



**Università di Trieste**  
**Corso di Laurea in Geologia**

**Anno accademico 2020 - 2021**

**Geologia Marina**

Parte IV

**Modulo 4.2 Indicatori di movimento di fluidi: Vulcani di Fango,  
chimneys, pockmarks, vents...**

Docente

**A. Camerlenghi**

## Outline

Review of main mechanisms of fluid flow:

- **Mud diapirs and mud volcanoes**
- Gas chimneys
- Pockmarks
- Seafloor vents in general
- Polygonal fault systems
- Diagenetic fronts
- Gas hydrates

<https://www.fluid-venting-system.org/contact.html>

## Mud volcanoes

Surface expressions of focused fluid flow inside hydrocarbon-bearing sedimentary basins. They can:

- indicate subsurface petroleum accumulations
- may react to or reveal precursor signals of earthquakes
- induce hazards for people and industrial facilities
- release large amounts of methane into the atmosphere.

## Definition of Mud Volcano

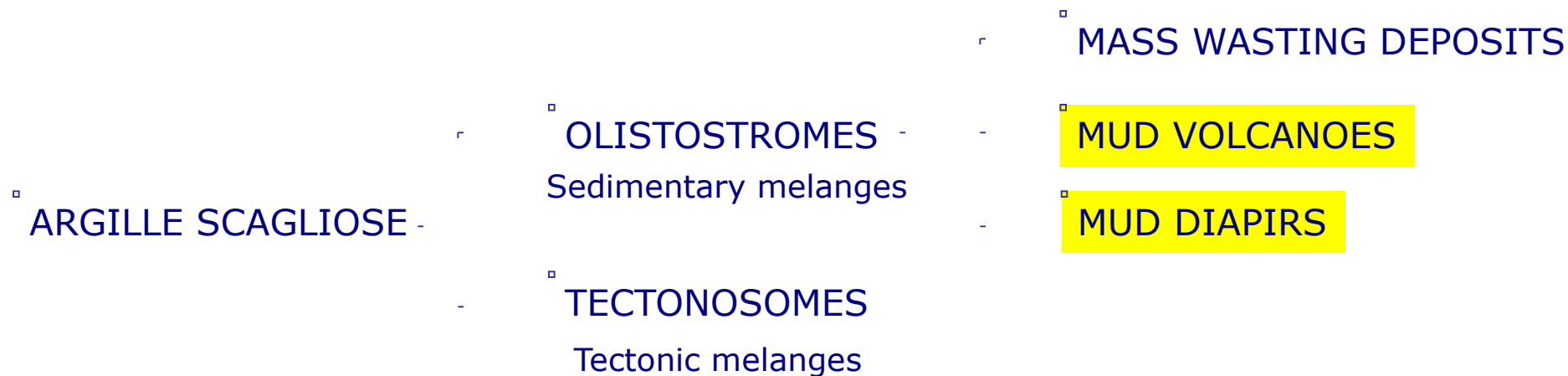
stacks of debris flow deposits composed of fluid-rich, fine-grained sediments expelled on the Earth's surface or on the sea floor. During the ascent, the mud is able to carry litho-clasts of various size, shape, age, and composition.

Mud volcanoes are often associated to sedimentary diatremes and mud diapirs (shale diapirs, or clay diapirs), all generated by subsurface overpressure of sedimentary (high accumulation rate), tectonic, or diagenetic origin following a state of under-consolidation in low-permeability sediments.

Although mud volcanoes occur in both divergent and convergent margins, they play an important role in the evolution of accretionary wedges, where they too participate in the world wide controversy about the origin and significance of mélanges.

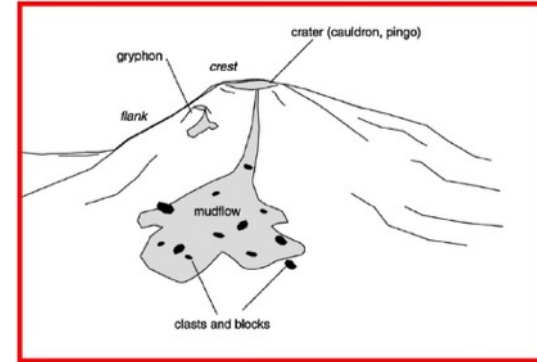
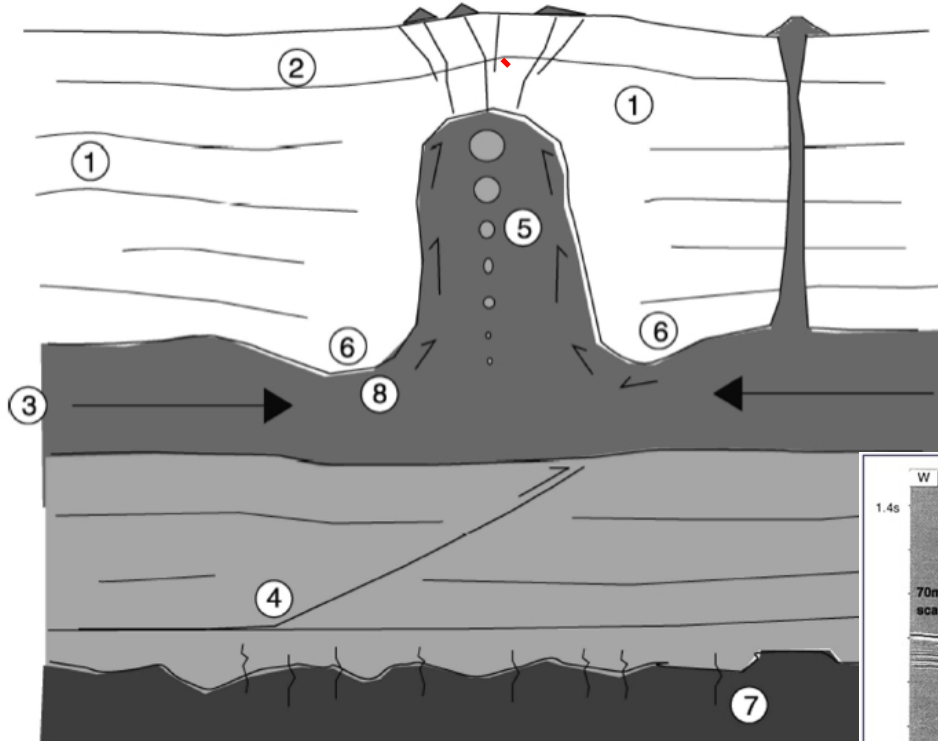
**Olistostromes**, or **sedimentary m $\grave{e}$ langes**: uplifted and at times deformed **chaotic** sedimentary bodies (Cretaceous to Pliocene) originated by subaqueous mass gravitational processes, such as debris-flows, and submarine slides and/or mud volcanoes/diapirs.

**Tectonosomes**, or **broken formations**: strongly deformed up to stratally disrupted Ligurian units, which retain their original stratigraphic coherence. They represent fossil, uplifted portions of the offscraping complexes of the Cretaceous-Eocene paleo-Apennine accretionary wedge.

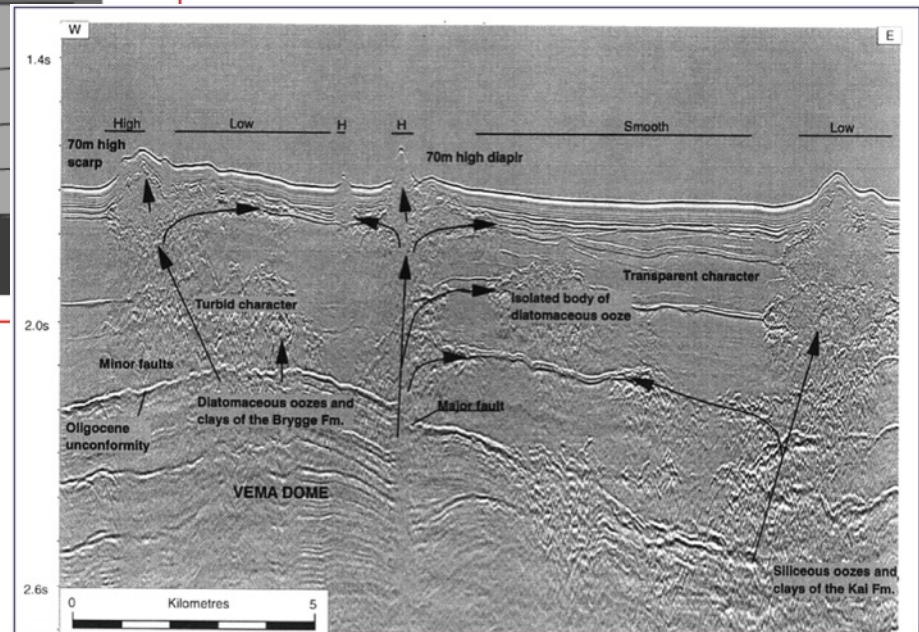
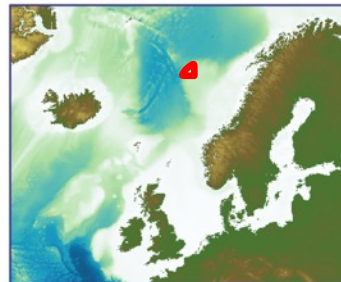


mud volcanoes  
overlying a diapir

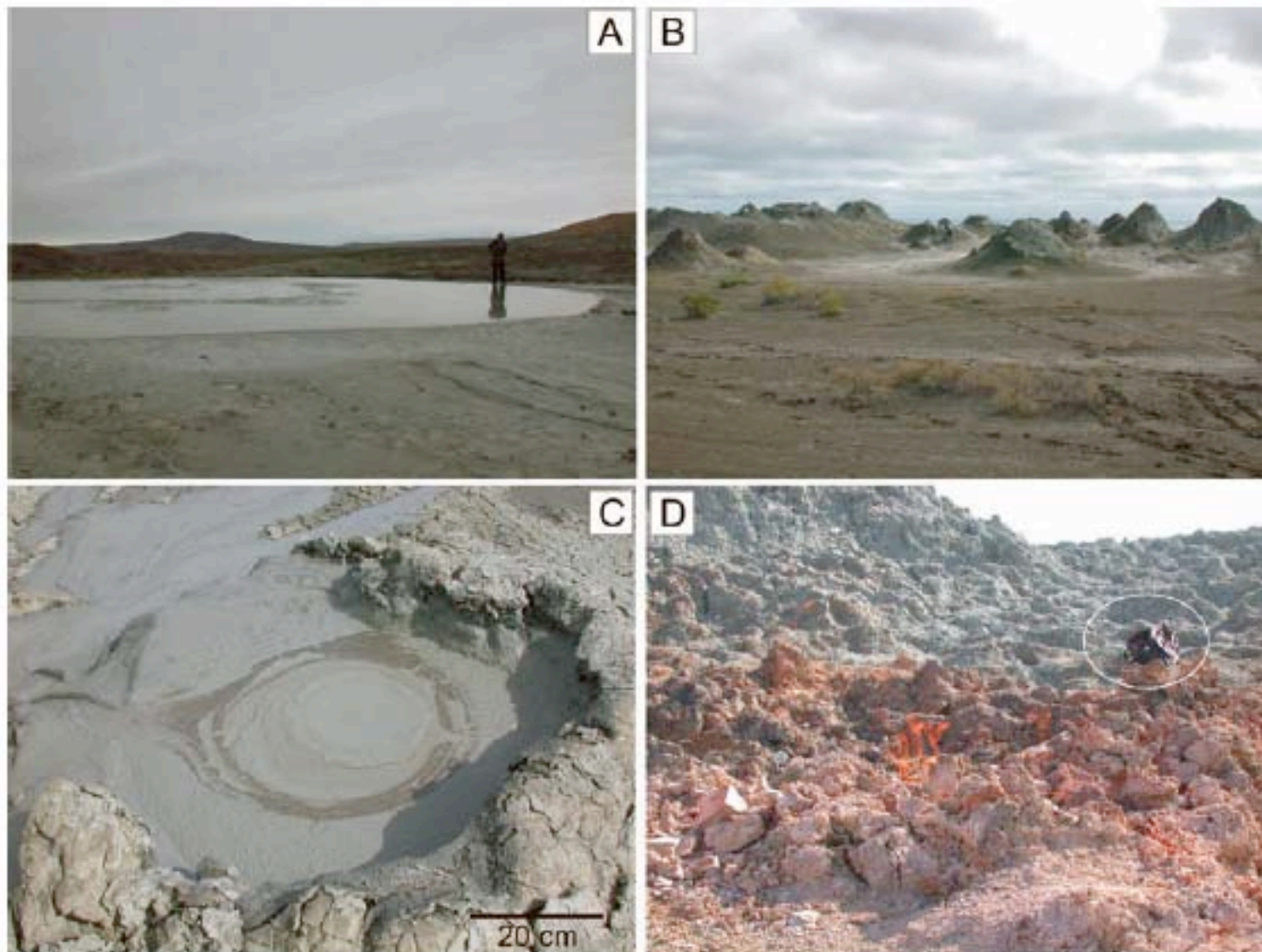
diatreme



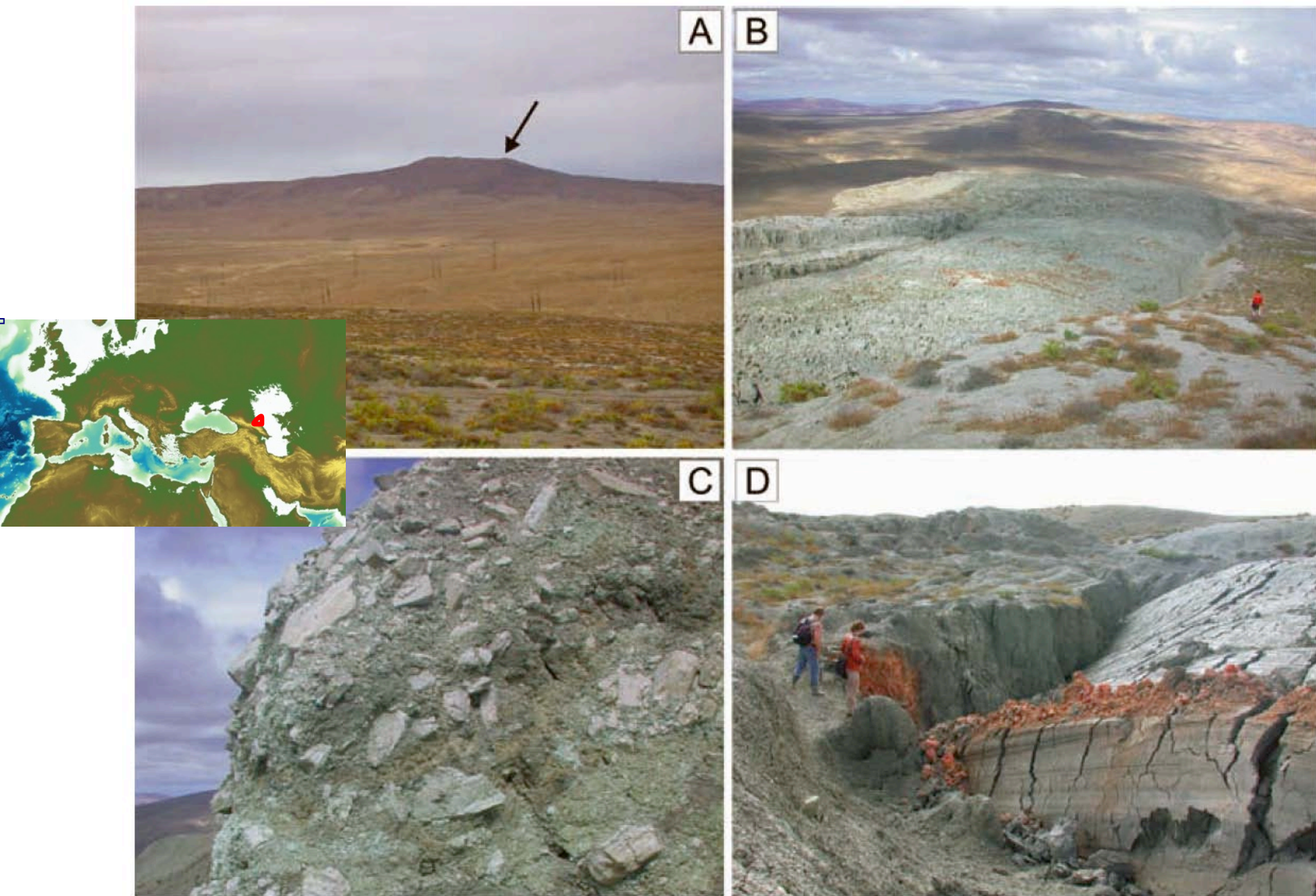
Kopf (2002)



Hovland et al. (1998)



Seep structures and deposits on dormant mud volcanoes. A Salse A at the crater field of the Dashgil mud volcano, with the gryphon field to the west (B). C Hydrocarbons (black mud) in a gryphon at Bakhar. D Burning hydrocarbon gas in the vent at Lokbatan. The fire has been burning for more than a year since the October 2001 eruption (Figs. 2 and 3)



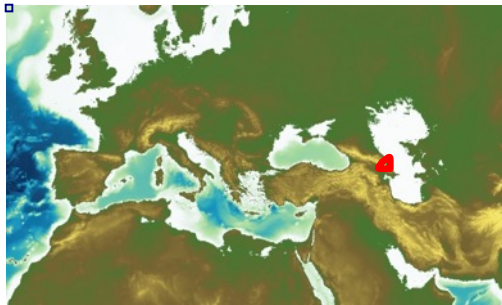




# NATURAL FIRES OF AZERBEIJAN

Marco Polo(?)

Images courtesy of Luis Piñero

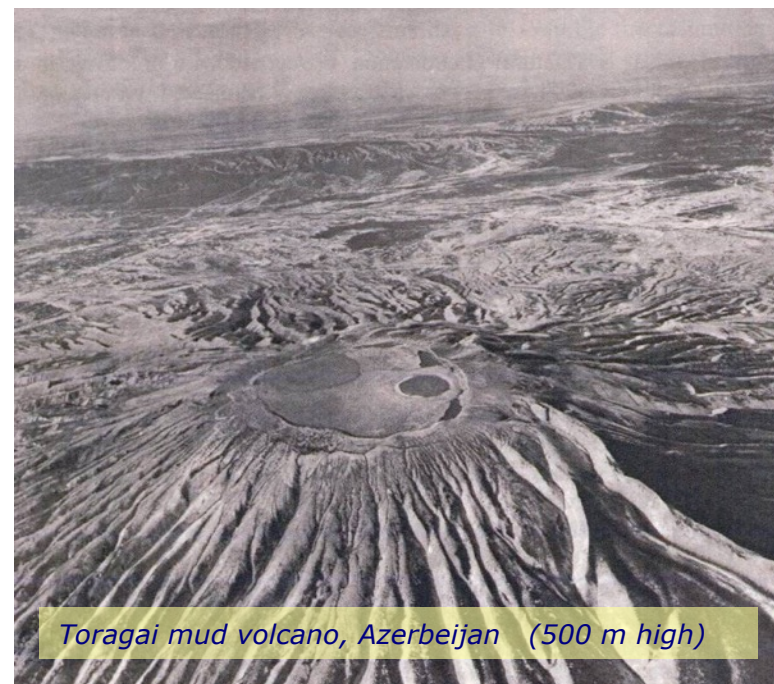


“The appearance of Zoroastrans in Azerbaijan and their cult of the eternal flame in the Temple of Fire of the Magi might be related to the fires from the mud volcanoes”



Planke et al. (2003)

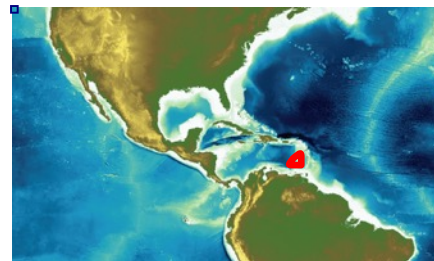
## Lokbatan Mud Volcano, Azerbaijan, 25 October 2001



<https://www.youtube.com/watch?v=0xCPXg5Ijeg>  
<https://www.youtube.com/watch?v=w9fsdozCxt4>  
[https://www.youtube.com/watch?v=97D5\\_H05p2Y](https://www.youtube.com/watch?v=97D5_H05p2Y)



*Eruption Piparo, 22/2/1987*



## Piparo, Trinidad 22 February 1987



<http://www.gstt.org/teaching/Devil's%20woodyard.htm>



CHECKING IT OUT: BEHIND: down, Opposition Leader Patrick Manning, a trained geologist, and Prime Minister Basdeo Pandey, clearly examine the mud which has come from the Piparo mud volcano last Saturday, with his



TESTING THE MUD: Slipping lightly, Prime Minister Basdeo Pandey examines the mud while visiting the site of the mud volcano which almost wiped out the entire Piparo Village in Central Trinidad last Saturday morning. Photo by TONY HOWELL.

# Piparo villagers to be relocated

By LOUIS B HOMER  
Mosque, Prime Minister Basdeo Pandey, who travelled by helicopter to the area, said the volcano eruption could be seen as another opportunity "to unite our people as one."  
25 miles of roadway. Those listed for immediate attention are Piparo Road, Guarscara Tabaquite Rd, Sisters Rd, cho Road, Hoseeene Road, and Nap Mayaro Road.

## Sunday Guardian

• 25519 • SUNDAY, FEBRUARY 23, 1997 •

**Teakwondo champion**  
Cherry-Anni Sankar in flying high — PAGE 19

**SUNSHINE'S**  
Daniella Callender cuddles up with teddy bear

**Courtney Walsh** is Windies captain against Indians — PAGE 6

**Jeanine Bonterra** is a shining star in ZONE

# Volcano erupts



## Mountain of mud leaves 31 Piparo families homeless

By LOUIS B HOMER  
A MUD volcano erupted in Piparo at 5:30 am, yesterday leaving 31 families homeless and 15 injured and 20 are listed under a 100-foot high mountain of mud. Villagers, who live on the edge of the newly formed crater, were yesterday, basically mourning household items as well as farm animals and even parts of houses, buried of another eruption.  
The officials who visited the area have issued a warning for people to stay away from the village since the volcano is still erupting.

A normally quiet area, Lightfoot Trees, the scene of disaster, was a hub of activity with hundreds of people, some coming to see the volcano and listen to the villagers tell of the horror of the eruption.  
Aim Khan, one of the Piparo villagers who lost his house to the volcano, was lucky to be awake when the eruption started.  
"It was about midnight after five o'clock when I heard the electricity wires crackling, then it started to spurt. Afterwards I heard the whole place crackling and the earth started to move, then I heard a rumble and there an explosion."  
"When I looked outside I saw a set of mud going up in the air for about 100 feet high. This lasted for about 15 minutes, then it quieted down and started again and lasted for over one hour". He took his family to stay with relatives who live further away from the volcano in Piparo.  
Another villager, Hulsah Sankar, involved a storm was coming on. Going outside to check, he saw mud spewing into the sky like fountains of smoke from a chimney.  
"The mud was about 60 feet in diameter. I had to run 100 feet because the mud from the volcano was so hot."  
The

## Trinidad Guardian

• 25520 • MONDAY, FEBRUARY 24, 1997 •

# Volcano takes first life

## Piparo resident dies after helping villagers

By LOUIS B HOMER  
A MUD volcano has taken its first life in the aftermath of the mud volcano which has wiped out the lives of over 100 people in Piparo, South Trinidad, on Saturday.  
Forty-eight-year-old Anthea Spencer, who lived about 200 feet from the mud volcano, died yesterday after she was struck by mud. She was found by mud which she had dug up for her family members for his wife.  
Spencer is believed to have been struck by mud while she was helping villagers to dig up the mud. She was found by mud which she had dug up for her family members for his wife.  
Spencer is believed to have been struck by mud while she was helping villagers to dig up the mud. She was found by mud which she had dug up for her family members for his wife.



