
30 m
Max. slope 8°
Slope 1.5°
4860
4930
Water depth (m)
SW
NE
c
Seafloor offset=8.25 m
Depression
Seafloor offset=6.75 m
3 km
6.5
6.6
s TWTT
Transparent layer (fluidized sediments ?)
Faults
e
2.5 km
Axial depressions
6.8
6.9
7.0
7.2
s TWTT
V2
V1
Sill
W
Cone-shaped depression
E
d
"Garoé" mound
e
f
Polygonal faults
LM-Q
M
V2
V1
LK-E
UK
516 m
688 m
1105 m
2020 m
7.0
8.0
9.0
s TWTT
Former seamount
Sill intrusions
Oceanic basement
0
5 km
6.4
6.6
0
5 km
f

Igneous sills intrusions



Igneous sills intrusions

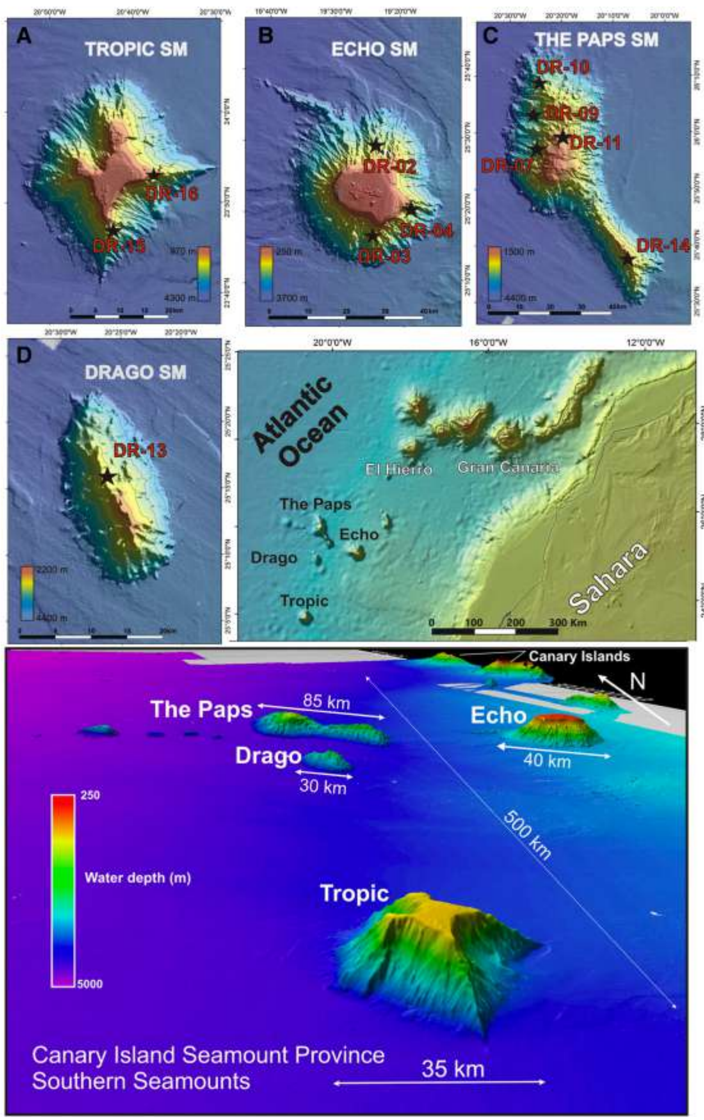


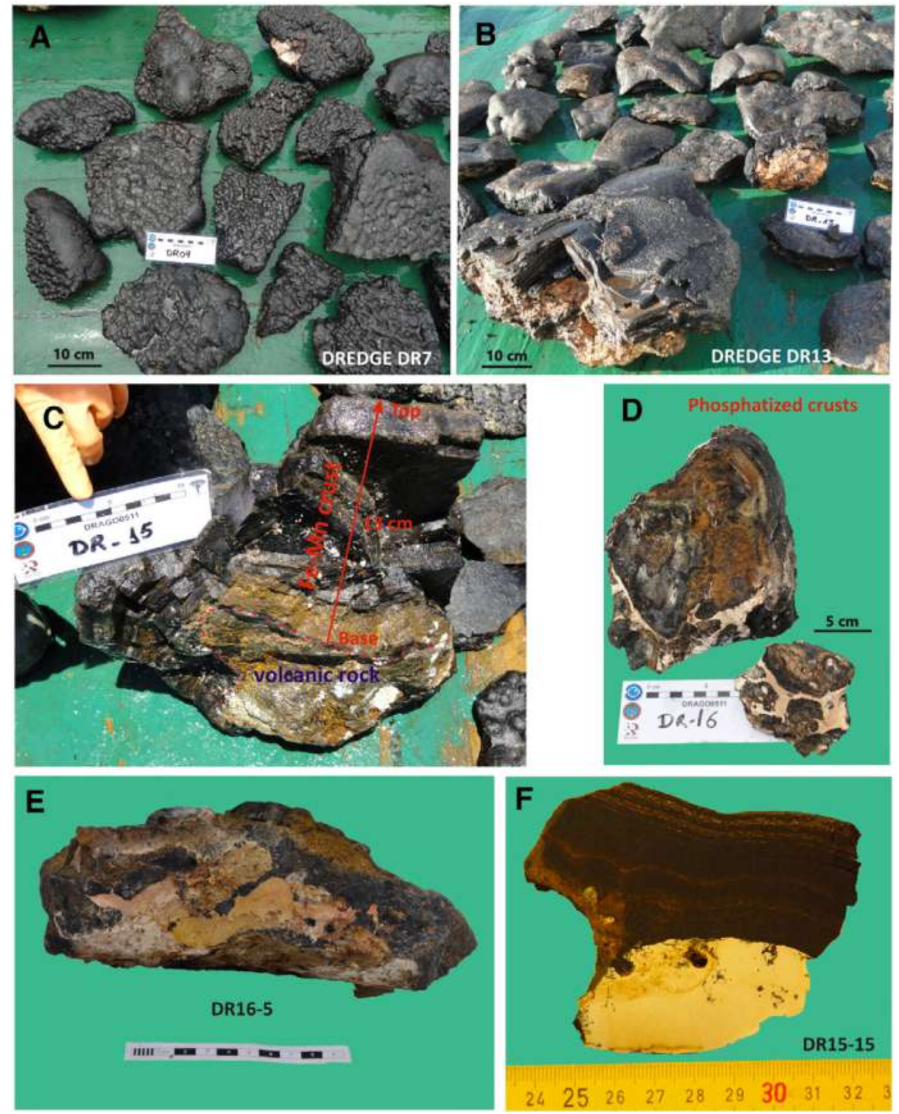
Teske et al., 2019

d) Remnant hydrothermalism and Fe-Mn crust formation

Hydrothermal mineralization of Fe-Mn crusts and stratabound associated with hot springs on ridges, volcanic islands and seamounts have been reported in different areas from the Pacific and Atlantic oceans and the Mediterranean Sea (e.g., Dekov and Savelli, 2004; Hein et al., 2005; Fitzgerald and Gillis, 2006; Pirajno, 2009).

The study of submarine volcanic systems linked to the emissions of hydrothermal fluids, has been the objective of several studies realized in Macaronesia, essentially focused on deep and shallow waters of the Canary Islands and Cape Verde. Holocene massive, veinlets, and disseminated barite deposits were recovered at 3100 m water depth in the Henry Seamount (south El Hierro Island) (Klugel et al., 2011). Hydrothermal-derived ferromanganese oxides have been recently discovered interlayered in hydrogenetic Fe-Mn crusts on seamounts from the Canary Islands, supporting the influence of the spring fluids to increase dissolved metals in the seawater chemistry and the accumulation of Fe-Mn crust deposits (Marino et al., 2019; Marino, 2020).