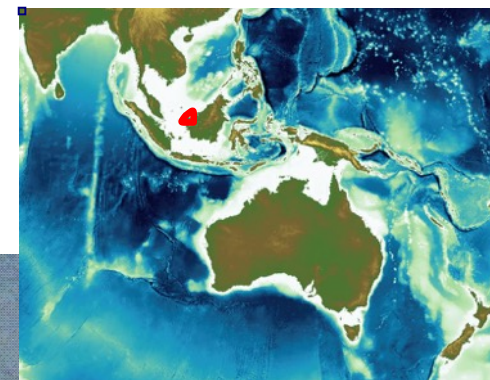
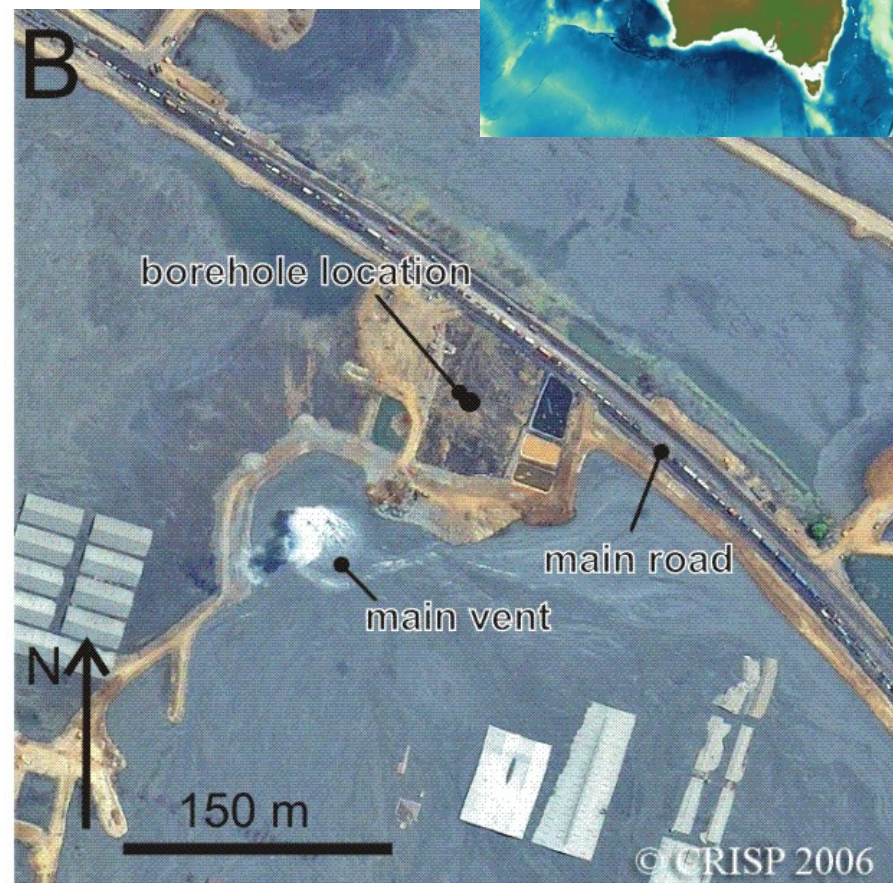
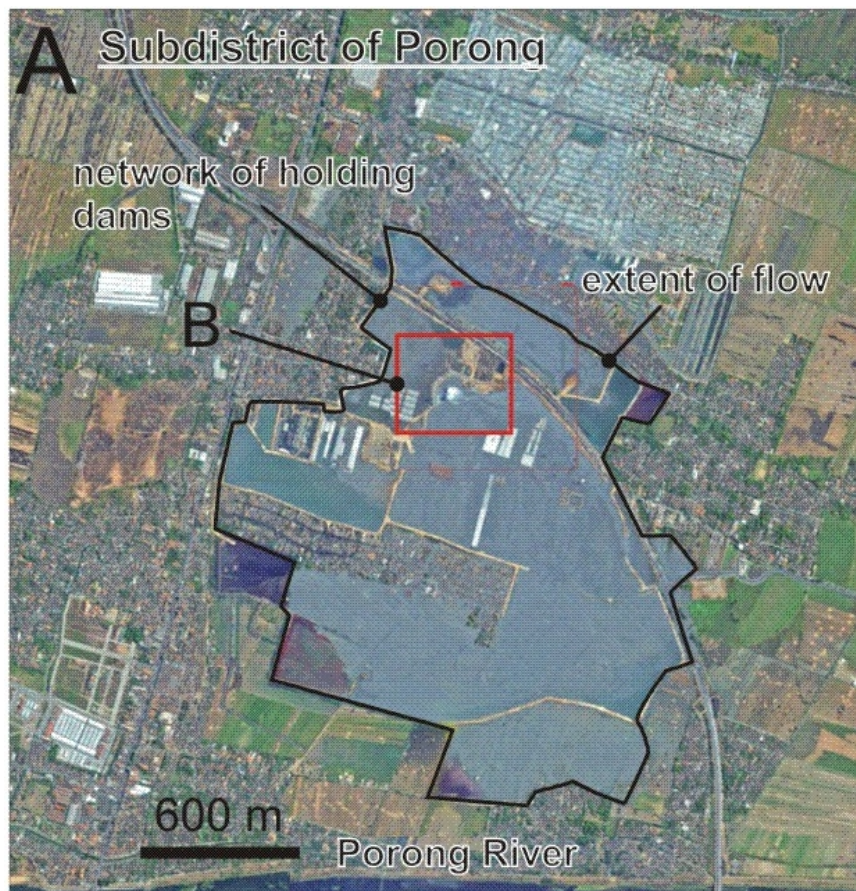
# Mud mass

## Piparo volcano erupts Page 3

BELOW: A HOUSE is left in ruins in the aftermath of the eruption of a mud volcano in Piparo early yesterday morning. This house was pushed over by the wall of mud on the left.  
RIGHT: MEMBERS of a Piparo family salvage what is left of their belongings from this second house which was pushed over and partially covered by mud following the early morning eruption.  
Photo: STEPHEN AJZZ

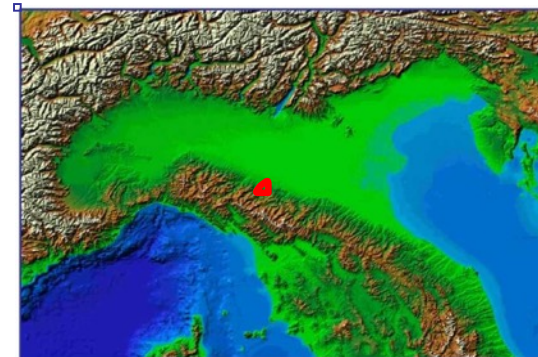
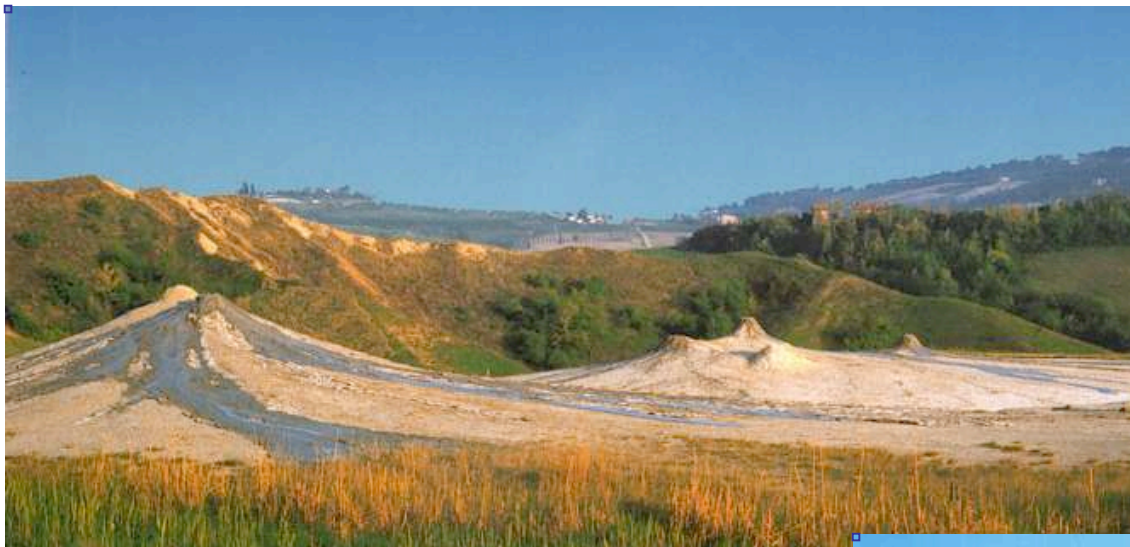


# THE ENVIRONMENTAL DISASTER OF THE MUD VOLCANOE TRIGGERED BY DRILLING FOR OIL IN JAVA: ISOLA DI GIAVA, MAY 29 2006





# MUD VOLCANOES **SALSE DI NIRANO, ITALY**



## How to recognize submarine mud volcanoes

1. Core samples showing ‘mud breccia’ containing sediments with a range of different ages, compositions and structures.
2. Strong backscatter on side-scan sonar records representing topographic features (craters, cones, mud flows, etc.).
3. Evidence of gas seepage and associated features (bacterial mats, cold-seep communities or methane derived authigenic carbonate – MDAC).
5. Seismic evidence of feeder channels and/or mud diapirs.



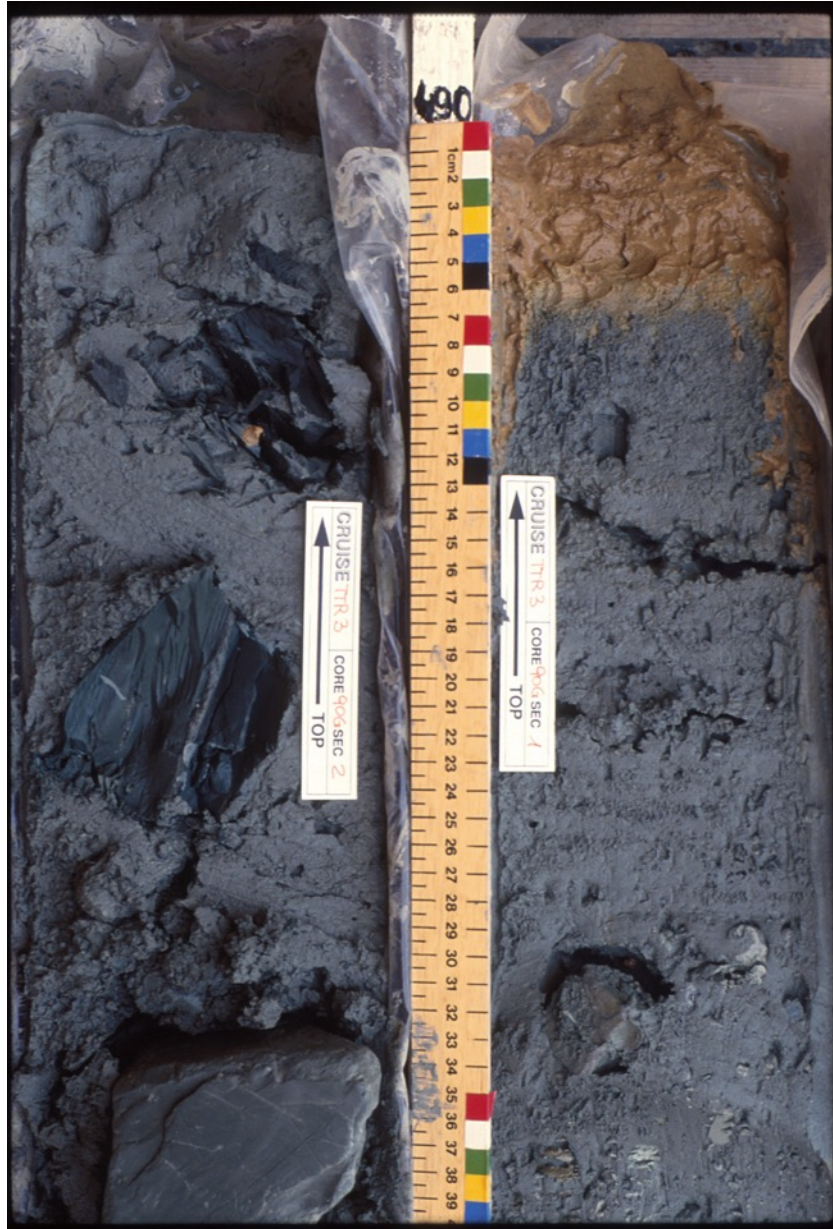
## Classification of mud breccia from Mediterranean Sea mud volcanoes according to sedimentary facies

<b>Lithotype or sedimentary facies</b>	<b>Description</b>
<b>A - MASSIVE</b>	Matrix-supported clasts of soft to indurated marls. No size sorting observed in clasts and matrix.
MASSIVE A1	centimetric to pluri-centimetric clasts. Stiff matrix.
MASSIVE A2	millimetric clasts. Stiff matrix.
MASSIVE A3	mousse-like texture of the matrix produced by gas micro-vesicles
<b>B - ORGANIZED</b>	The mud breccia shows internal textural changes. The breccia can be either matrix- or clast-supported.
ORGANIZED B1	sub-horizontal (in sediment cores) bedding produced by thin layers of millimetric clasts sorted by size. No embricate structures observed.
ORGANIZED B2	upward graded grain-supported mud breccia. The matrix/clasts ratio increases upwards.
ORGANIZED B3	matrix supported mud breccia with patches (clouds) of different colors and composition.

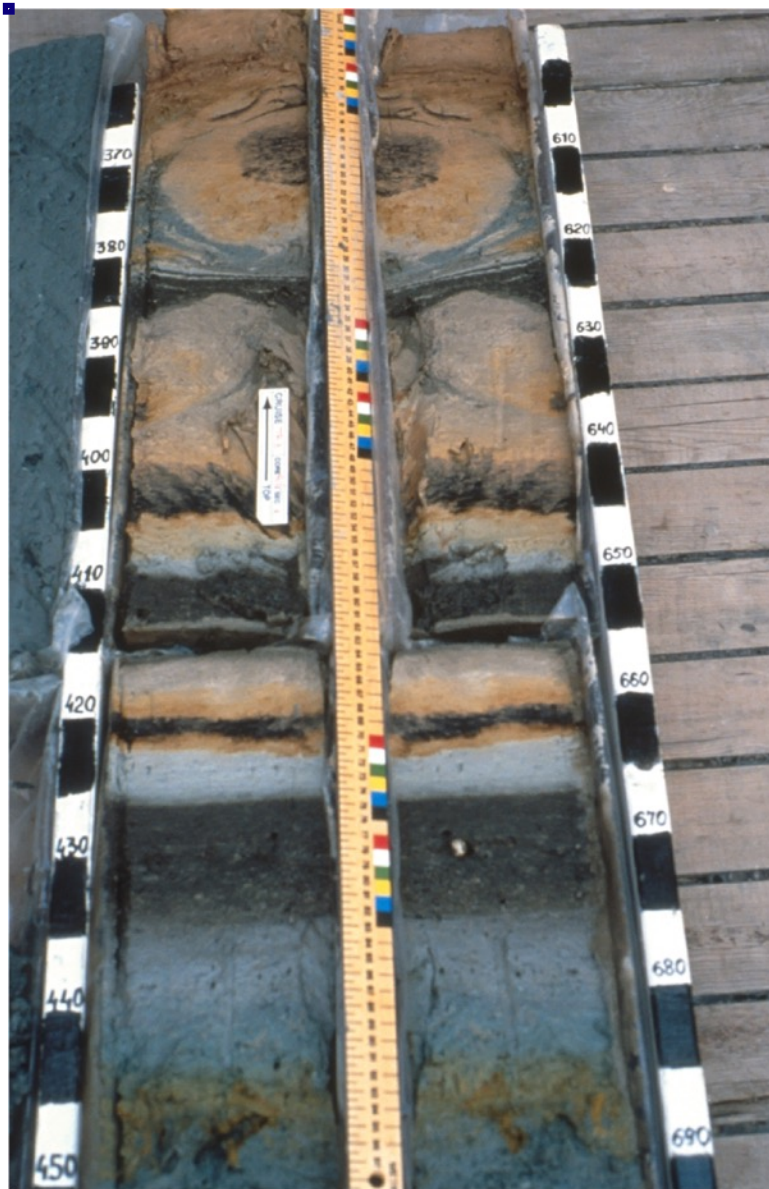
(adapted from Camerlenghi et al., 1992 and Staffini et al., 1993).



Dimitrov, 2002



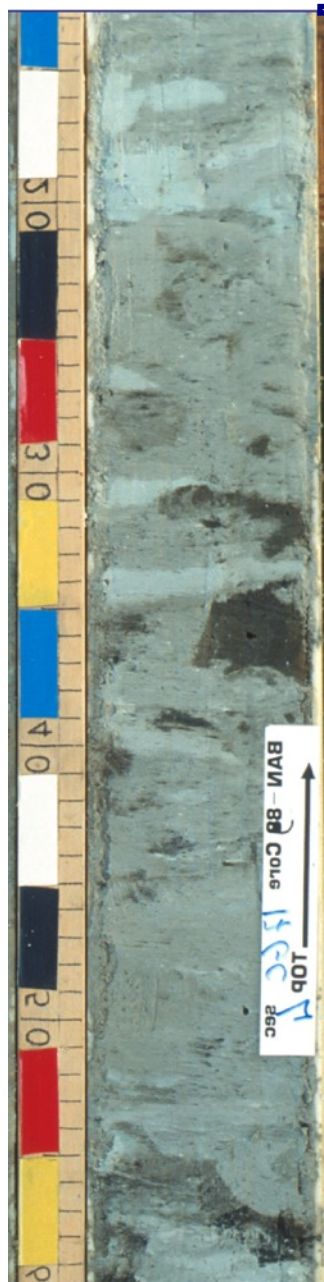
**Clasts**



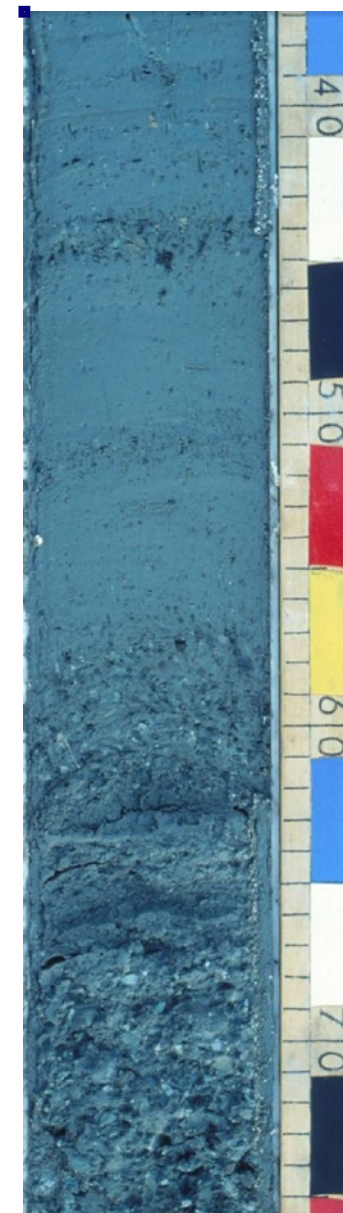
**slumps**



**Mud-breccia oxidized**

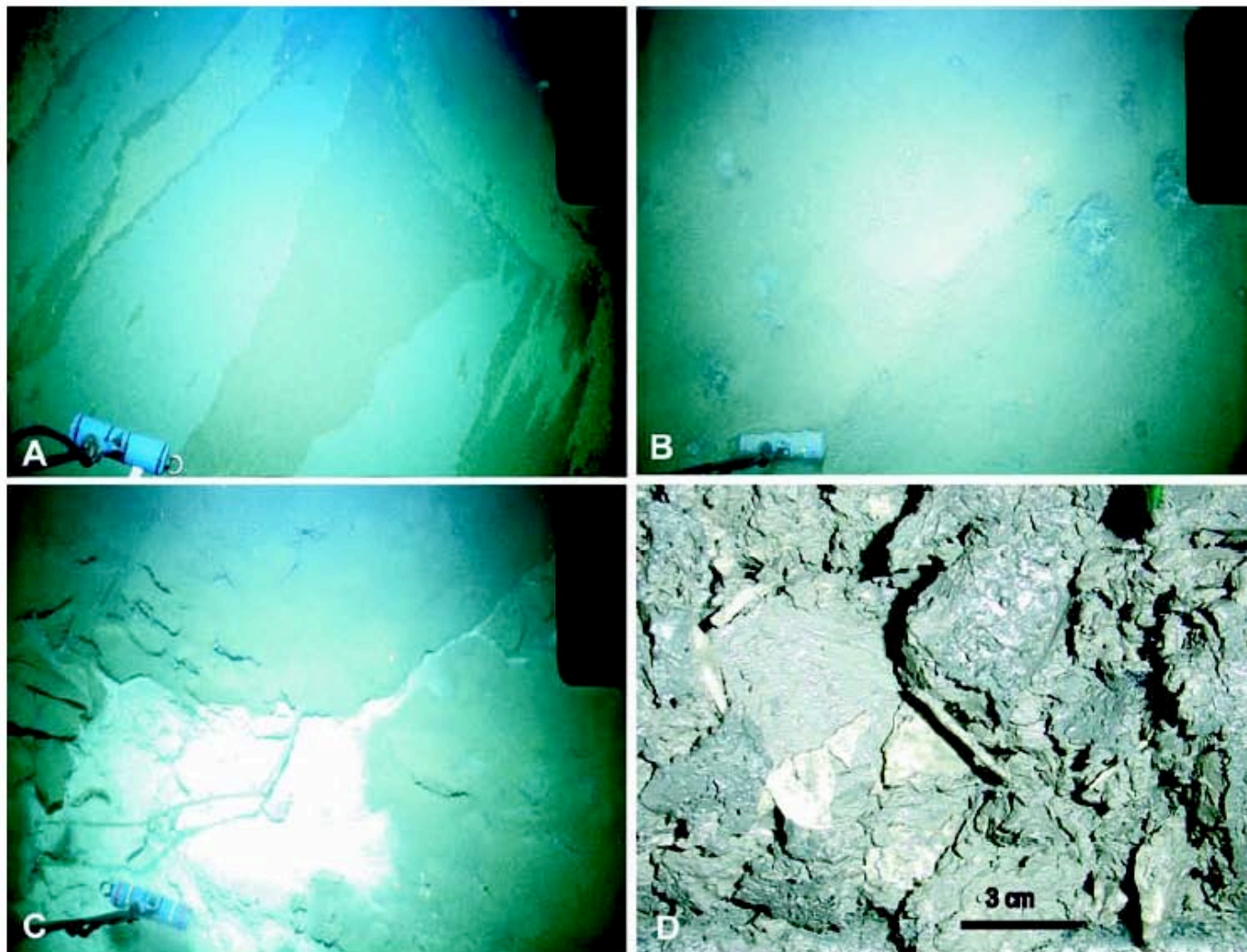


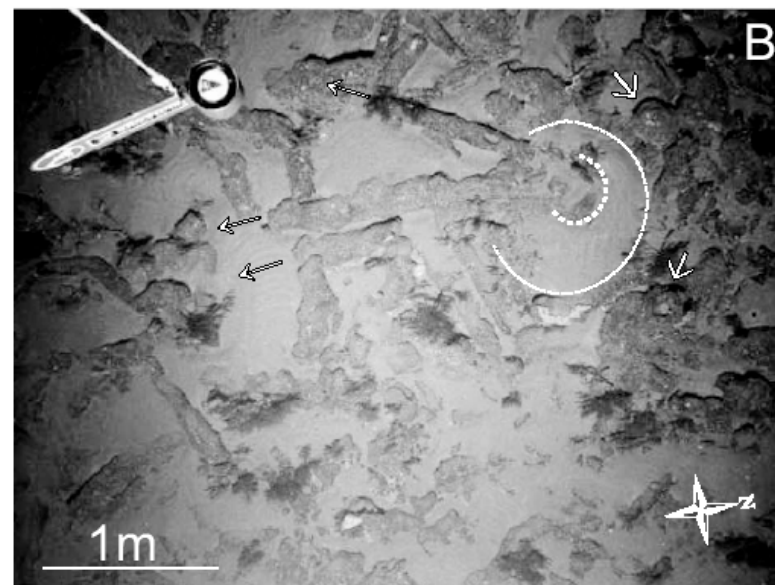
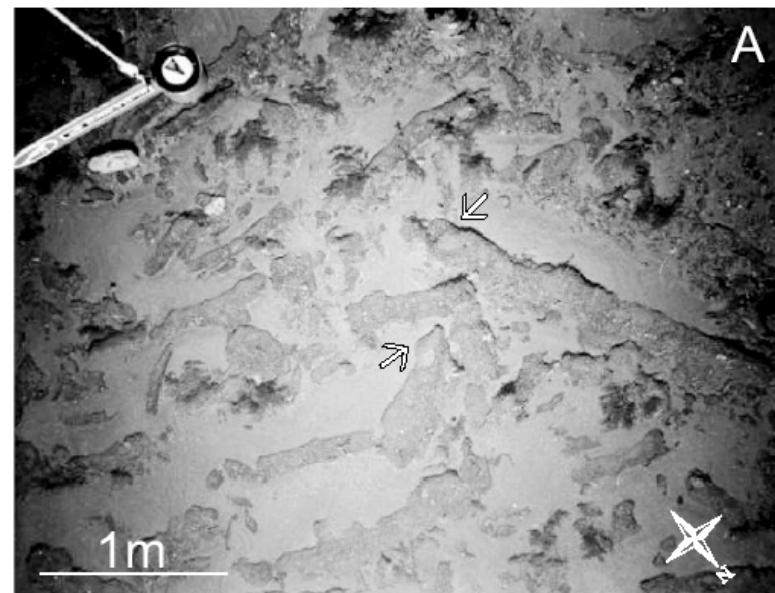
Mousse facies



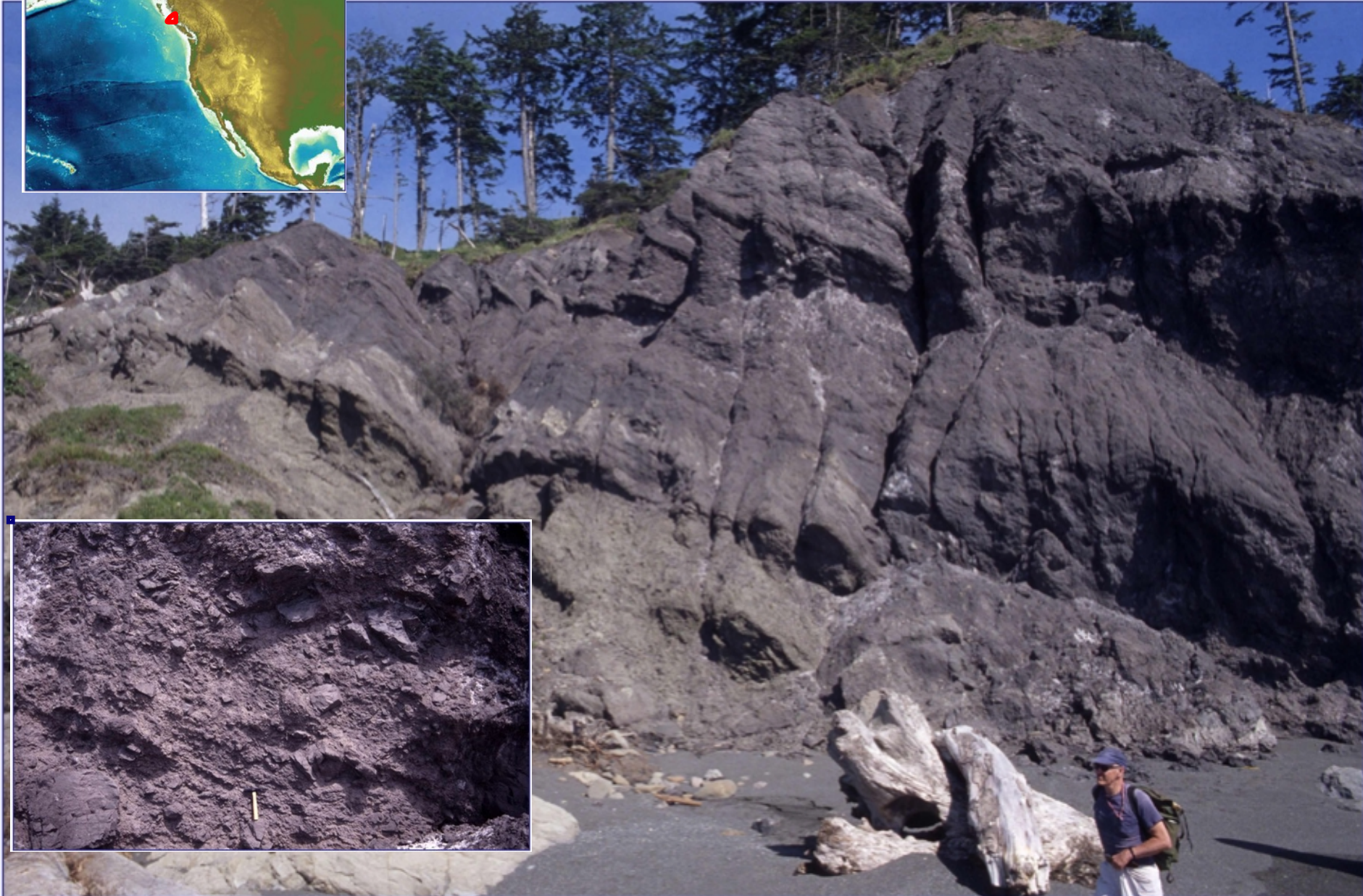
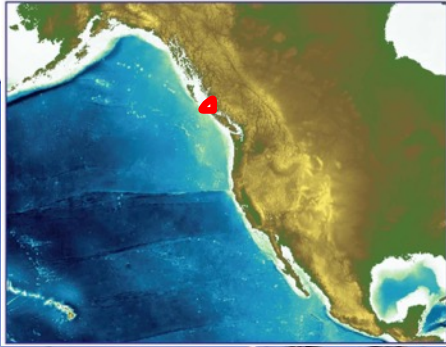
Organized facies

**Fig. 4** Seafloor and sediment images from DMV (4A-C): **A** recent mud flow sheets from a seafloor fissure; **B** small vent sites from an area of seepage on DMV; **C** white bacterial mat in a seafloor crack on DMV; **D** fractured gas hydrate slabs in sediments from Odessa mudflow core M52/1-18





# FOSSIL MUD VOLCANO, OLIMPIC PENINSULA





## Degree of Overpressure

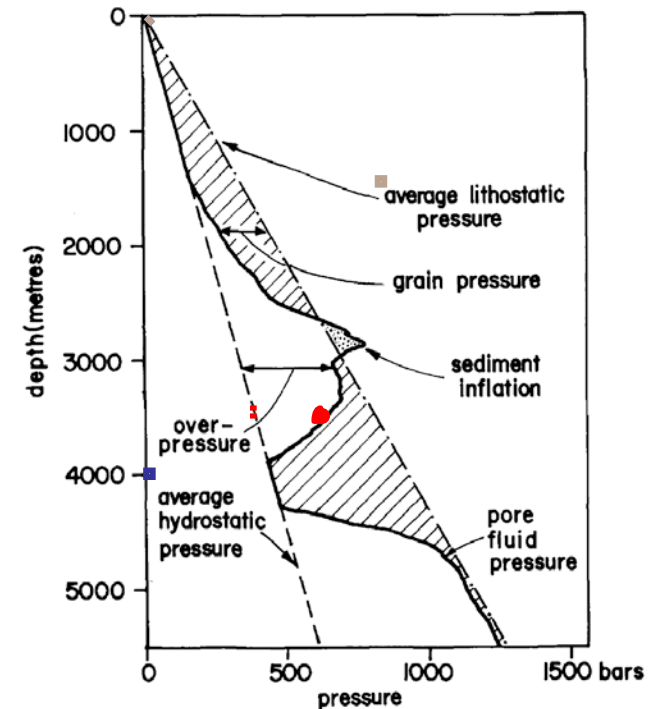
$$\lambda = (P_f - P_{hy}) / (P_d - P_{hy})$$

$P_f$  = Pore pressure

$P_{hy}$  = Hydrostatic Pressure

$P_d$  = Total Stress

### SEDIMENT COMPACTION AND INFLATION GRAIN PRESSURE AND OVERPRESSURE

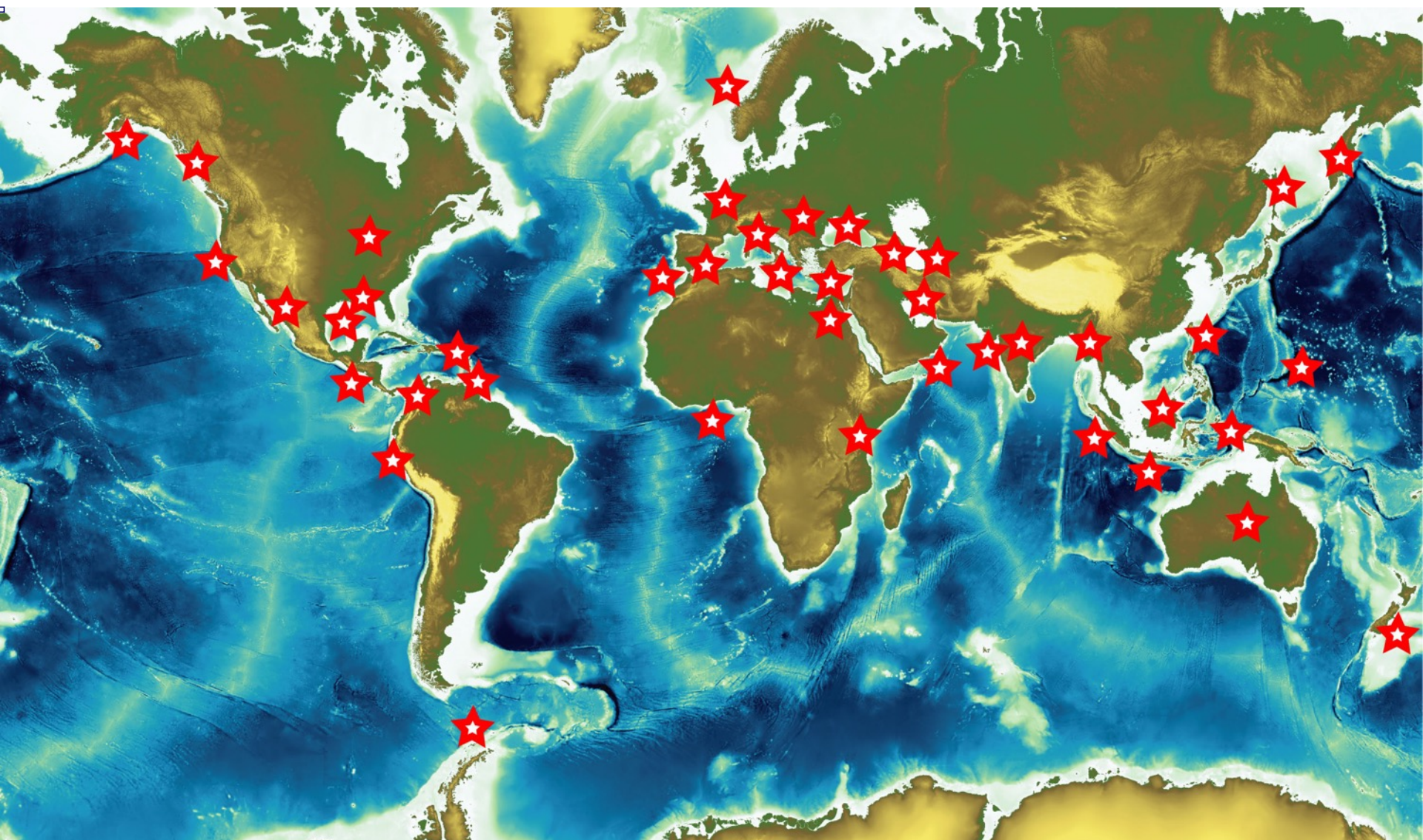


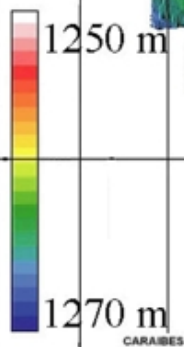
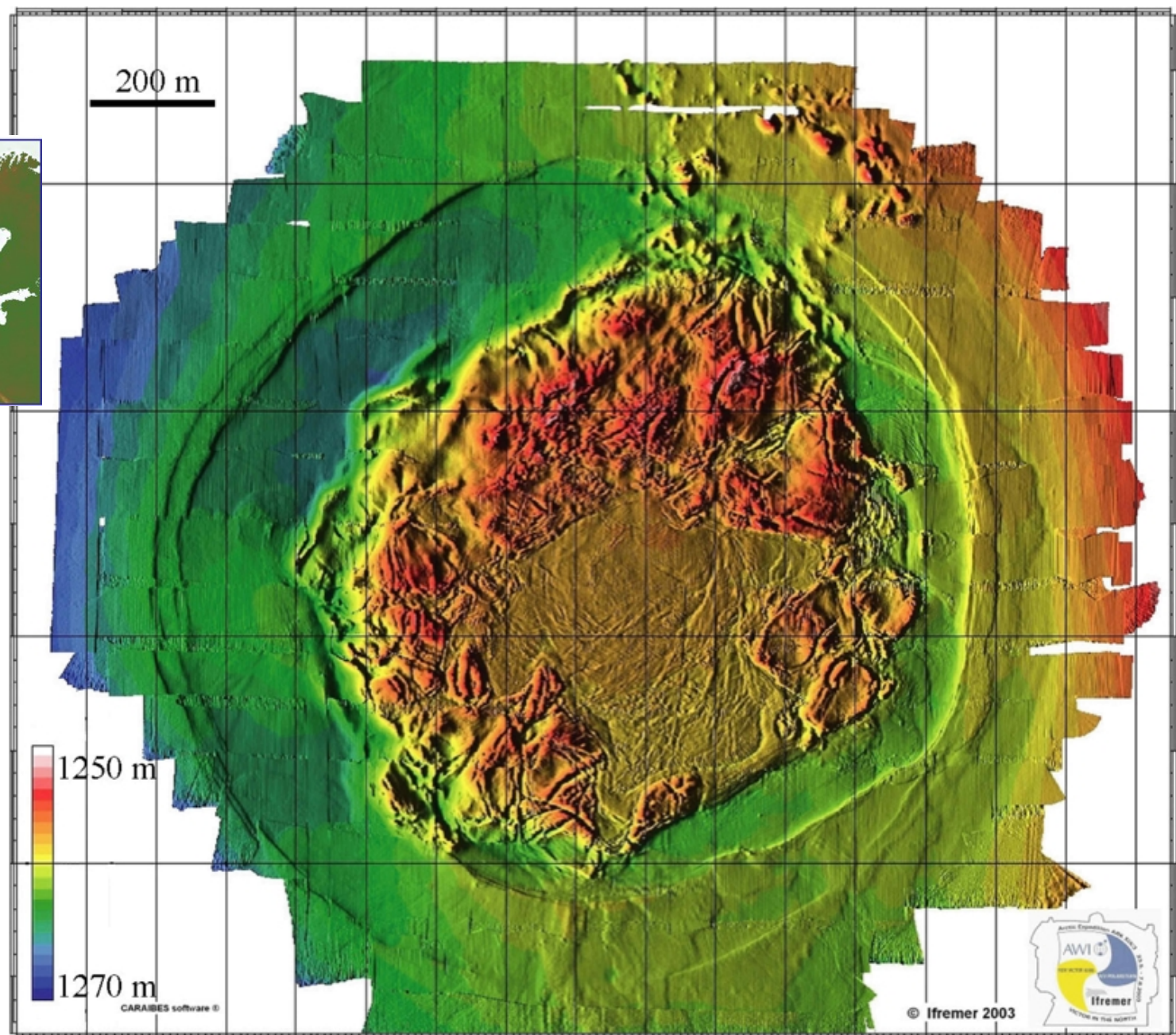
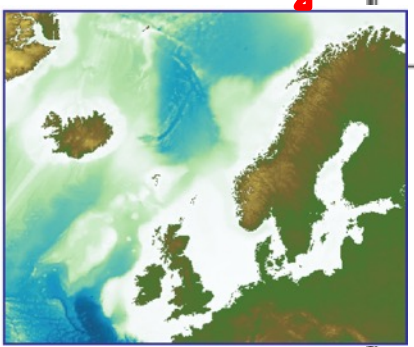
$$\lambda = 0 \text{ if } P_f = P_{hy}$$

$$\lambda = 1 \text{ if } P_f = P_d = \text{fluid movement (liquid mud)}$$

Mud diapirs move when  $0 < \lambda < 1$

## MUD VOLCANOES IN THE WORLD

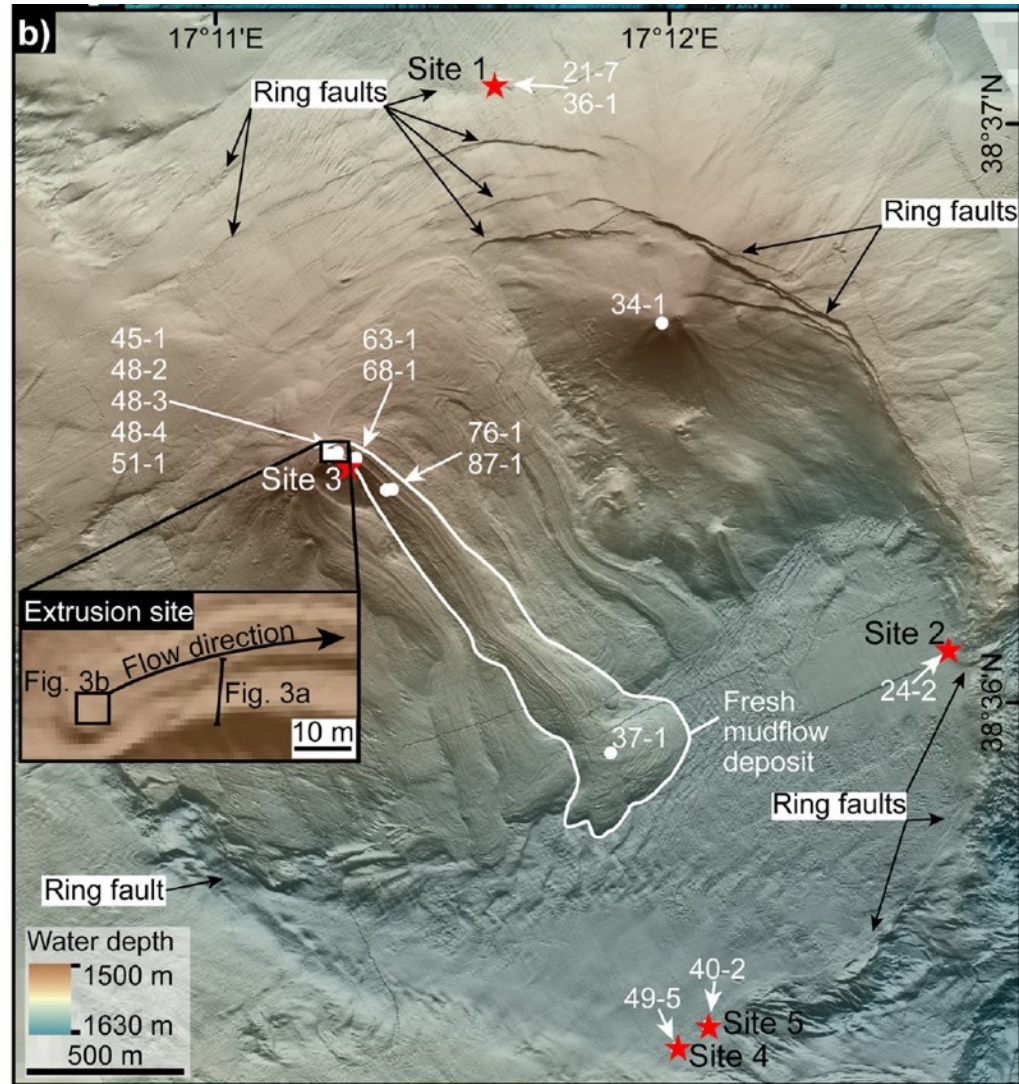
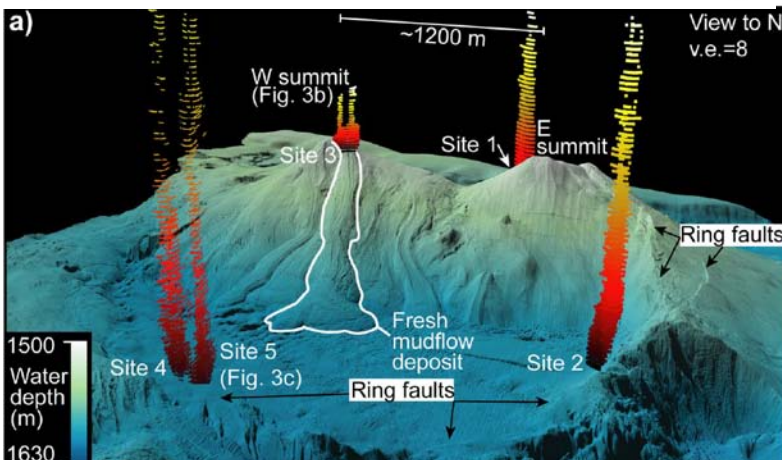
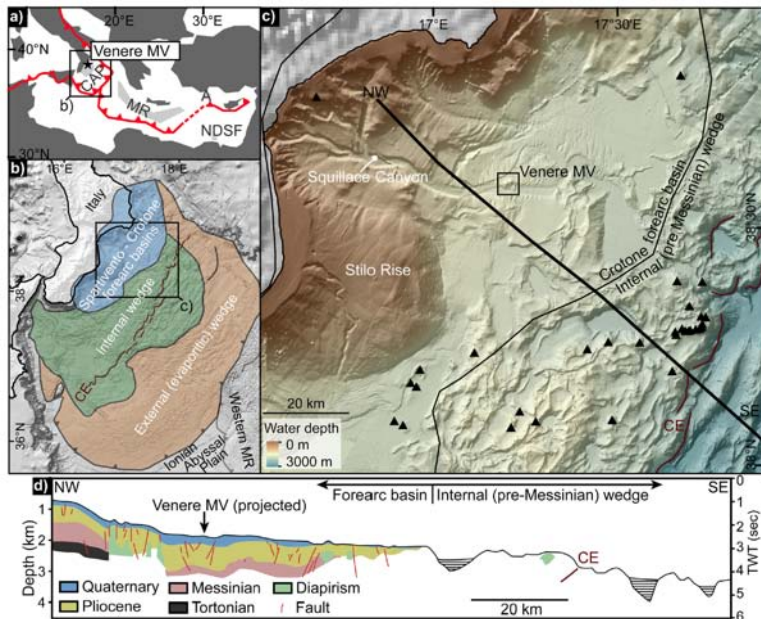




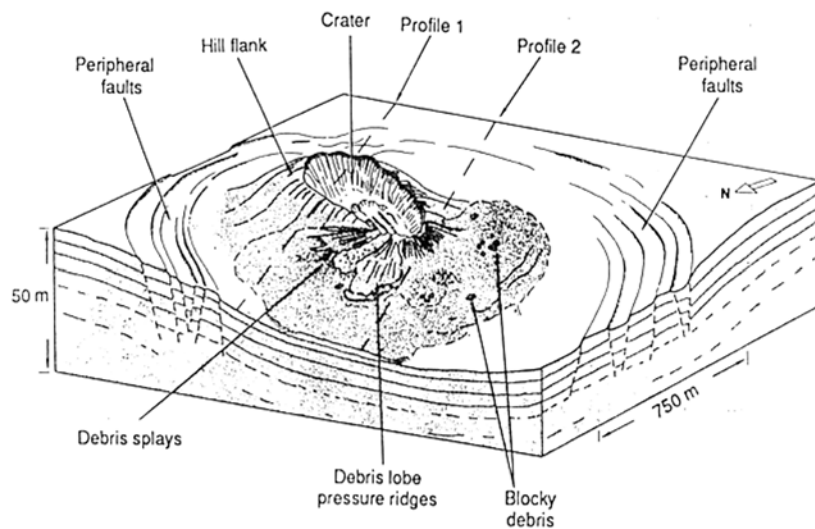
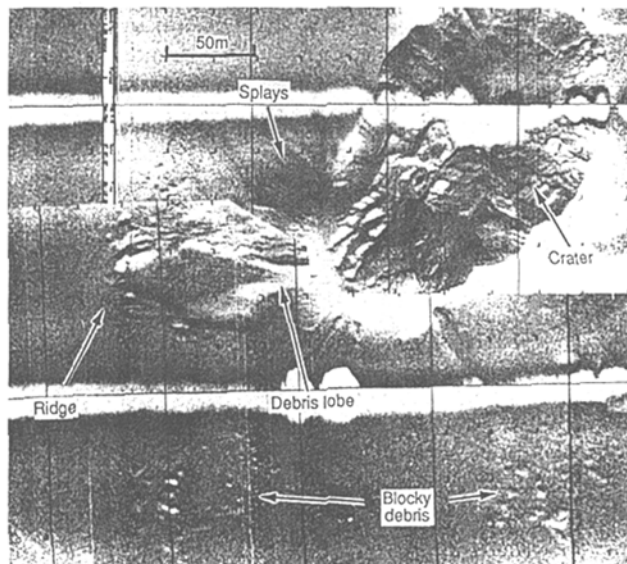
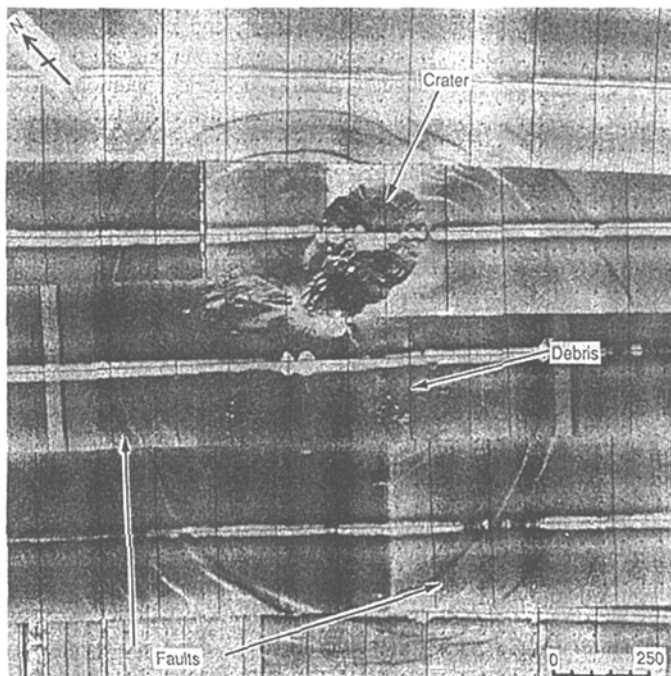
CARAIBES software ©

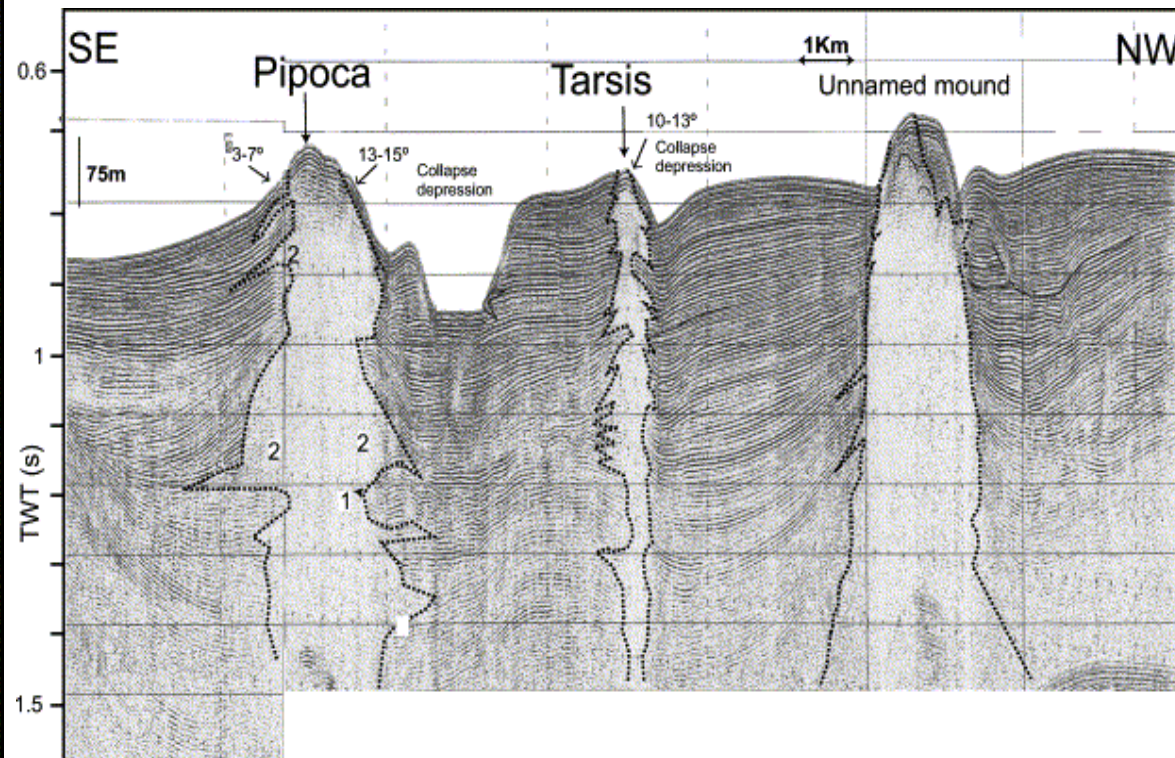
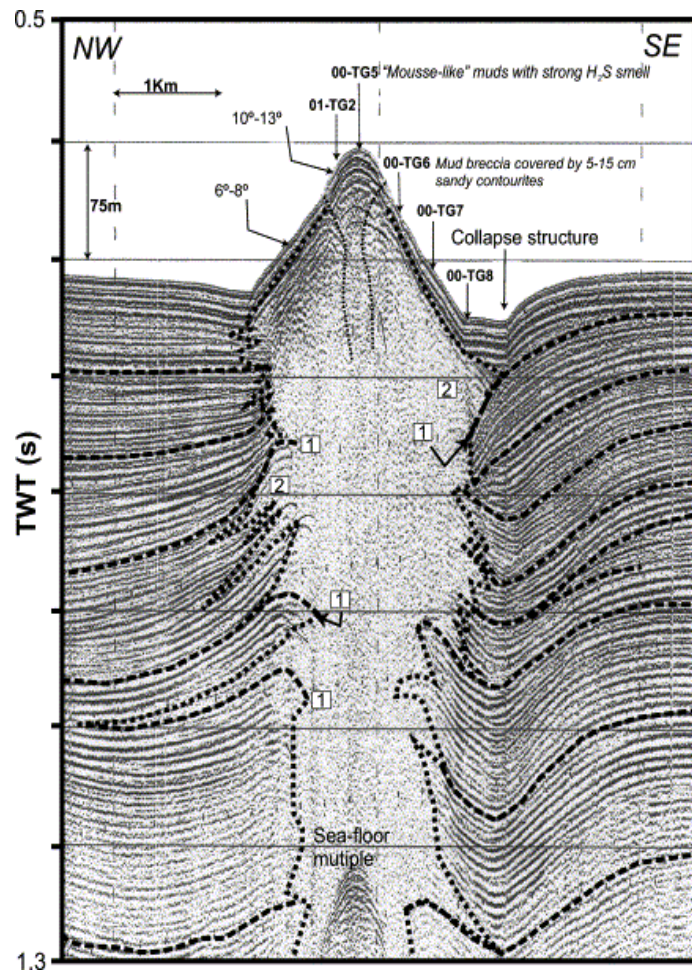
© Ifremer 2003