Marino et al.m 2017

Alt, J.C., 2003. Hydrothermal fluxes at mid-ocean ridges and on ridge flanks. C. R. Geoscience 335. doi:10.1016/j.crte.2003.02.001

Denny, A. R., D. S. Kelley, and G. L. Fruh-Green (2015), Geologic evolution of the Lost City Hydrothermal Field, Geochem. Geophys. Geosyst., 17, 375–394, doi:10.1002/2015GC005869

Medialdea, T., Somoza, L., González, F.J., Vázquez, J.T., de Ignacio, C., Sumino, H., Sánchez-Guillamón, O., Orihashi, Y., León, R. and Palomino, D. (2017). Evidence of a modern deep-water magmatic hydrothermal system in the Canary Basin (Eastern Central Atlantic Ocean). GEOCHEMISTRY, GEOPHYSICS, GEOSYSTEMS 18 (8): 3138-3164.

Somoza, L., et al. 2004. Evidence for hydrothermal venting and sediment volcanism discharged after recent short-lived volcanic eruptions at Deception Island, Bransfield Strait, Antarctica. Marine Geology 203 (1-2): 119-140.

Somoza L, Medialdea T, González FJ, Calado A, Afonso A, Albuquerque M, Asensio-Ramos M, Bettencourt R, Blasco I, Candón JA, Carreiro-Silva M, Cid C, De Ignacio C, López-Pamo E, Machancoses S, Ramos B, Ribeiro LP, Rincón-Tomás B, Santofimia E, Souto M, Tojeira I, Viegas C and Madureira P (2020) Multidisciplinary Scientific Cruise to the Northern Mid-Atlantic Ridge and Azores Archipelago. Front. Mar. Sci. 7:568035. doi: 10.3389/fmars.2020.568035