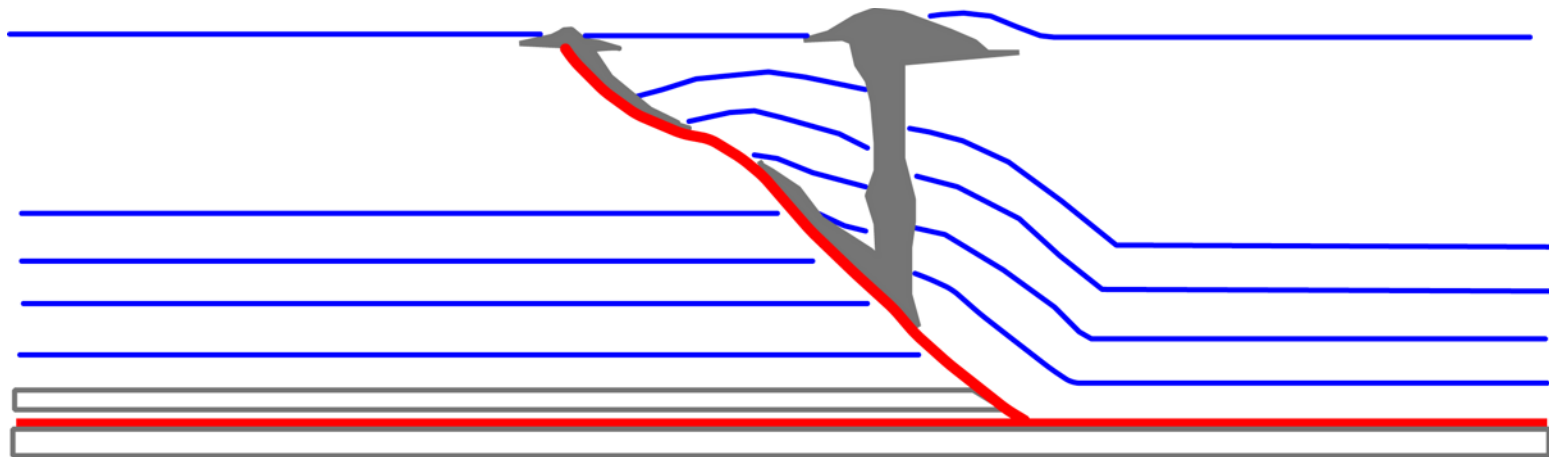
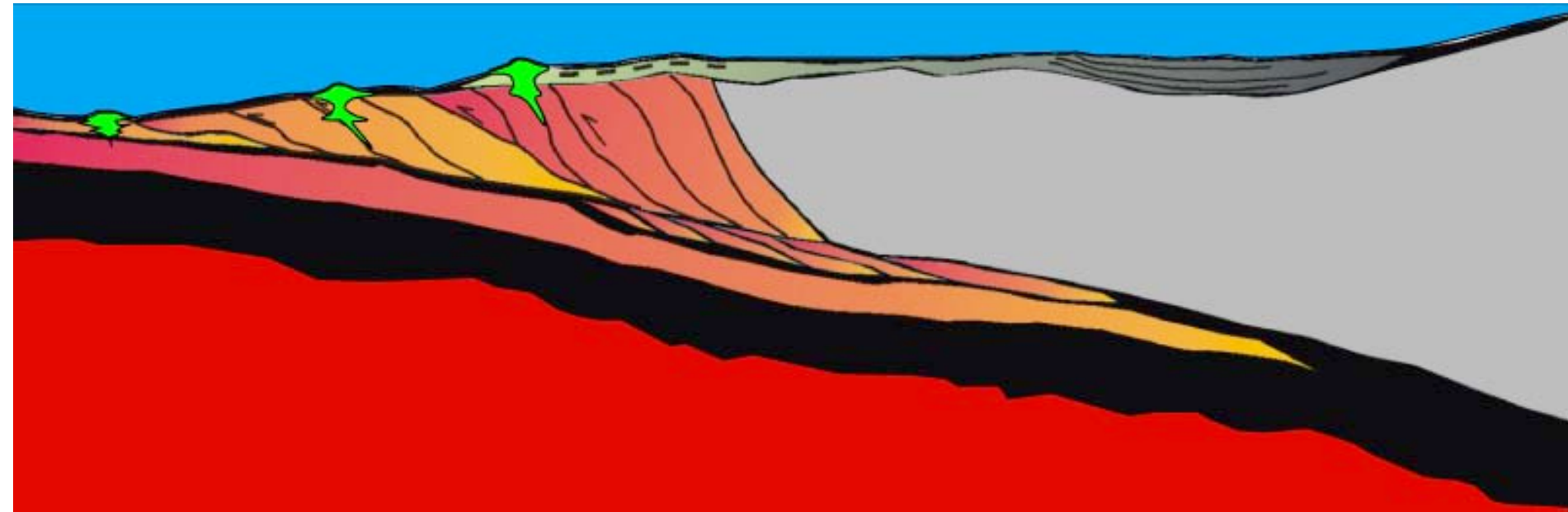
# Mud volcanoes in the Gulf of Mexico



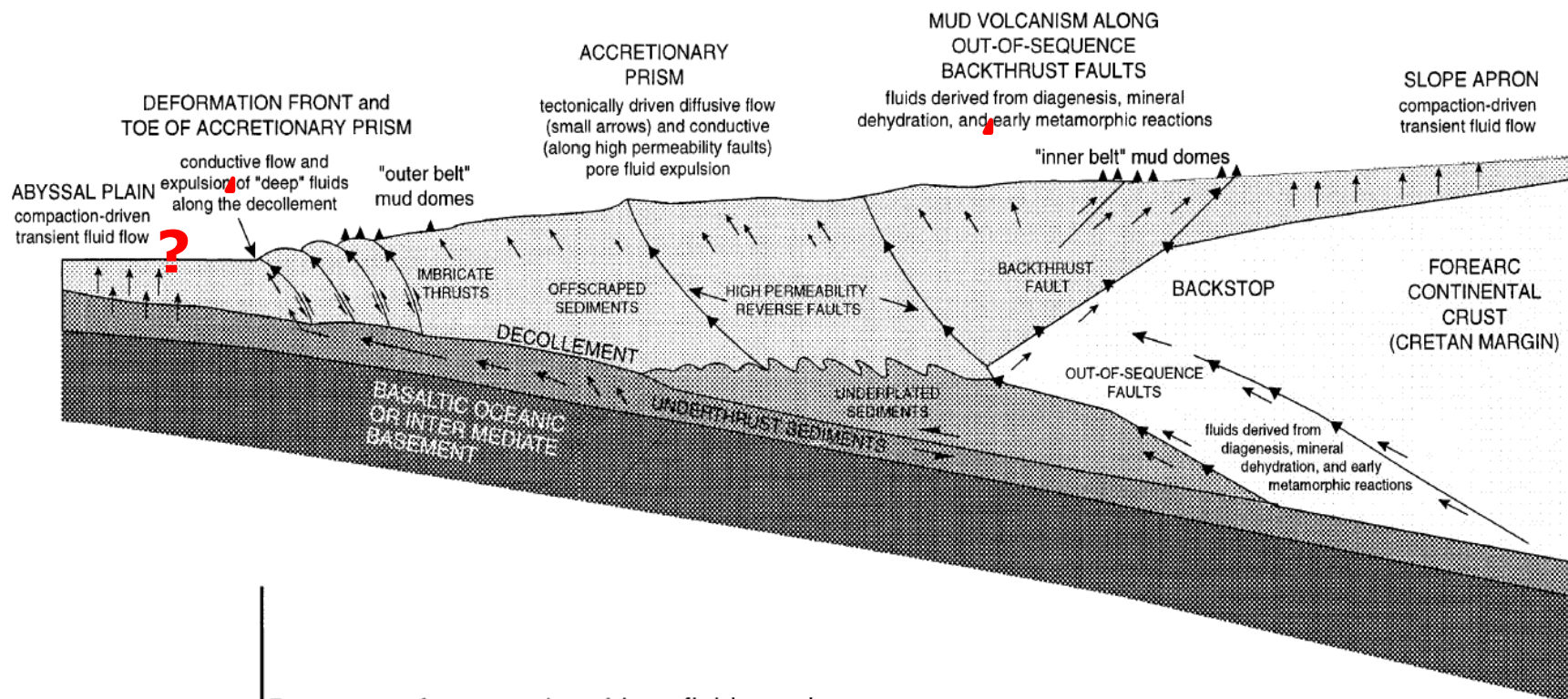


# Geological setting of mud volcanoes





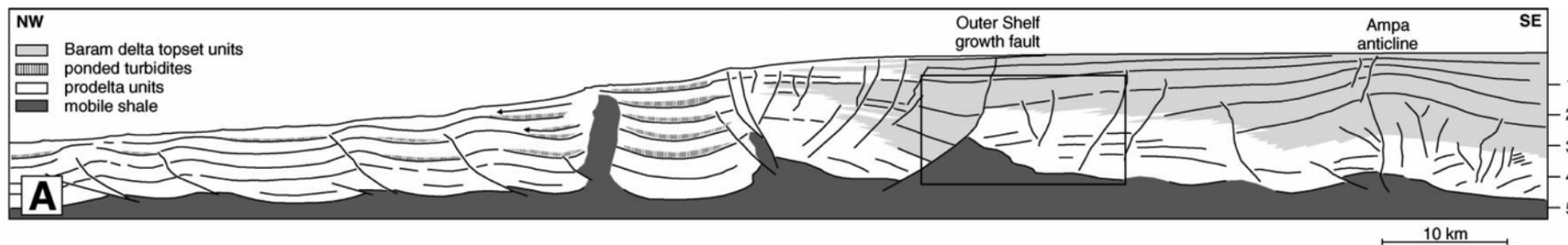




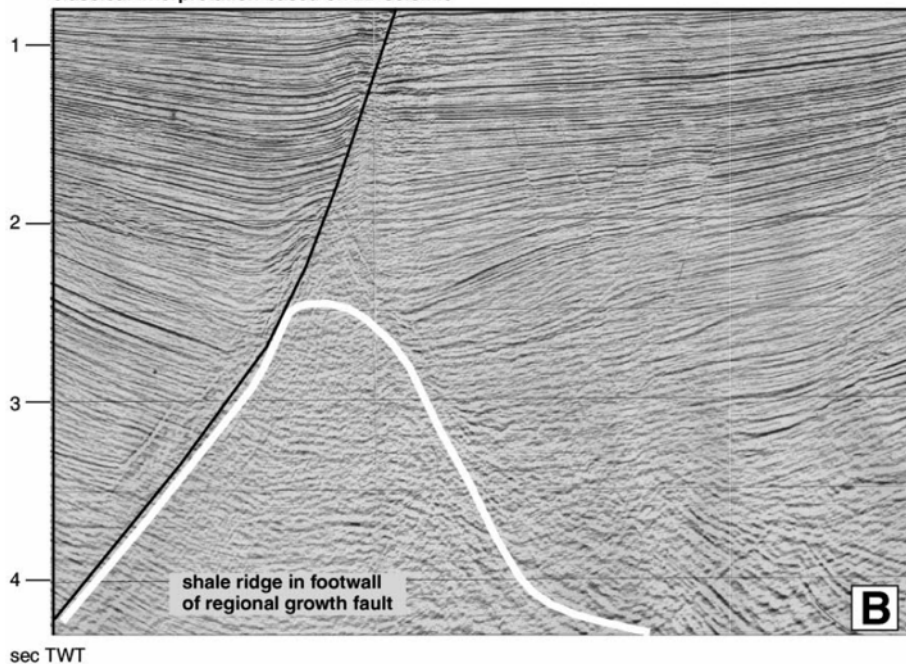
Decrease of compaction-driven fluid supply with distance from the deformation front

Increase of fluid supplied by diagenetic and metamorphic reaction with burial and enhanced tectonic compressive stress in the backstop region

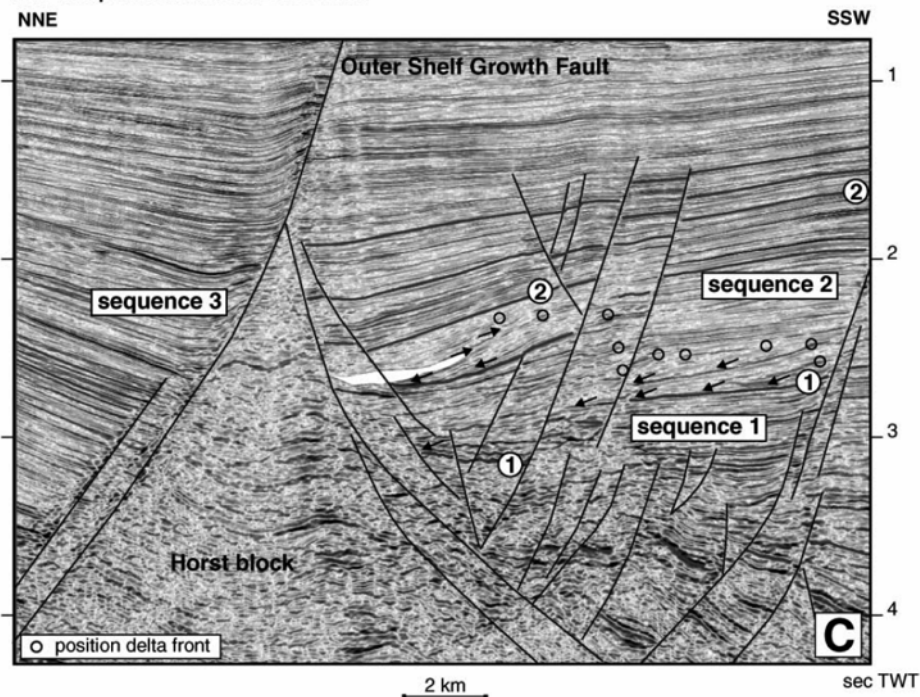
## Shale tectonics, Offshore Brunei



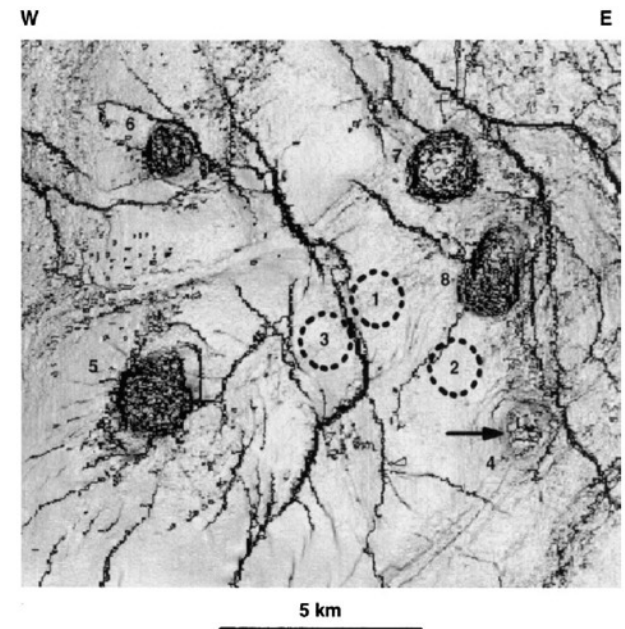
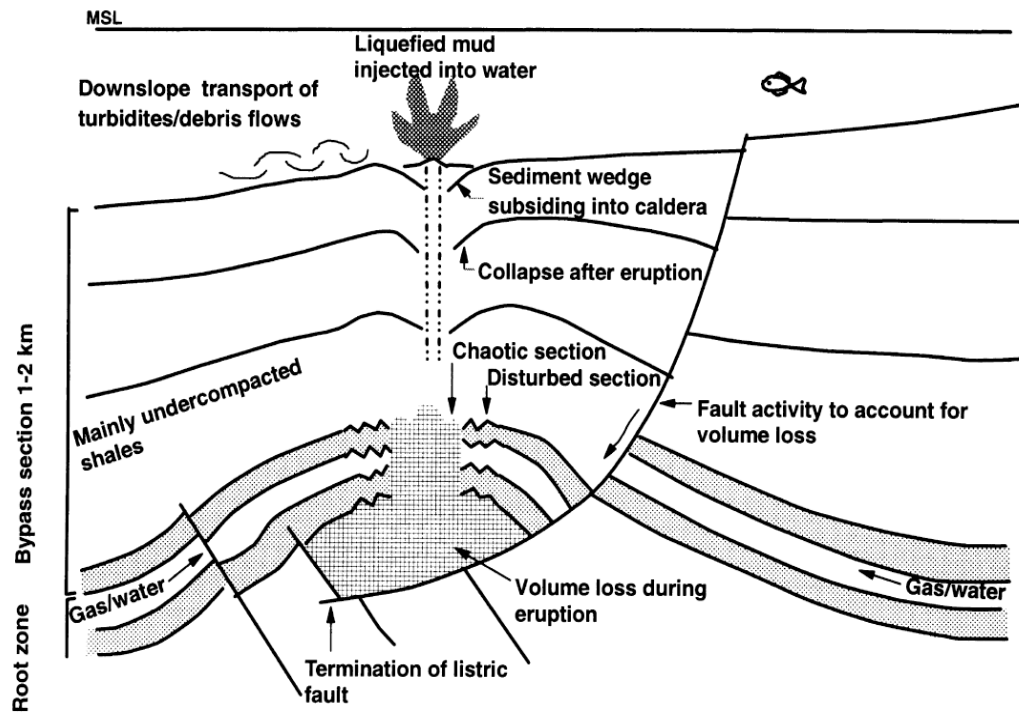
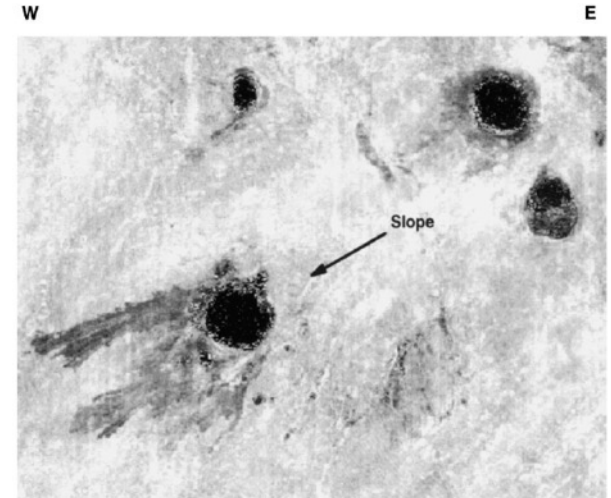
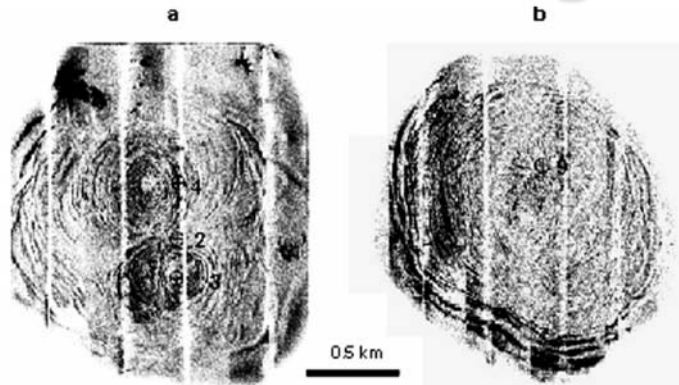
classical interpretation based on 2D seismic

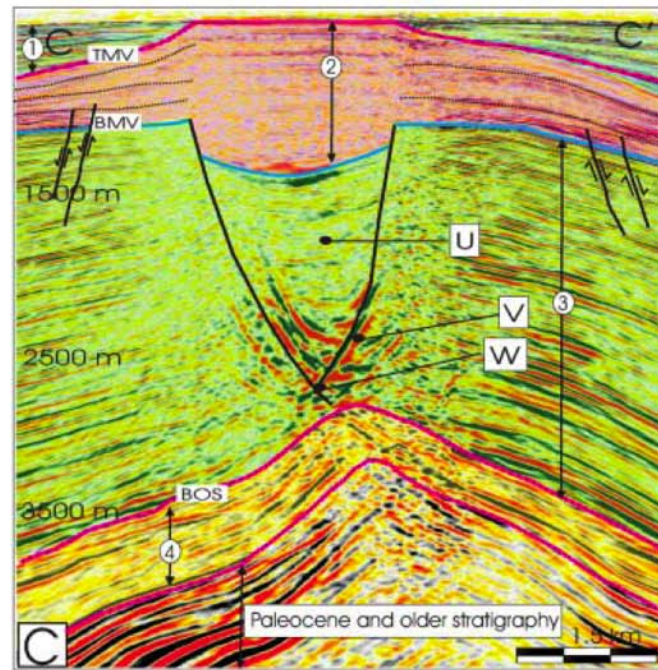
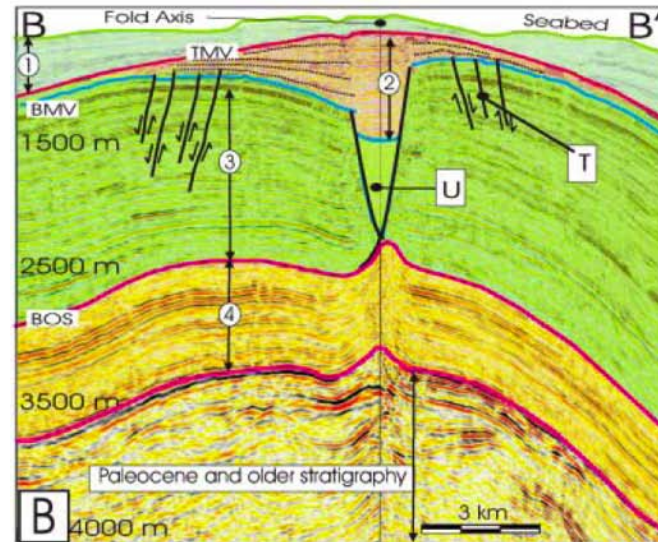
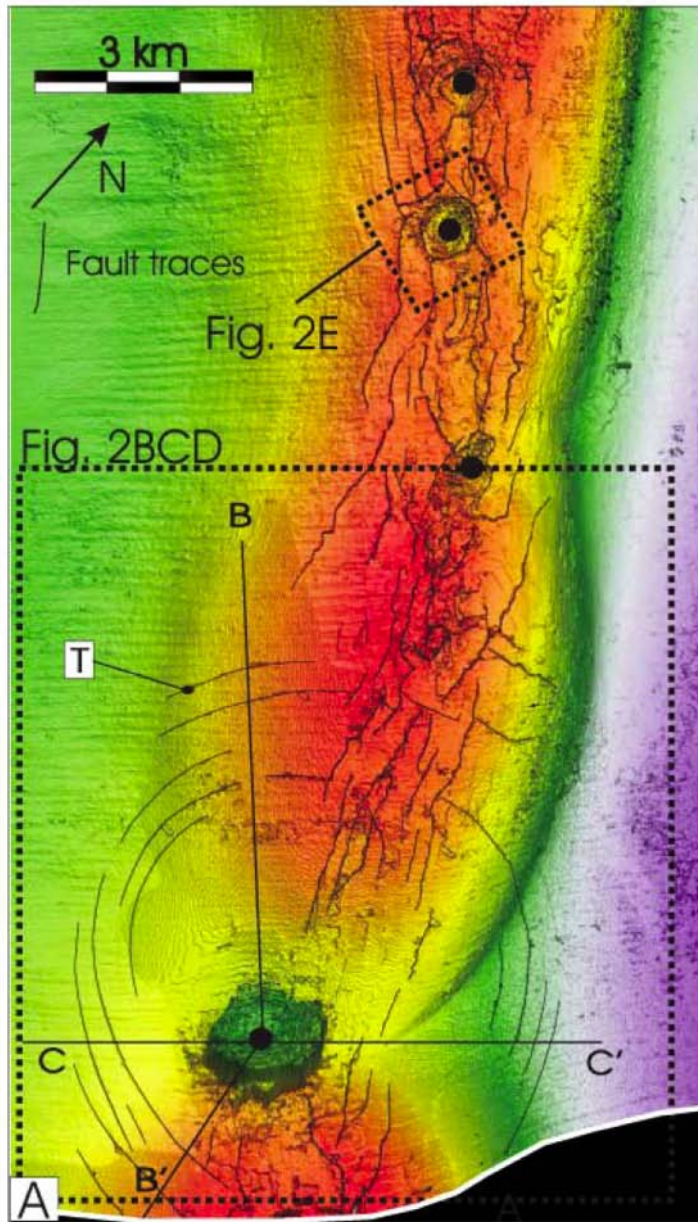


new interpretation based on 3D seismic



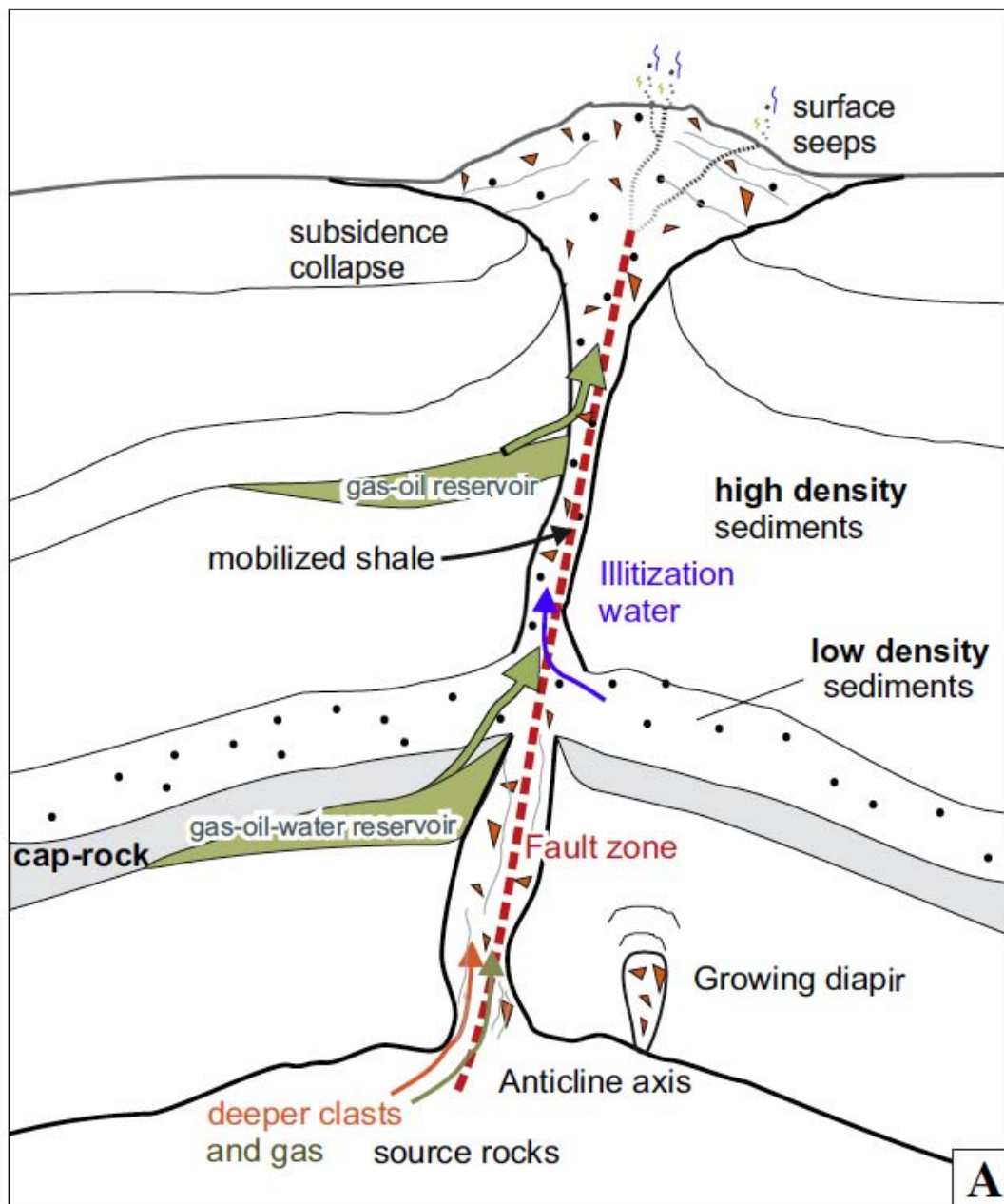
# Mud volcanoes offshore Nigeria



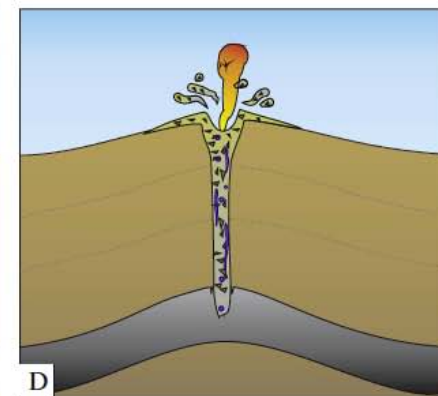
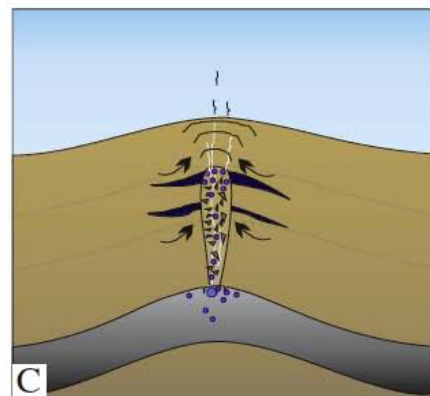
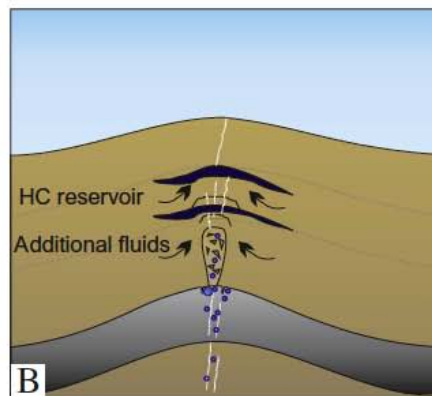
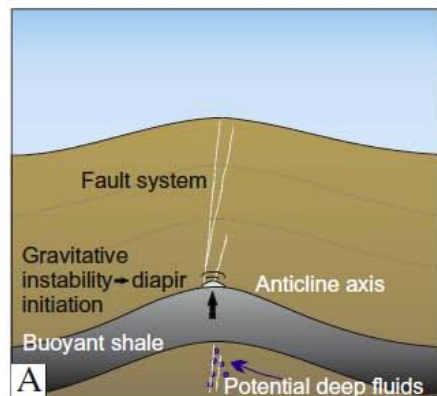


Davies and Stewart, 2005, J. Geol. Soc. London

## Mechanisms of emplacement



# Mechanisms of emplacement



*Diapir initiation in buoyant shales with potential deep fluids migration along structural highs (e.g. anticline axes) or fault networks*

*Fluids migration from different units and overpressure increase, diapiric structure development and brecciation during its growth*

*Overpressured diapir reaches critical depth. Overburden cannot contain fluids rich diapir. System in unstable conditions ready for triggering*

*Blast of gas. The sudden pressure release allows large amount of fluidized and gas saturated sediments to reach the surface*

## THE DISCOVERY OF SUBMARINE MUD VOLCANOES IN THE MEDITERRANEAN SEA

- **1981** Mud volcanoes were first reported in the Eastern Mediterranean by M.B. Cita, W.B. Ryan and L. Paggi.



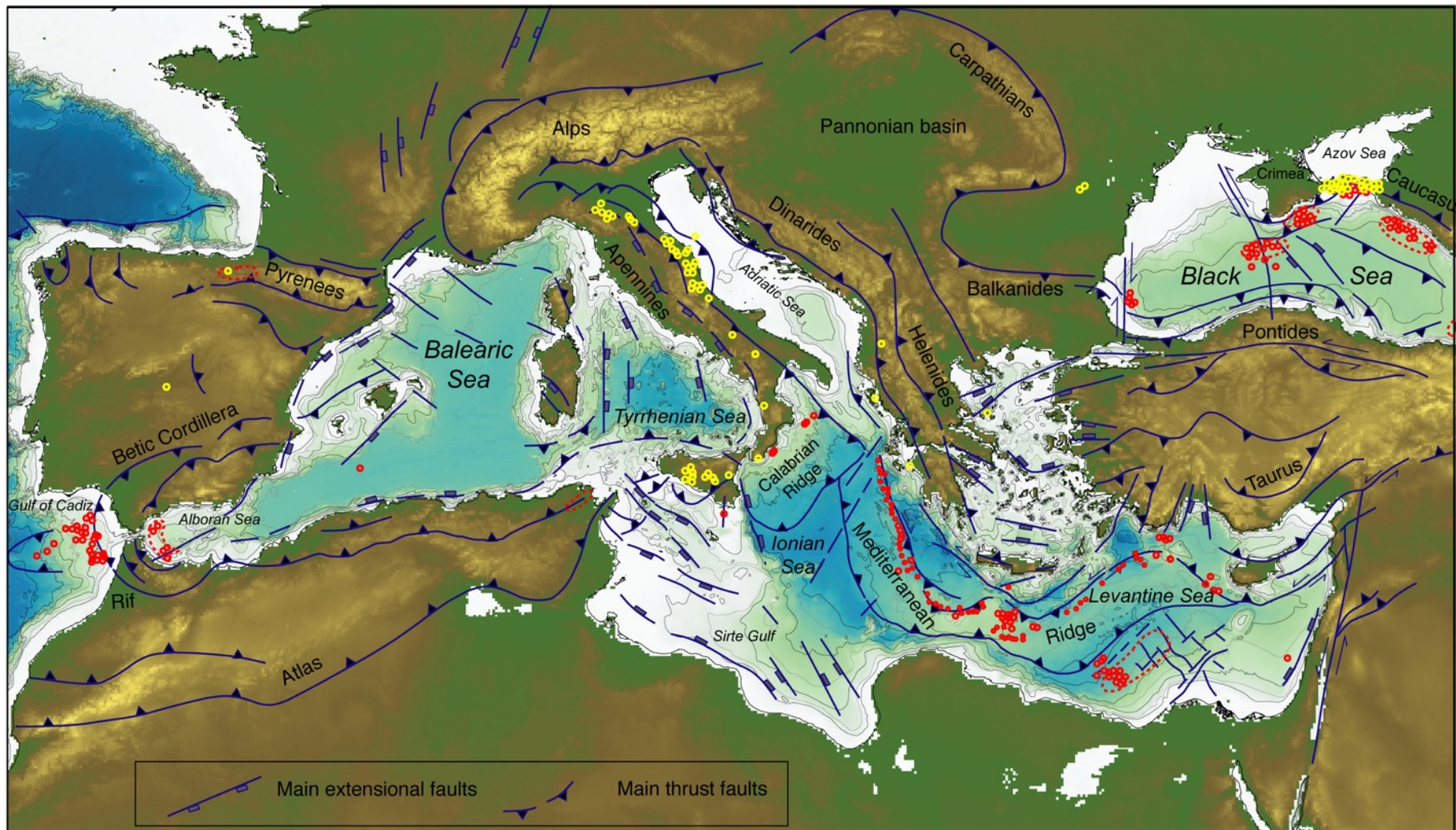
The Prometheus dome was identified according to:

Morphology: wrinkled surface of small concentric ridges;

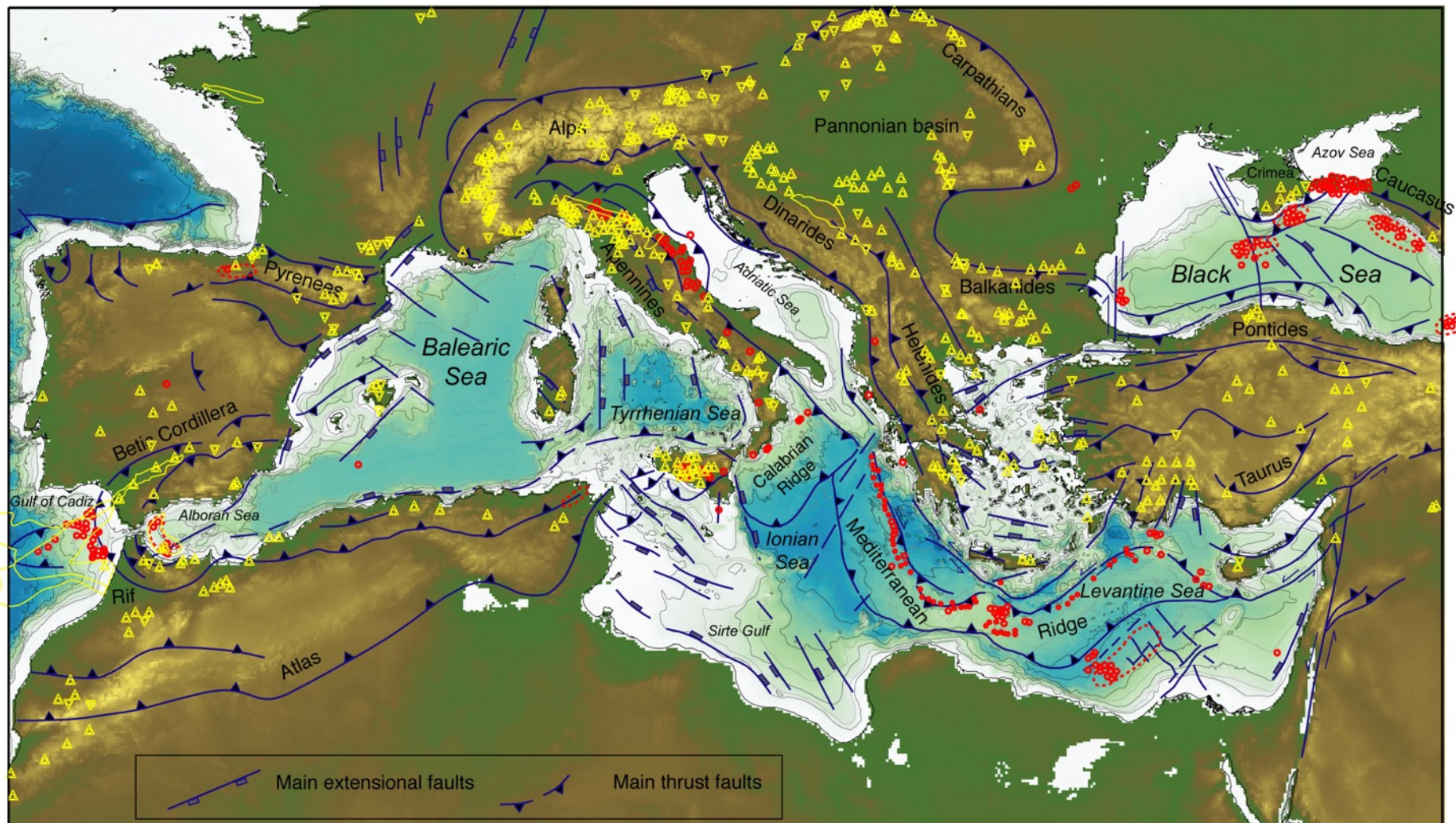
Acoustic character: no penetration, no coherent reflections

Lithologic composition : **MUD BRECCIA**, structureless pebbly mud with dominantly angular semi-indurated clasts of various, non carbonatic composition. The matrix contains foraminiferal species dating to the Aptian-Cenomanian.

It was interpreted as a SHALE DIAPIR, and a comparison between the chaotic sedimentary facies of the Prometheus dome and the Argille Scagliose was immediately presented to the public.







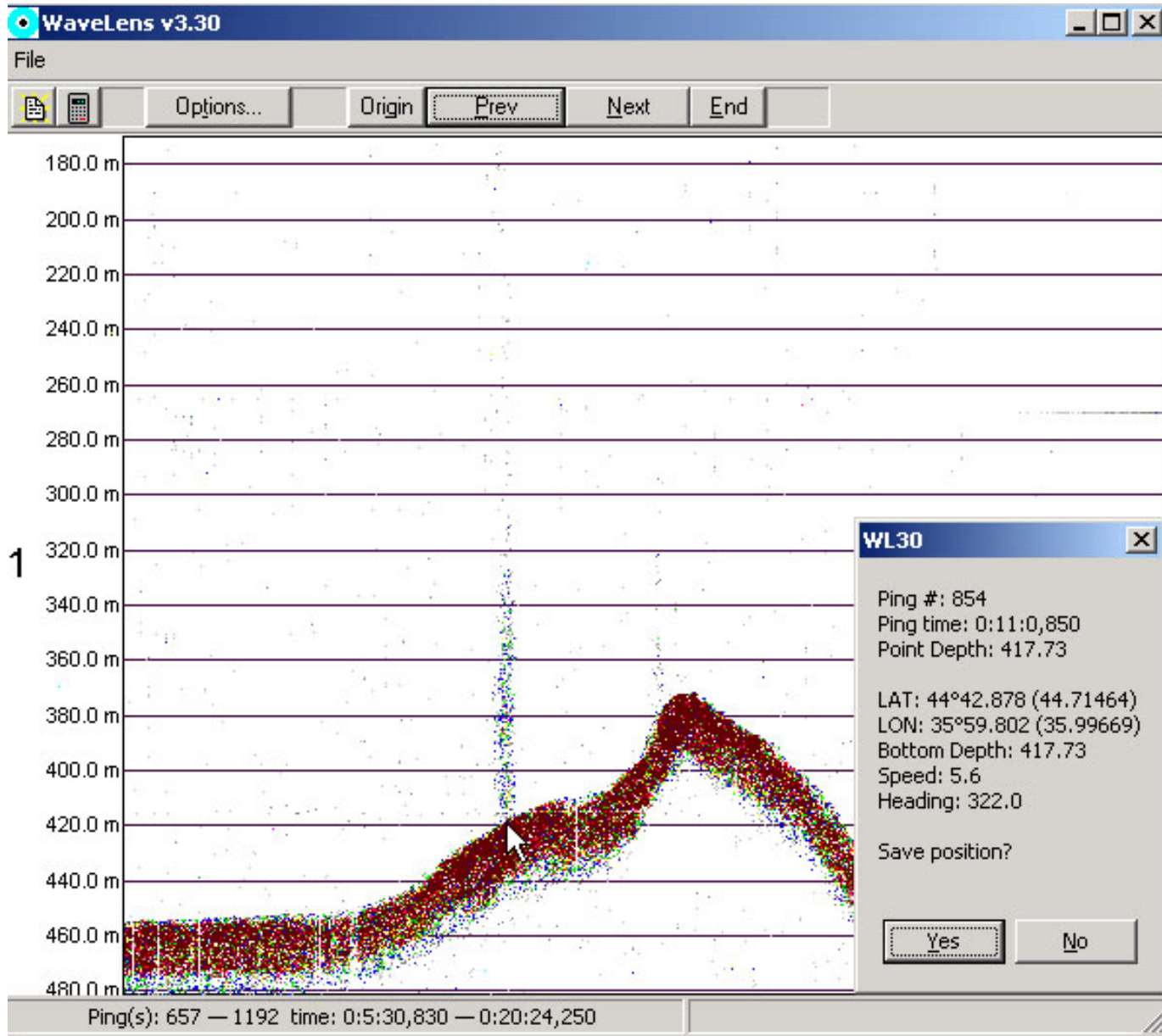
## References:

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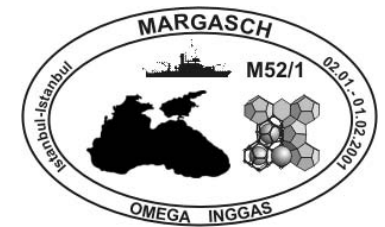
## Outline

Review of main mechanisms of fluid flow:

- Mud diapirs and mud volcanoes
- **Gas chimneys**
- **Pockmarks**
- **Seafloor vents in general**
- **Polygonal fault systems**
- **Diagenetic fronts**
- Gas hydrates

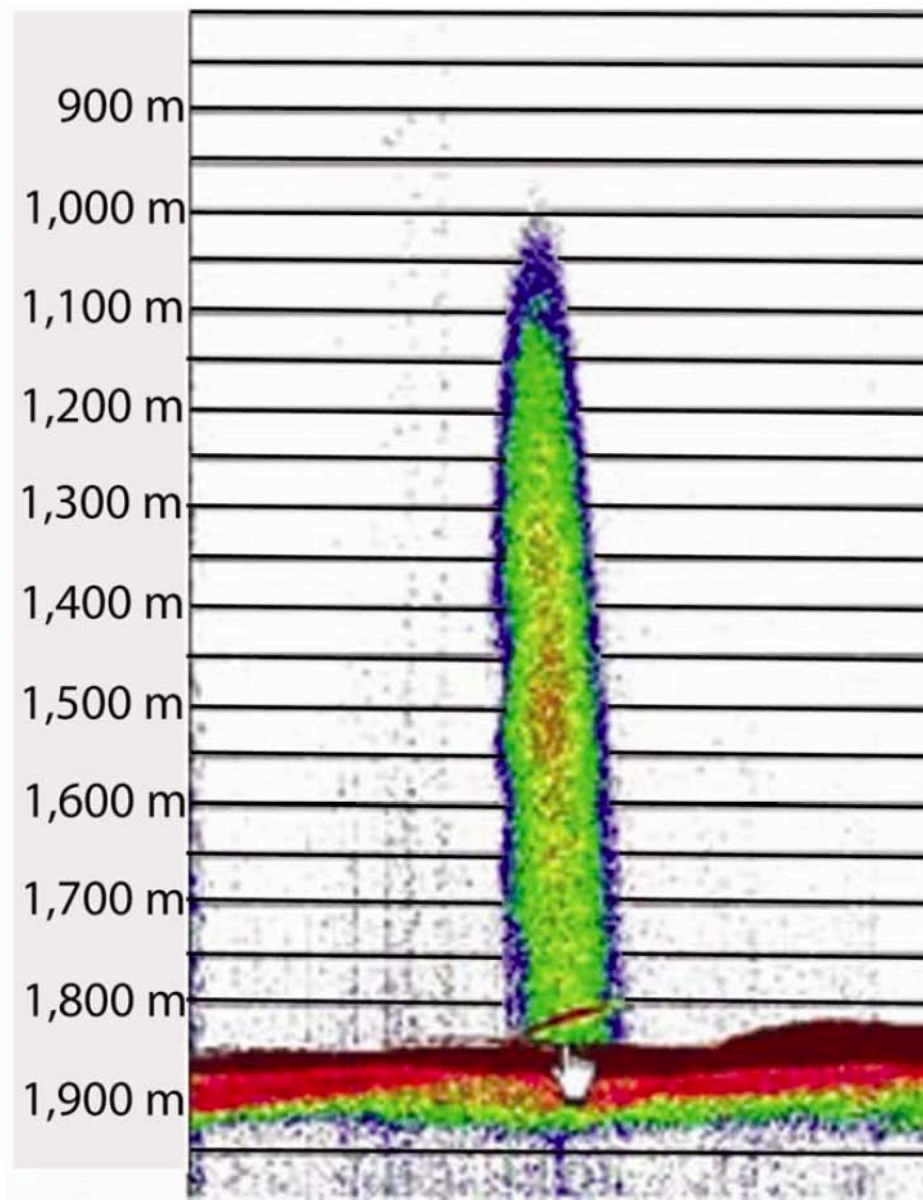


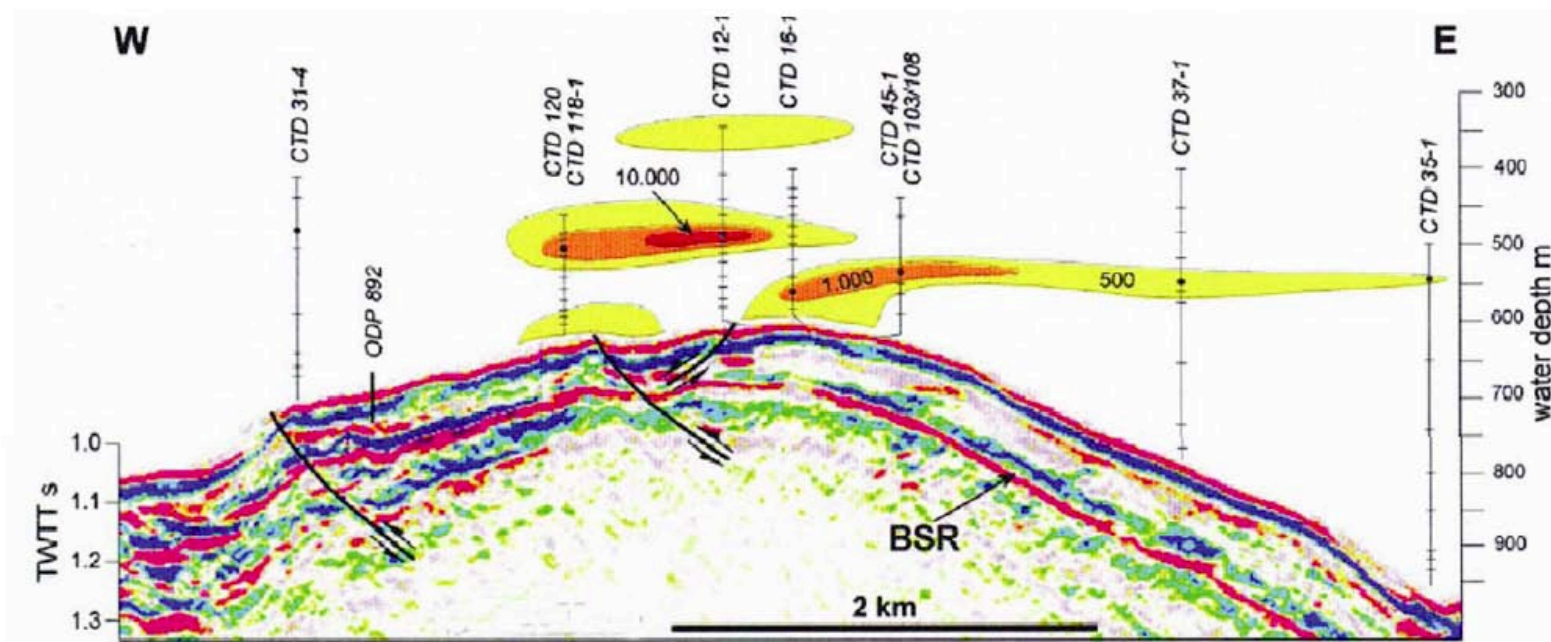
G. Bohrmann, Initial results from M52/1 MARGASCH



Parametric echo sounder image of a 'flare' (intense water column target caused by vigorous gas seepage) rising 850 m from the seabed in the NW Black Sea.

Judd and Hovland, 2007. *Seabed Fluid Flow*.





Methane concentration in the  
seawater from methane sensors  
on CTD casts

**Gas chimneys** are vertical zones in some way or other have been 'disturbed' by previous or on-going gas migration.

Exactly what has caused this acoustically-detected disturbance is still unknown, although it is believed that small (metre-sized) parcels of trapped gas and slightly displaced sediments may be involved. In many cases, rather than a distinct chimney, gas may be present as an amorphous cloud.

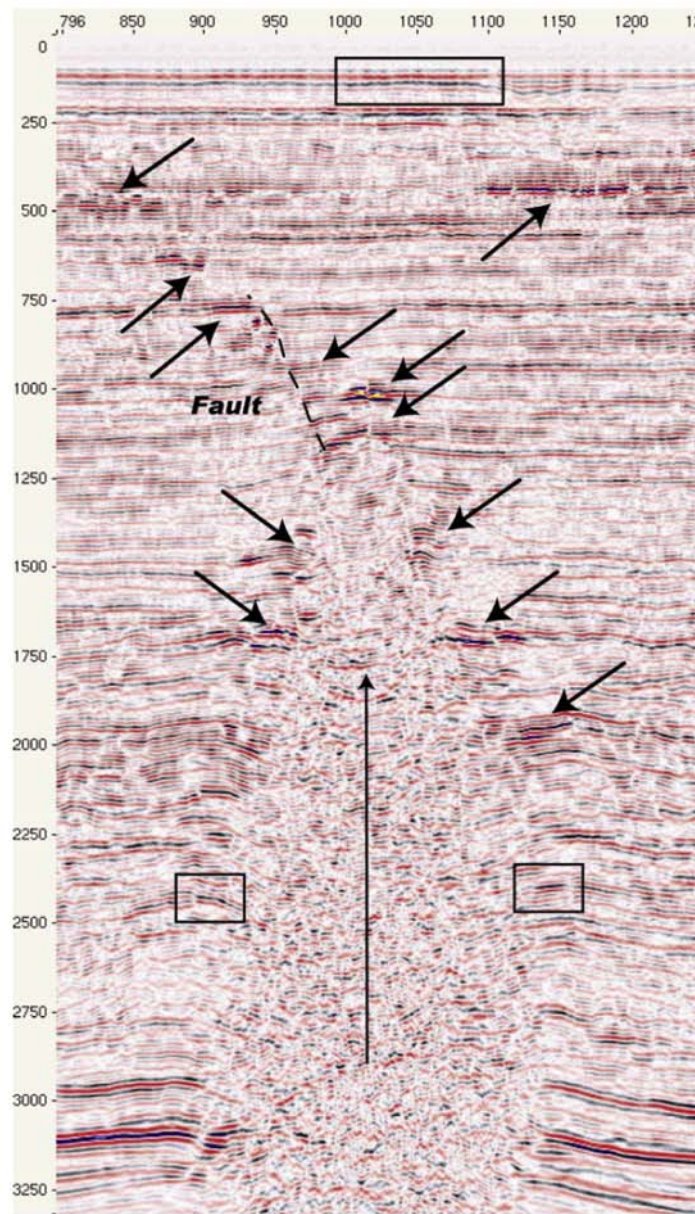
**Gas accumulations provoke a high acoustic impedance contrast**

**>>>> High reflectivity.**

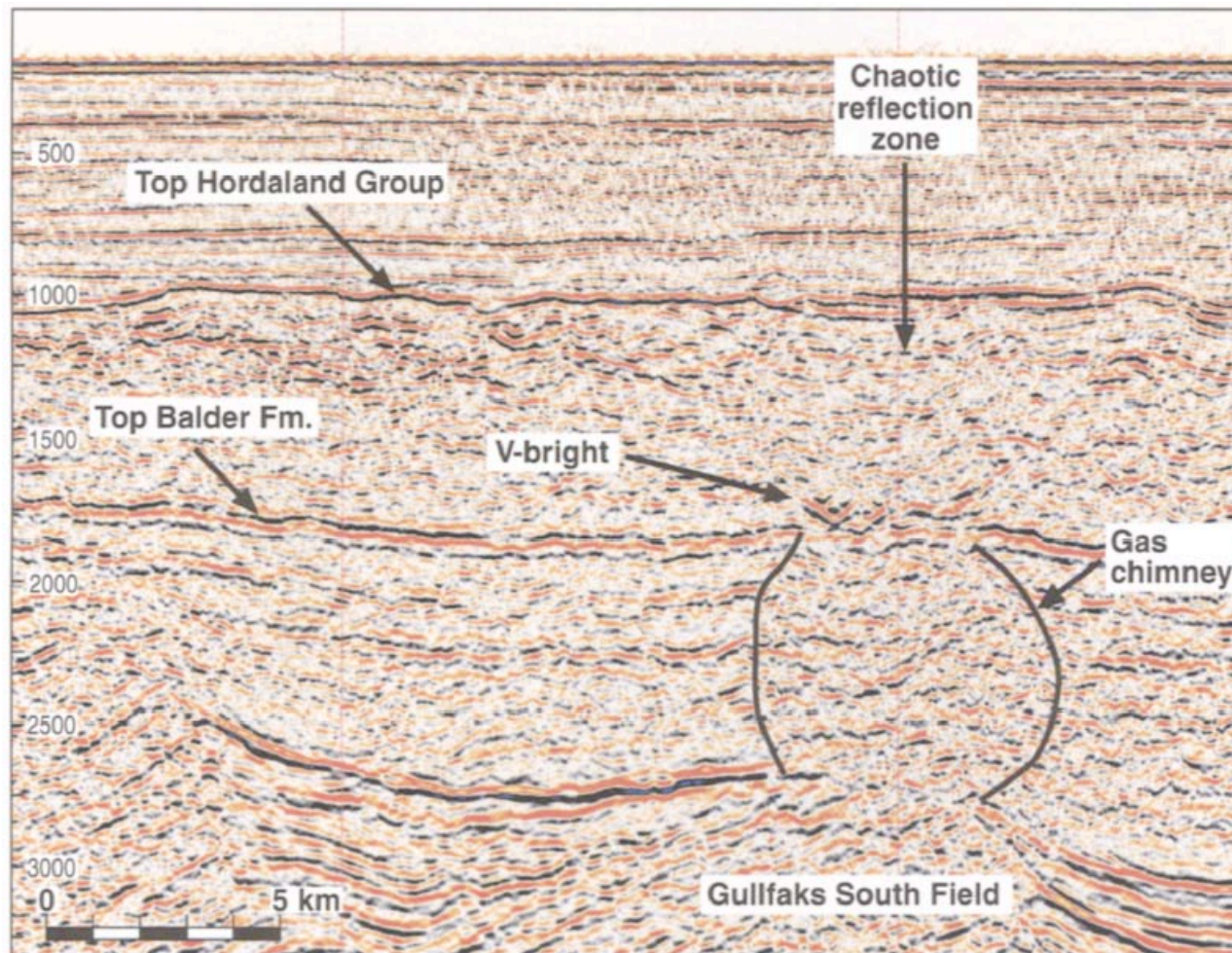
- **Enhanced seismic reflections**
- **Bright spots**
- **Flat spots**
- **Acoustic blanking**
- **Columnar disturbances, gas chimneys, pipes**
- **BSR (in case of gas hydrates)**

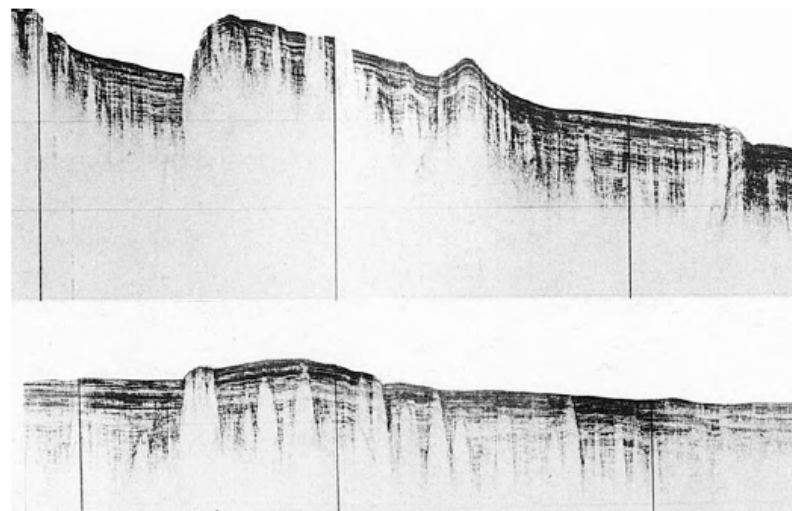
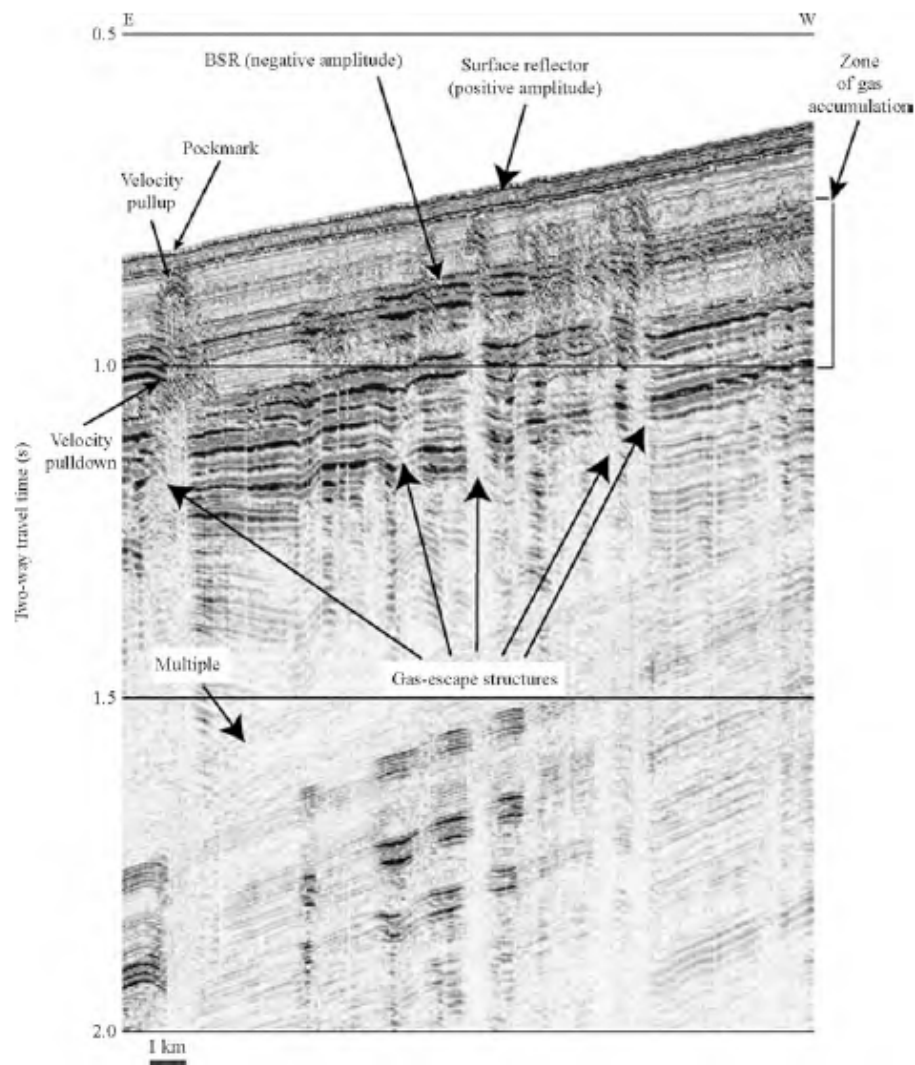
Seismic section across the Tommeliten Delta structure, a salt piercement diapir. The noisy zone is interpreted as a gas chimney through which gas rises vertically (as indicated by the large arrow). Some gas escapes laterally to produce brightening of adjacent reflectors, and reducing the acoustic velocity ( $v_p$ ) to produce 'pull down' (examples are in the rectangles).

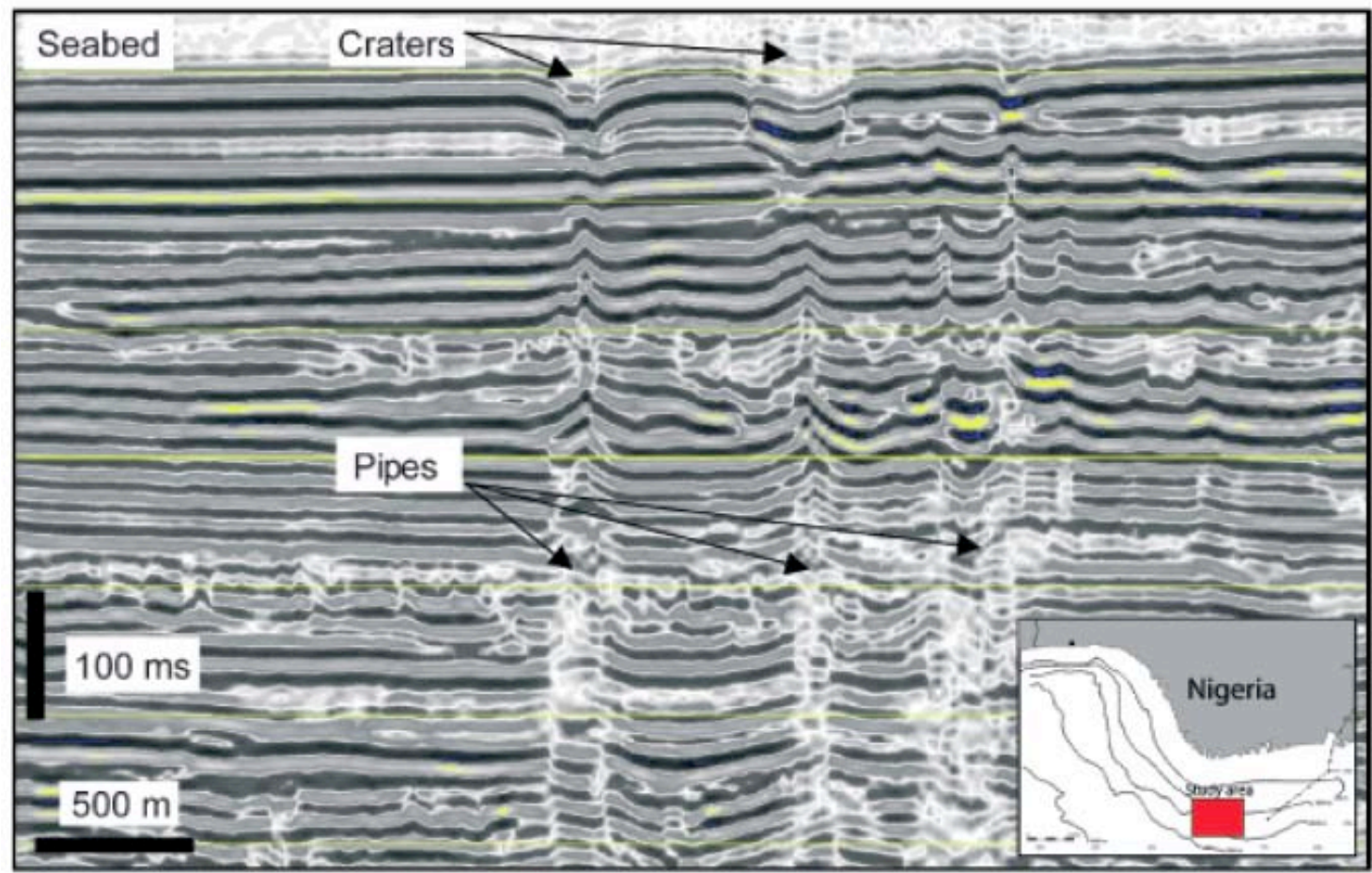
Judd and Hovland, 2007. *Seabed Fluid Flow.*

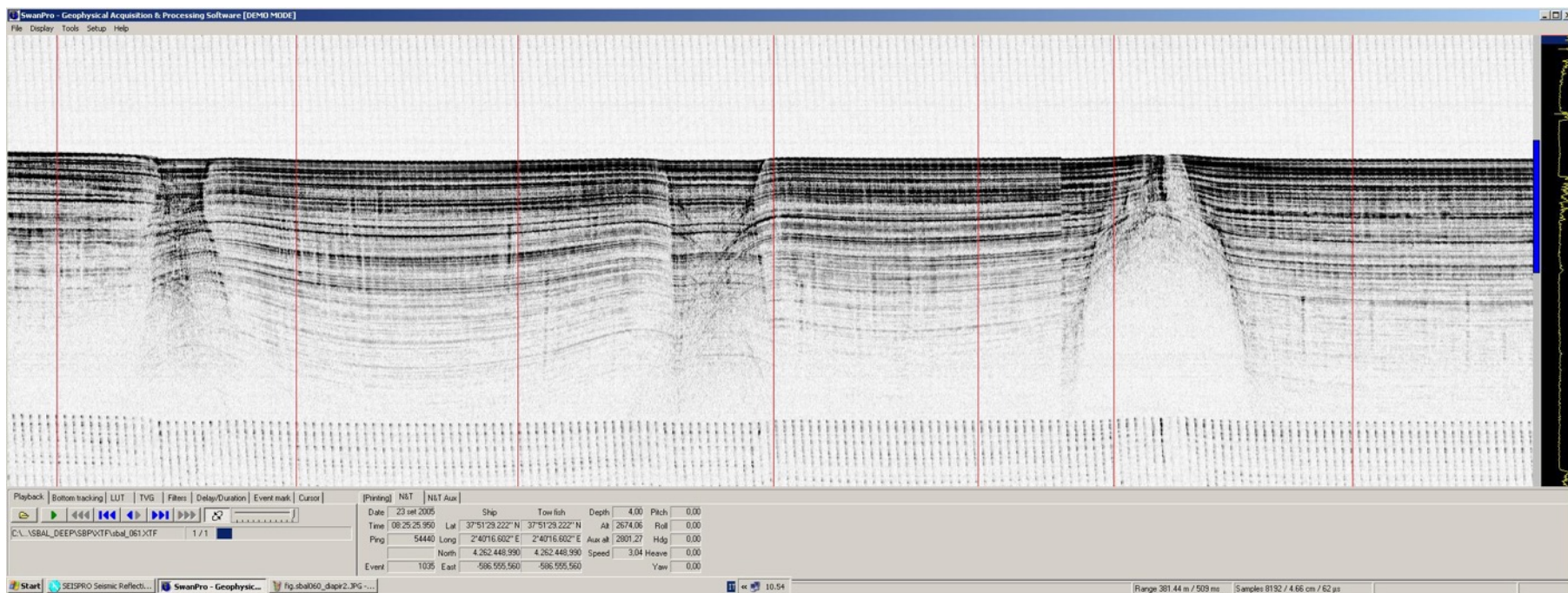
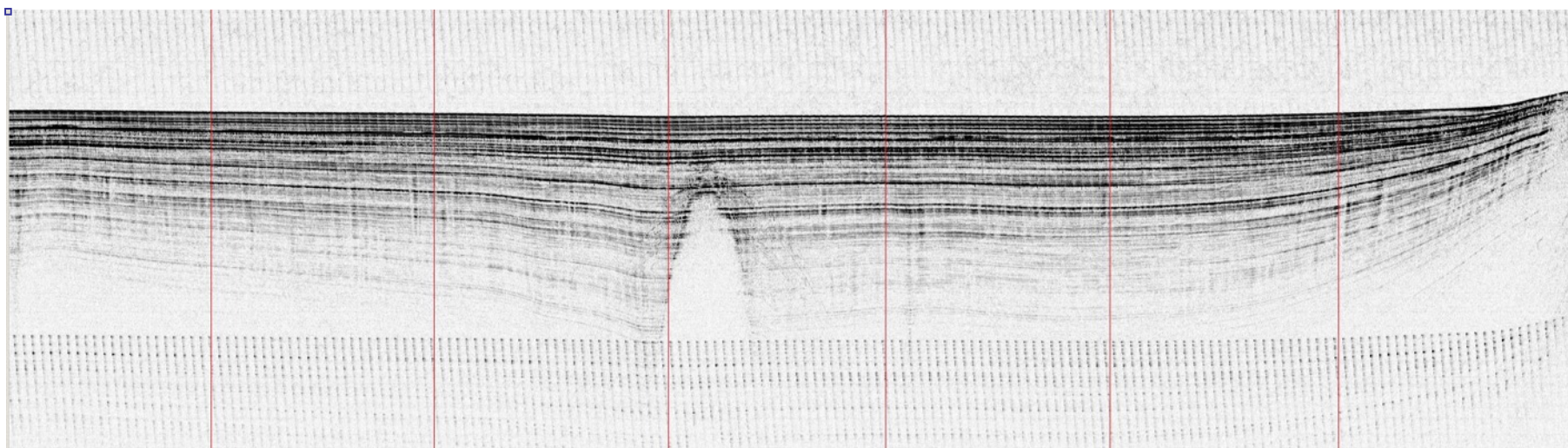












**Pockmarks** are shallow seabed depressions, typically several tens of metres across and a few metres deep.

Generally, they are formed in soft, fine-grained seabed sediments by the escape of fluids (gas or water, but mainly methane) into the water column.

Judd and Hovland, 2007. *Seabed Fluid Flow.*

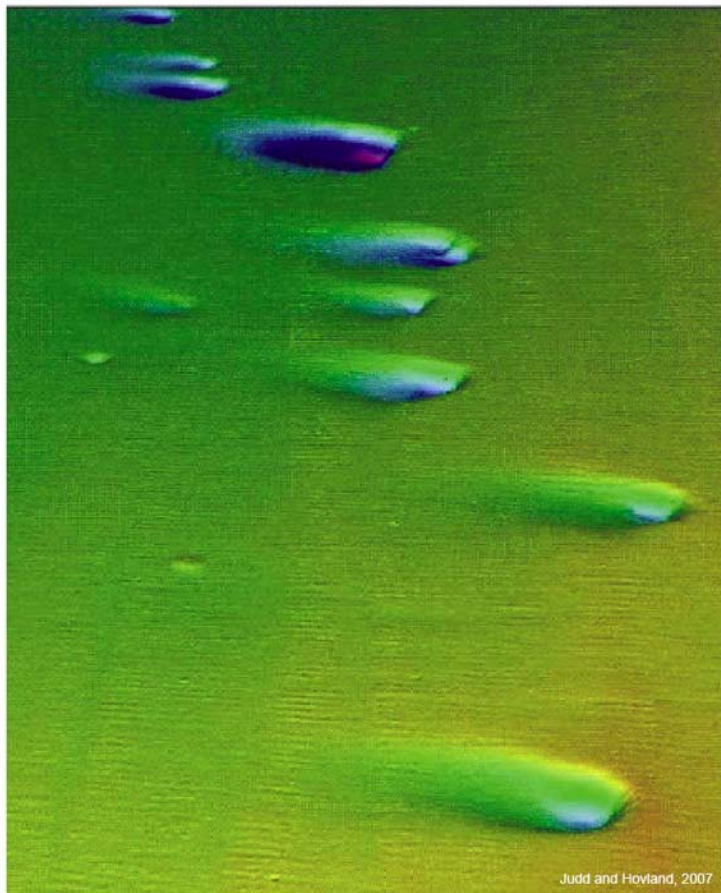


Figure 2.6: Assymmetric pockmarks, Witch Ground Basin, UK North Sea. Multi-beam echo sounder image [Image acquired by the UK government (Department of Trade and Industry) as part of the Strategic Environmental Assessment process.]

Judd and Hovland, 2007. *Seabed Fluid Flow.*

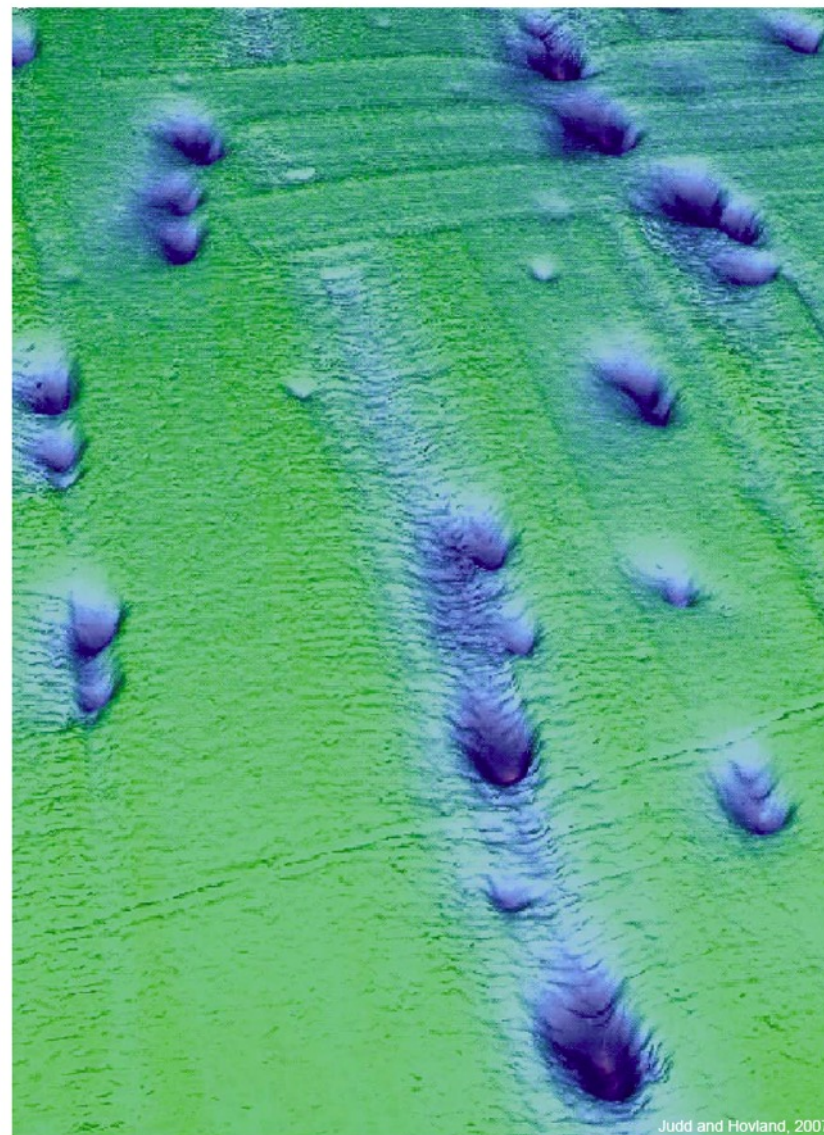


Figure 2.3: Typical North Sea pockmarks, Witch Ground Basin, UK North Sea. Multi-beam echo sounder image [Image acquired by the UK government (Department of Trade and Industry) as part of the Strategic Environmental Assessment process.]

Judd and Hovland, 2007. *Seabed Fluid Flow.*

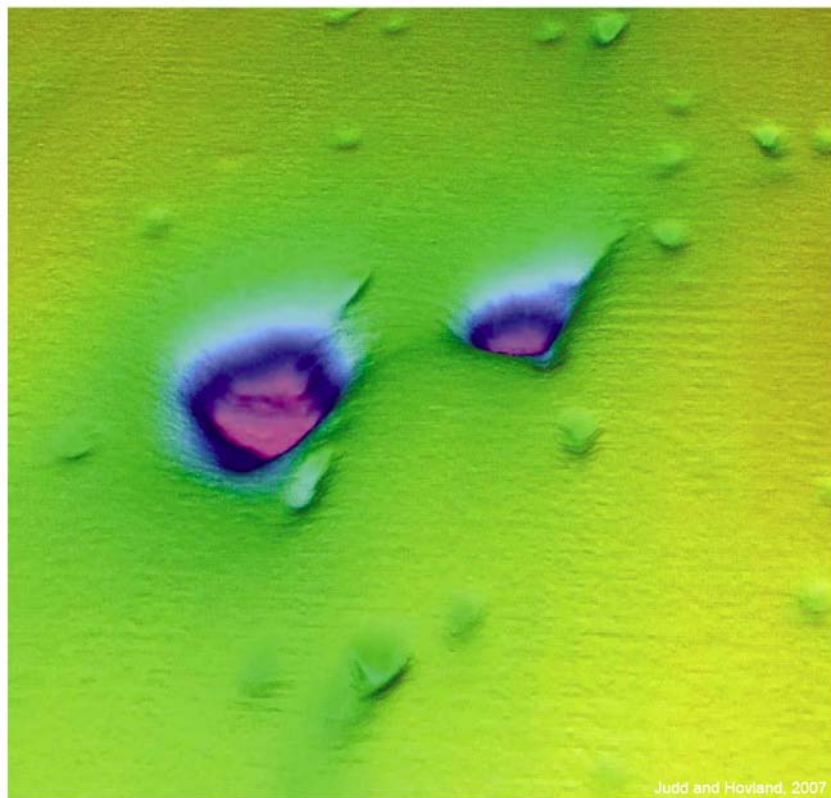


Figure 2.40: MBES image of the *Scanner* pockmark, Block UK15/25, North Sea. [Image acquired by the UK government (Department of Trade and Industry) as part of the Strategic Environmental Assessment process.]

Judd and Hovland, 2007. *Seabed Fluid Flow.*

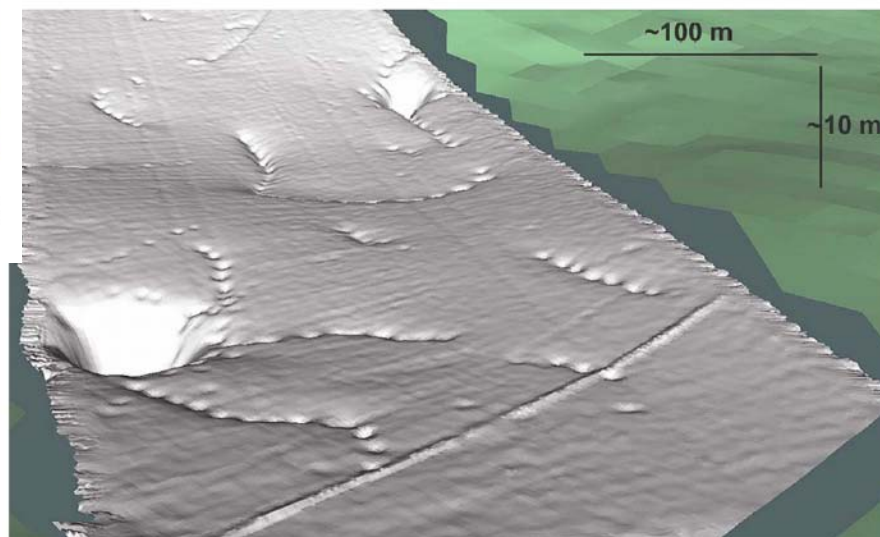


Figure 2.8: MBES image of pockmark strings in the Norwegian Sea. These strings have no preferred orientation, and some lead to (or from) large standard pockmarks. The 26 inch Haltenpipe pipeline is visible on the lower part of the image.

Judd and Hovland, 2007. *Seabed Fluid Flow*.

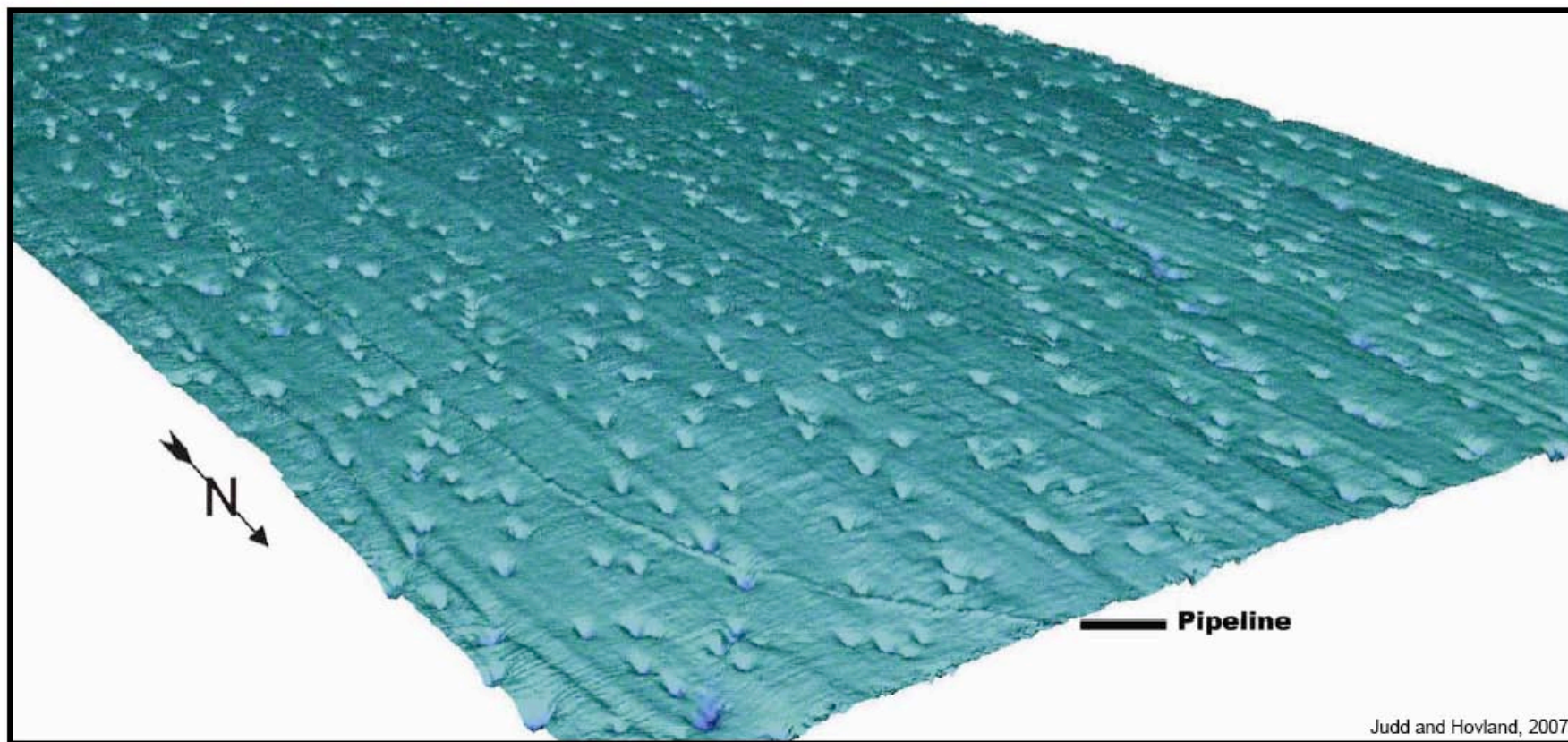


Figure 2.16: Pockmarks in the northern part of the South Fladen Pockmark Study Area; MBES survey, 2001. The pipeline (Scott-Forties Unity pipeline; 24 inch, 61 cm, diameter) gives an idea of the scale. [Image acquired by the UK government (Department of Trade and Industry) as part of the Strategic Environmental Assessment process.]



Judd and Hovland, 2007. *Seabed Fluid Flow.*

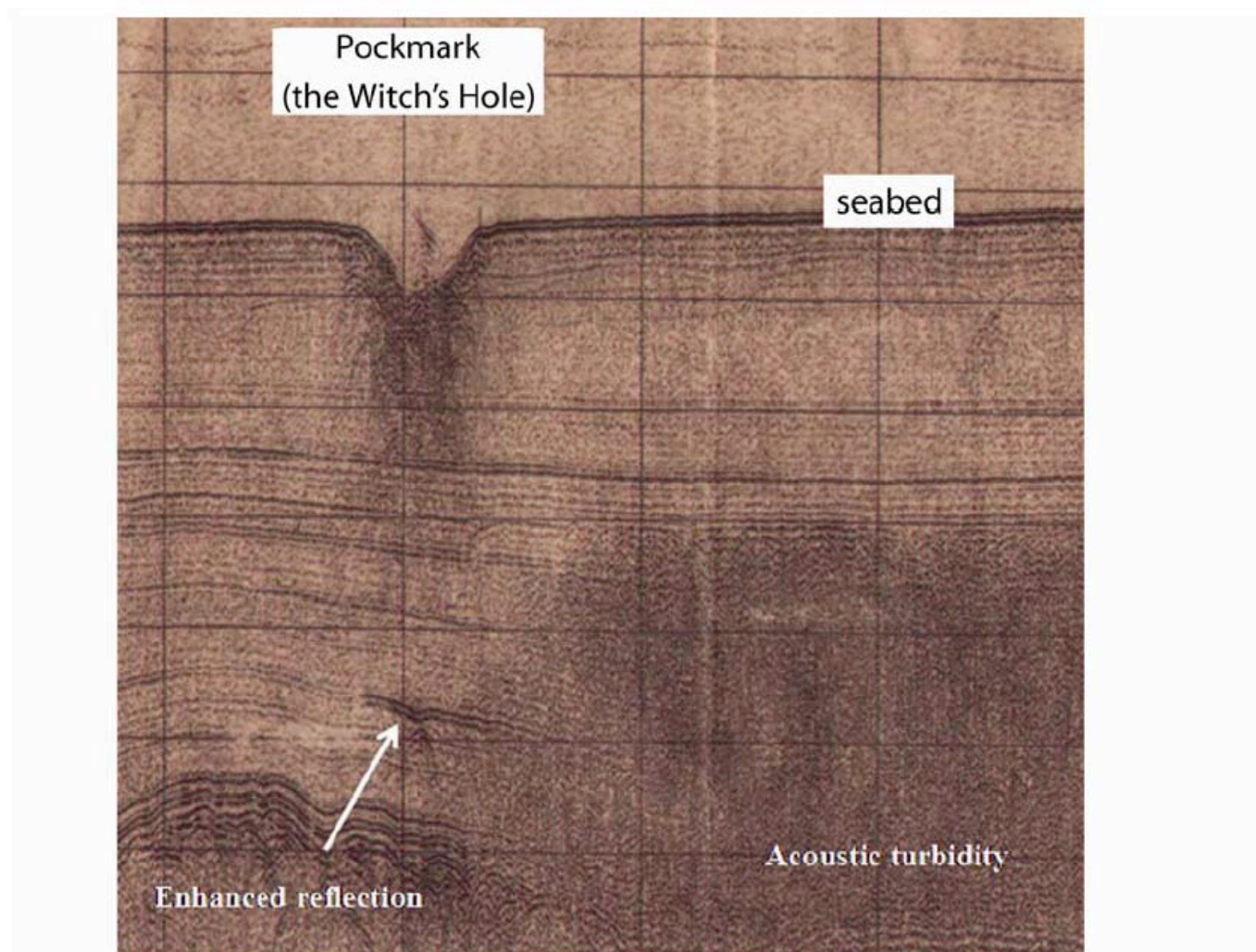


Figure 2.19: Boomer profile across the Witch's Hole, an unusual pockmark in the South Fladen area. [Reproduced by permission of the British Geological Survey. © NERC. All rights reserved. IPR/67-34C.]

Judd and Hovland, 2007. *Seabed Fluid Flow.*

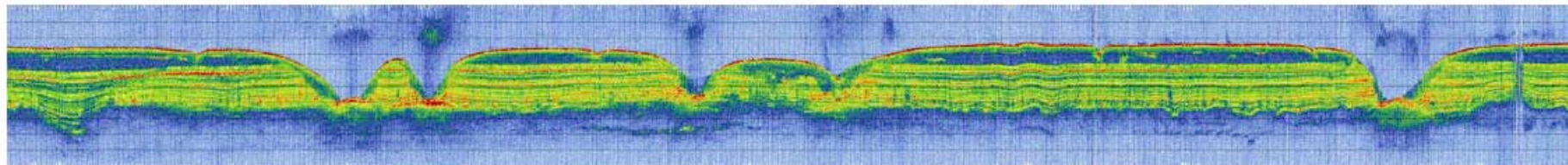
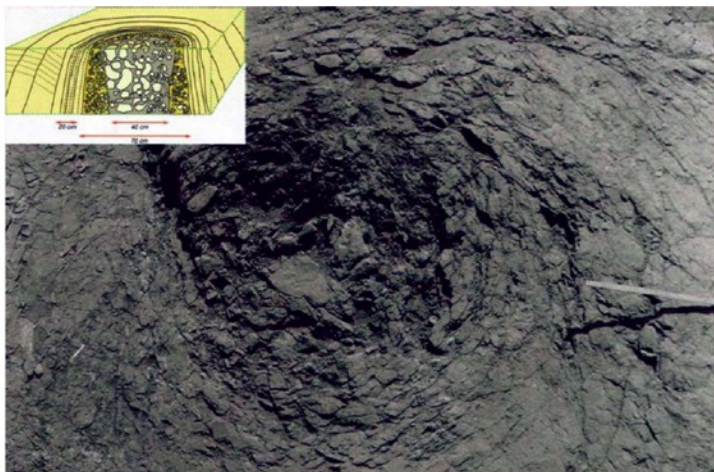
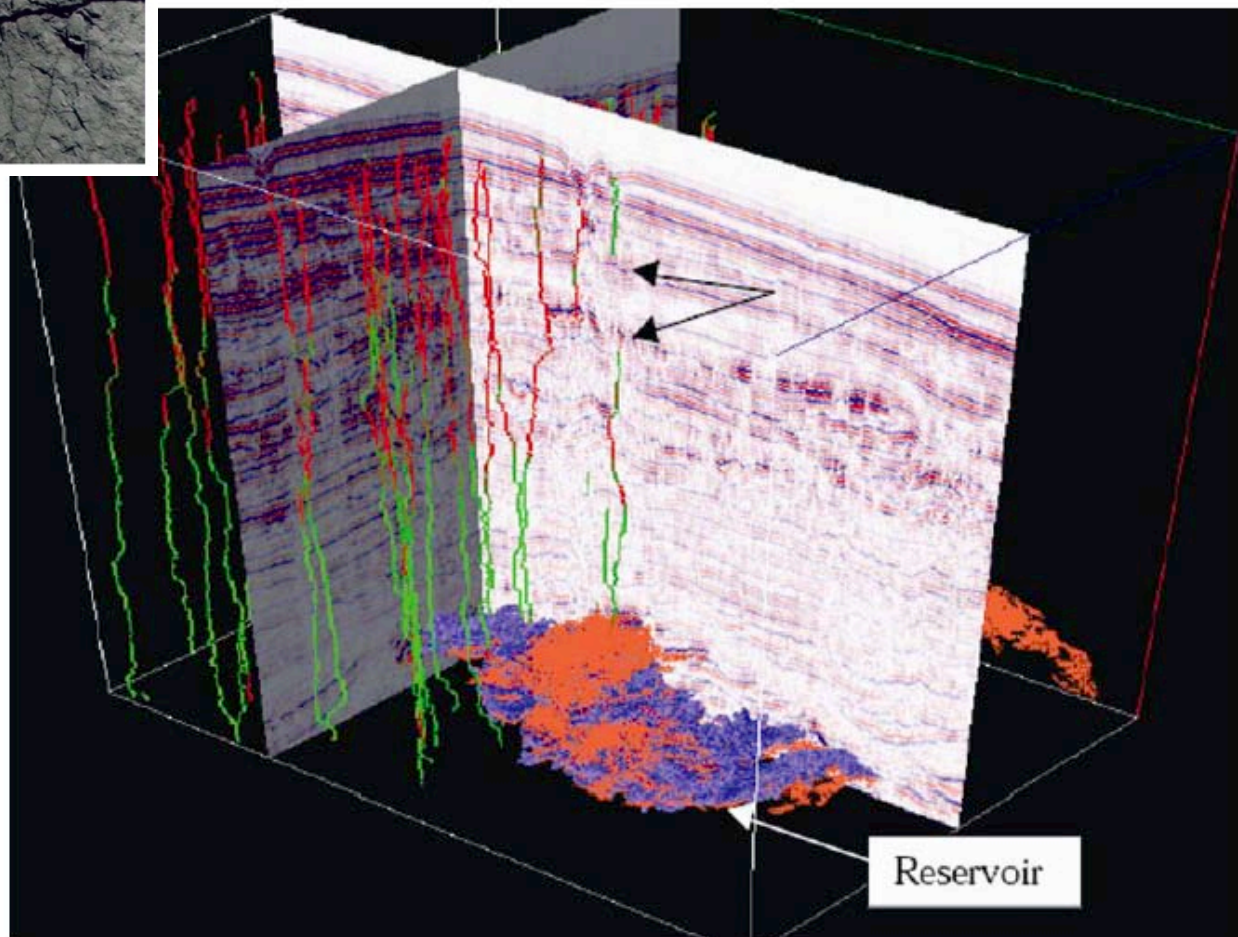


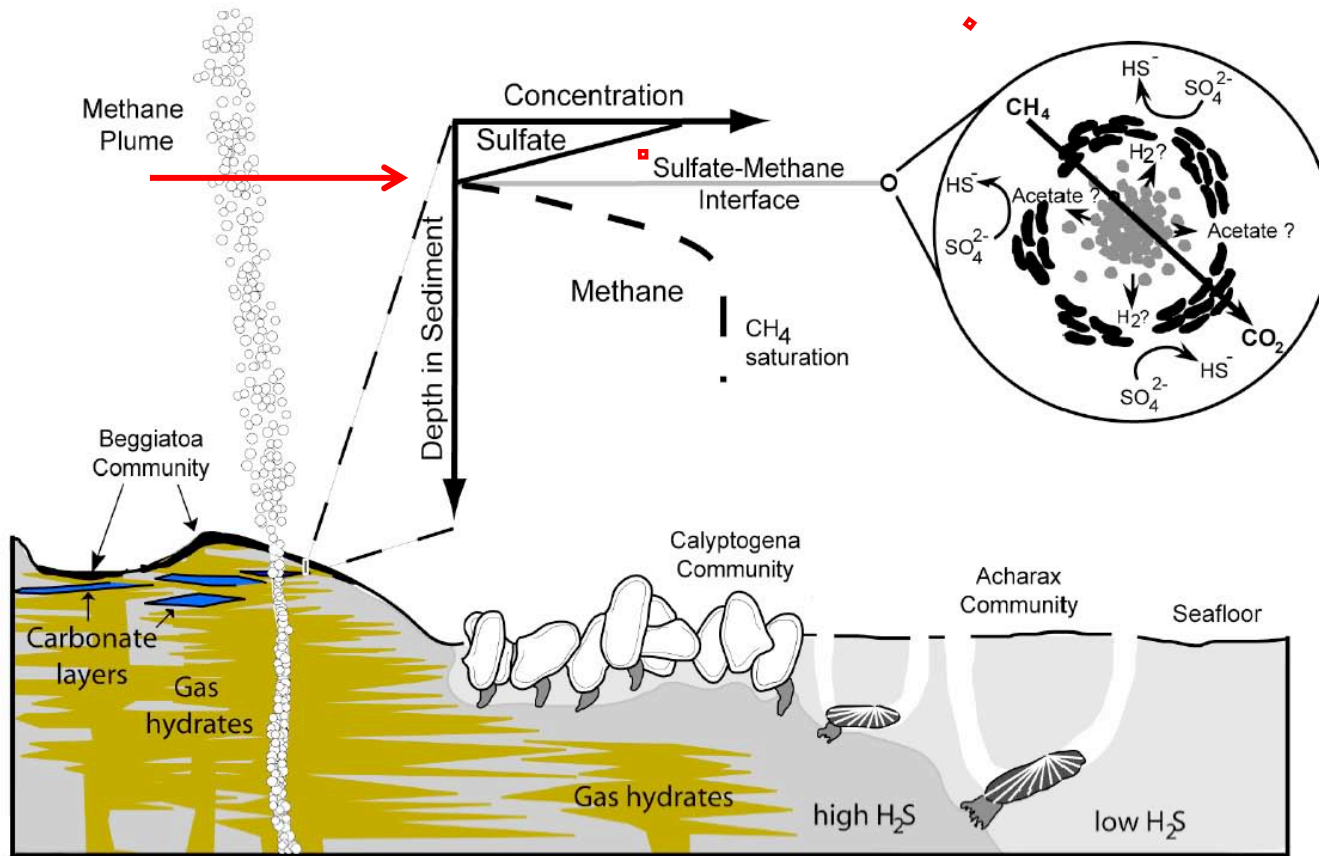
Figure 2.44: Seep plumes from the Scanner (left), Scotia (centre), and Challenger (right) pockmarks, Block UK15/25, North Sea acquired during the Heincke 180 cruise, October 2002 (Alfred Wegener Institute) using the parametric sediment echo sounder system (SES-2000DS) developed at Rostock University, Germany; this scan shows depths from 140 to 190 m. [courtesy of Gerdt Wendt, University of Rostock.]

Judd and Hovland, 2007. *Seabed Fluid Flow*.



Judd and Hovland, 2007. *Seabed Fluid Flow*.





Bathymodiolus heckeriae mussel beds. (A) Juvenile and adult mussels at Marker 'E'. (B) Dead mussels and octopus. (C) Extensive bed of live mussels of relatively uniform size, partially covered by bacterial mats, at Marker 'B'. (D) Dead mussels at the eastward periphery of Marker 'B'. (E) Mussels with a chiridotid holothurian and Alvinocaris sp. (F) Mussels with Alvinocaris sp. And ophiuroids. Scale bars: A–D : 10 cm, E; F : 5 cm.

# Chemosynthetic organisms at cold seeps

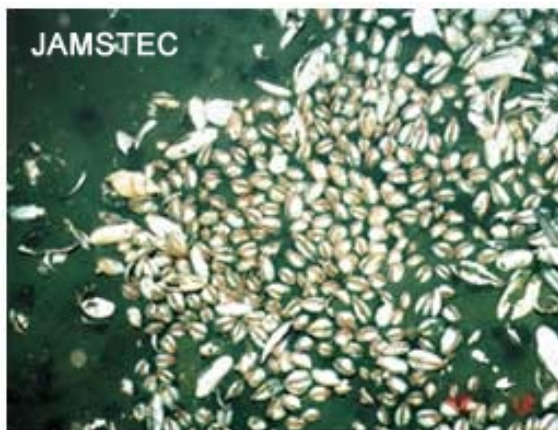
Free-living filamentous sulfur bacteria: *Beggiatoa*



tube worms: *Lamellibrachia*



clams: *Calyptogena*



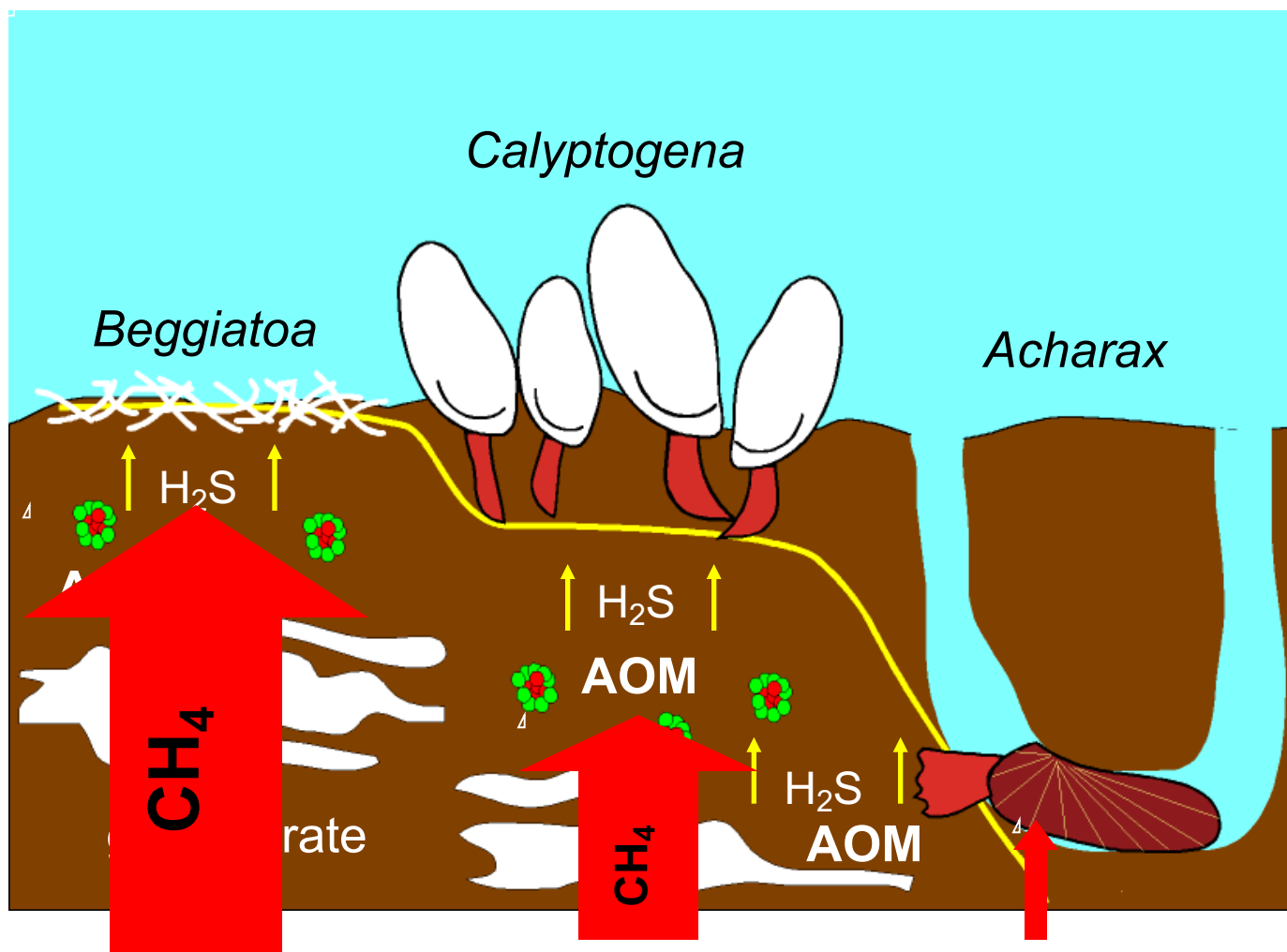
mussels: *Bathimodiolus*



mussels: *Acharax / Solemya*



# Gradient of chemosynthetic communities



Thanks to Tine Treude, Max Plank Institute, Bremen Germany

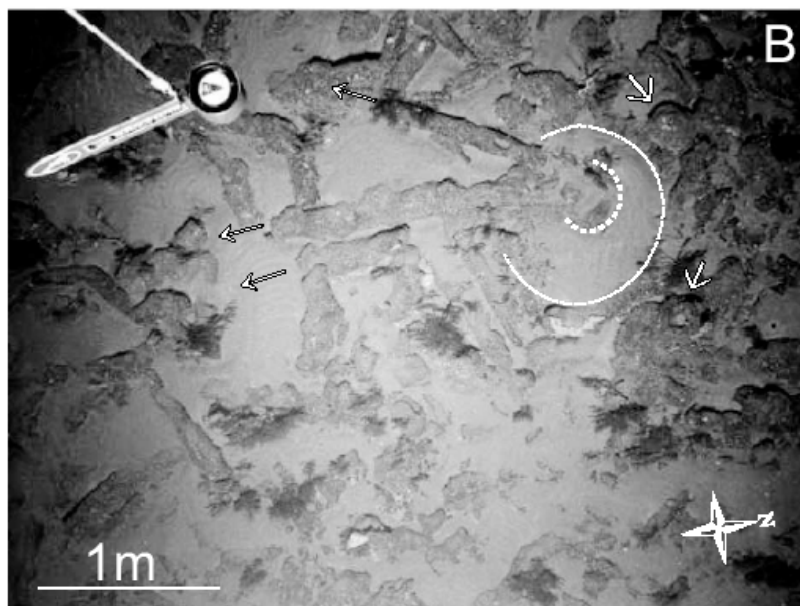
# CARBONATI METANO DERIVATI

## Methane-derived authigenic carbonate (MDAC)

# Pipe-like chimneys in Gulf of Cadiz Mud Volcanoes

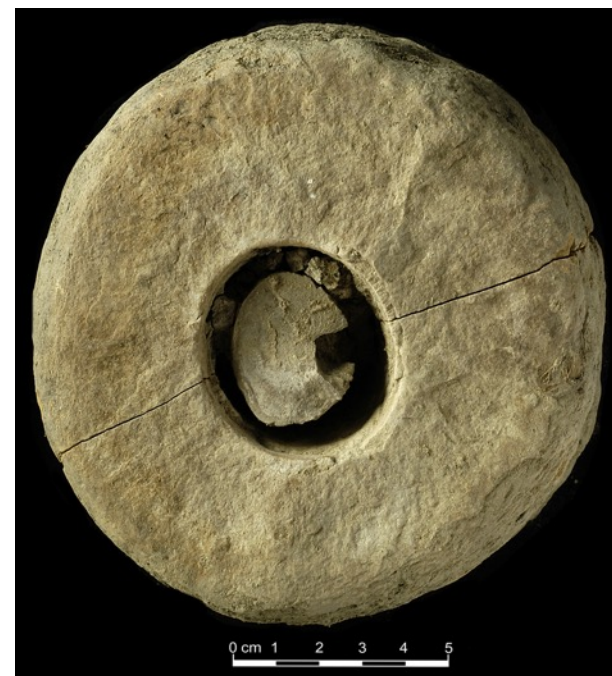
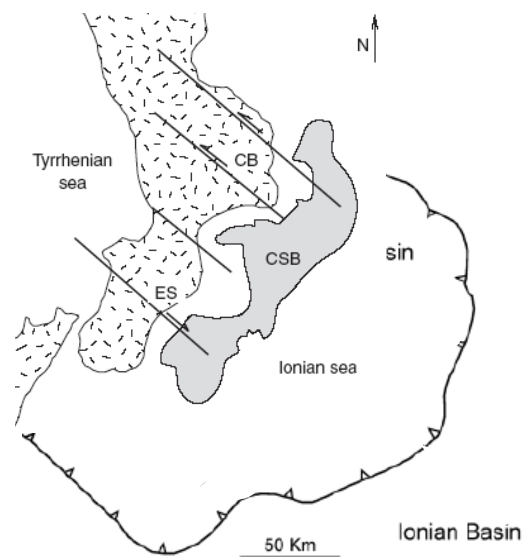
Composed of authigenic carbonates with iron oxides.

Carbonates are moderately depleted in  $^{13}\text{C}$ , ranging from - 46‰ to -20 ‰ PDB



Diaz del Rio al., Marine Geology 195 (2003) 177-200





Courtesy, Domenico Rio, University of Parma

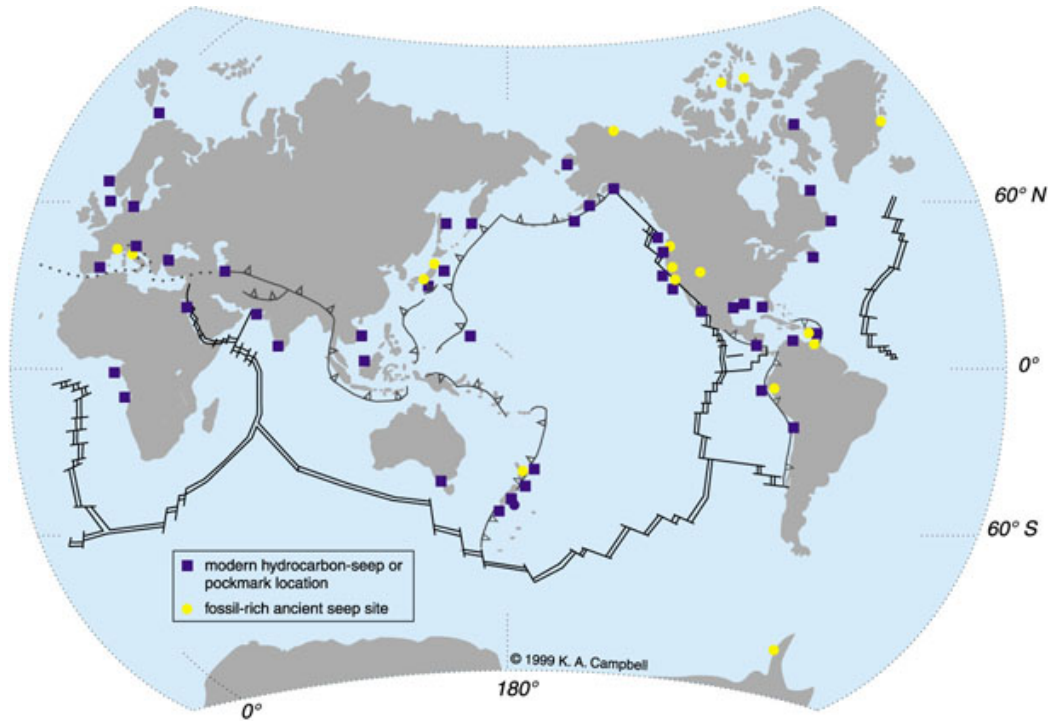
## FOSSIL DEWATERING CHIMNEYS IN PLIOCENE MARLS, CROTONE BASIN



Aiello, I.W. (2005). Fossil seep structures of the Monterey Bay region and tectonic/structural controls on fluid flow in an active transform margin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 227(1), 124-142.



Jensen *et al.*, 1992



## Authigenic Carbonates:

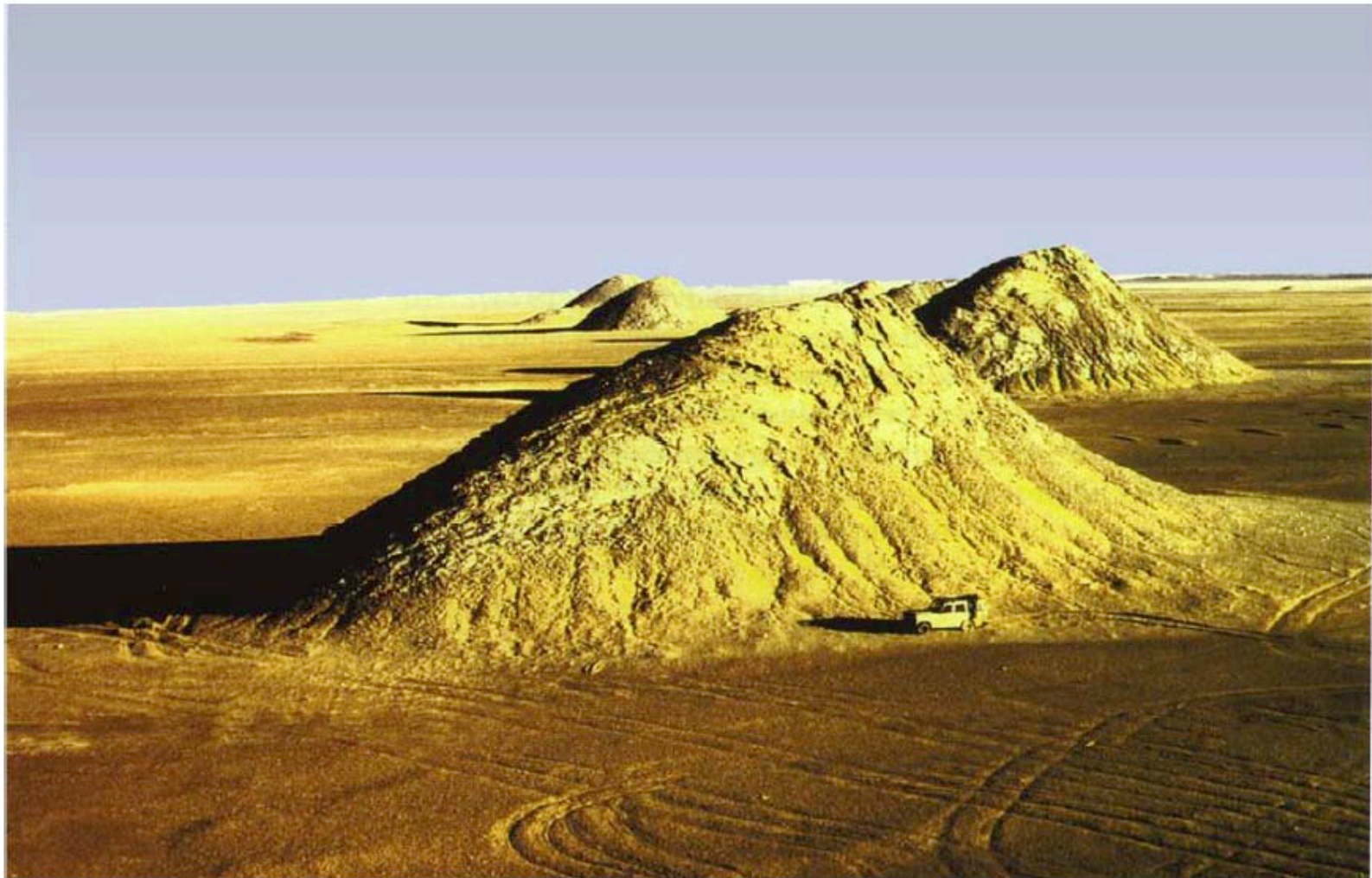
Isotopically light

Organic markers indicate presence of methane oxidizers

Serve as habitat for bottom fish (e.g. rock fish)



**Judd and Hovland, 2007. Seabed Fluid Flow.**



## Anaerobic oxidation of methane (AOM) via sulfate reduction.

Microbial consortia of **methanotrophic archaea** and **sulfate-reducing bacteria** identified on gas hydrate-bearing samples (Boetius et al. 2000).

The Methane Oxidizing Archaea oxidize methane in anaerobic conditions:



This reaction must occur simultaneously to that of Sulphate Reducing Bacteria:



## Calcium carbonate precipitation Methane-Derived Authigenic Carbonate (MDAC)

Anaerobic oxidation of methane (AOM) increases alkalinity and consumes sulfate, facilitating carbonate precipitation according to the following reactions:



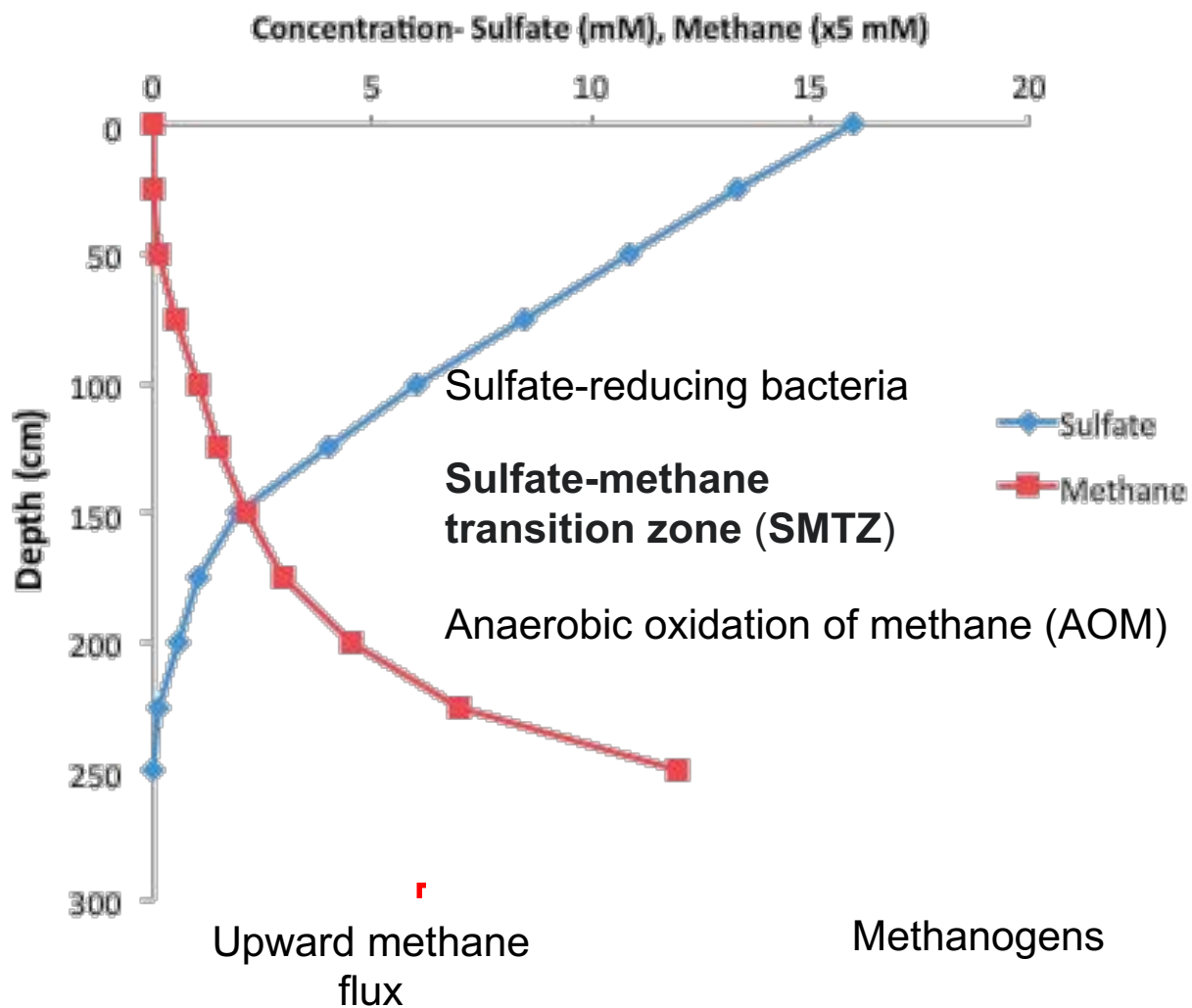
Bicarbonate  
from bacterial action

**alkaline**  
**seawater**

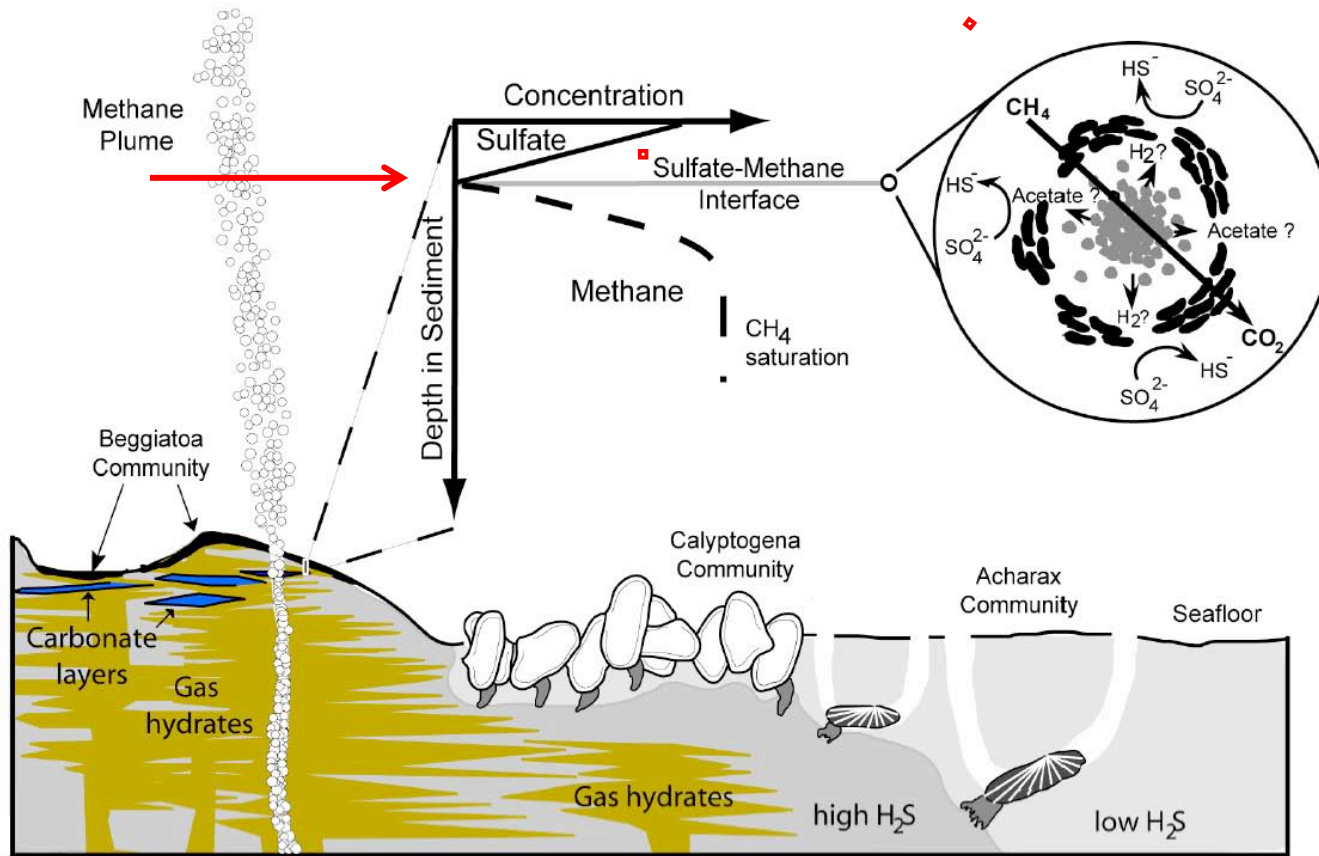
calcium ions  
present in seawater

calcium  
carbonate deposited

Alkalinity is the capacity of water to resist acidification. It should not be confused with basicity which is an absolute measurement on the pH scale.







Bathymodiolus heckeriae mussel beds. (A) Juvenile and adult mussels at Marker 'E'. (B) Dead mussels and octopus. (C) Extensive bed of live mussels of relatively uniform size, partially covered by bacterial mats, at Marker 'B'. (D) Dead mussels at the eastward periphery of Marker 'B'. (E) Mussels with a chiridotid holothurian and Alvinocaris sp. (F) Mussels with Alvinocaris sp. And ophiuroids. Scale bars: A–D : 10 cm, E; F : 5 cm.

Van Dover et al. (2003). *Deep Sea Research*

- Foraminifera form their skeleton in **isotopic equilibrium** with ambient seawater
- The isotopic composition of the skeleton of benthic foraminifera reflects the **micro-habitat** where they live

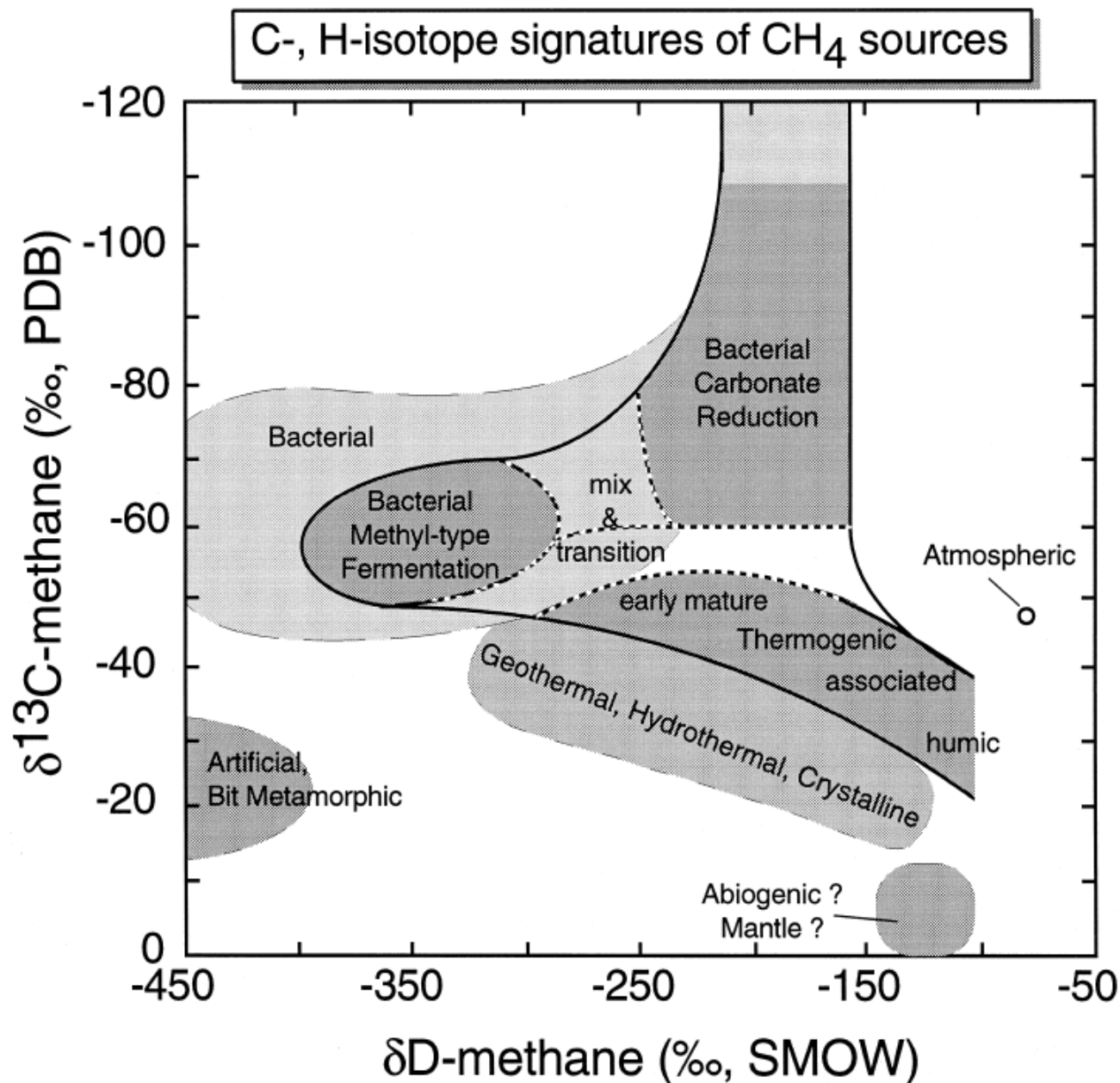
The  $\delta^{13}\text{C}$  of foraminifera depends on the  $\delta^{13}\text{C}$  of the Dissolved Inorganic Carbon (DIC) of the water in which they live:

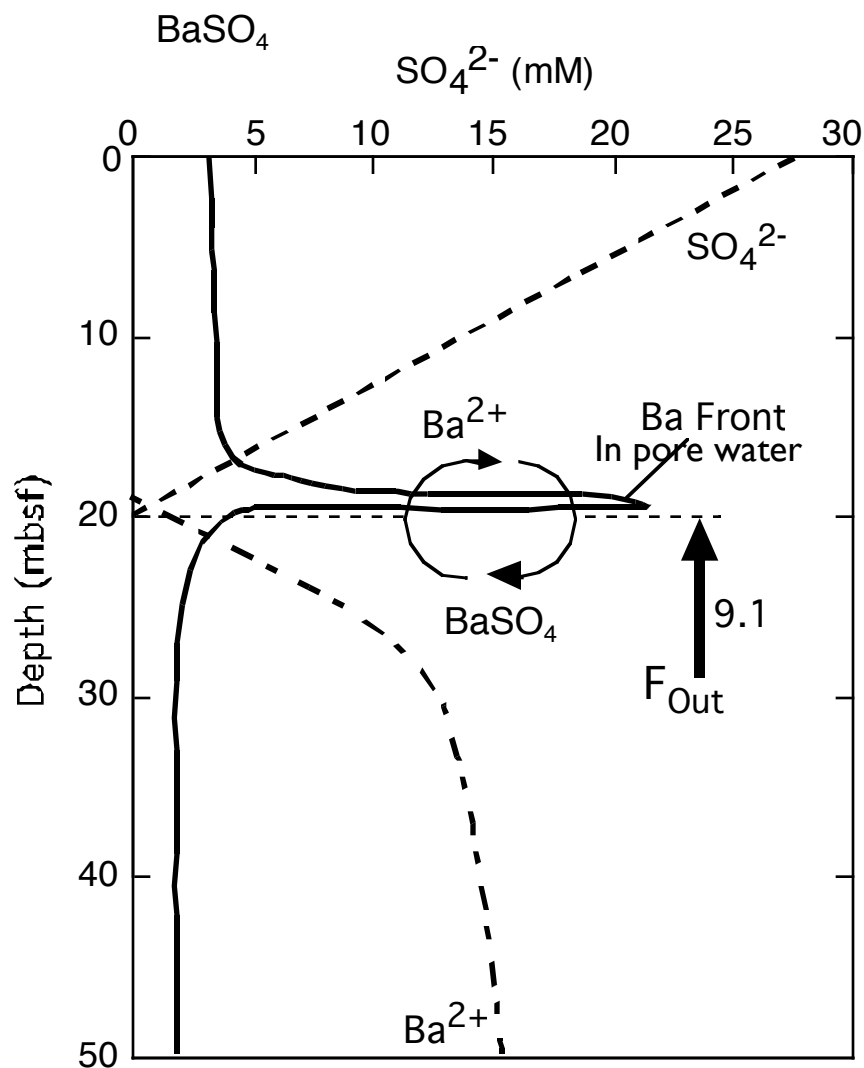
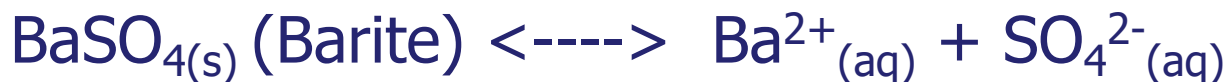
**Normal marine environment:  $\delta^{13}\text{C}_{\text{DIC}} \cong 0\text{‰}$**

(Peterson e Fry, 1987)

**Methane seeps environment:  $\delta^{13}\text{C}_{\text{DIC}} \cong -30 / -60\text{‰}$**

(Aharon *et al.*, 1992)



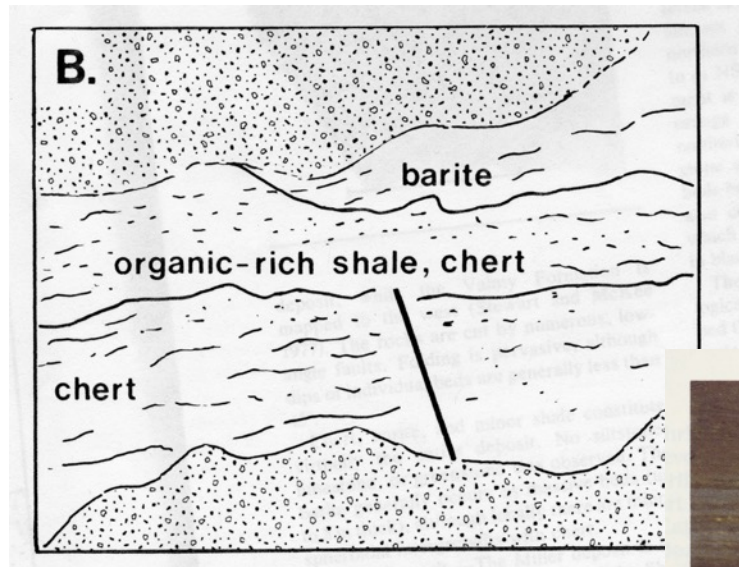


### Coupled Sulfate / Barium Profiles

1. High concentrations of barite in pelagic sediments underlying high productivity waters are thought to result from **biologically mediated precipitation of barium sulfate within the water column.**
2. In organic-rich, rapidly accumulating sediment, sulfate is consumed by microbial reduction of organic carbon. **Barite is dissolved under conditions of sulfate depletion leading to high barium concentrations in the pore fluids.**
3. **When barium-rich fluids discharge at the seafloor, barite forms by reaction with seawater sulfate, forming “cold-seep barite” deposits.**

***Paleozoic Bedded barites* from Nevada, Arkansas, Mexico and South China are associated with:**

- Organic shales
- Chert and phosphorite
- Some carbonate



***Cold seep barites* along continental margins are associated with:**

- Organic-rich facies
- Opal-rich sediments
- Phosphorites
- Some carbonates



Jewell and Stallard, J. Geol., 99, 1991

ODP Leg 112

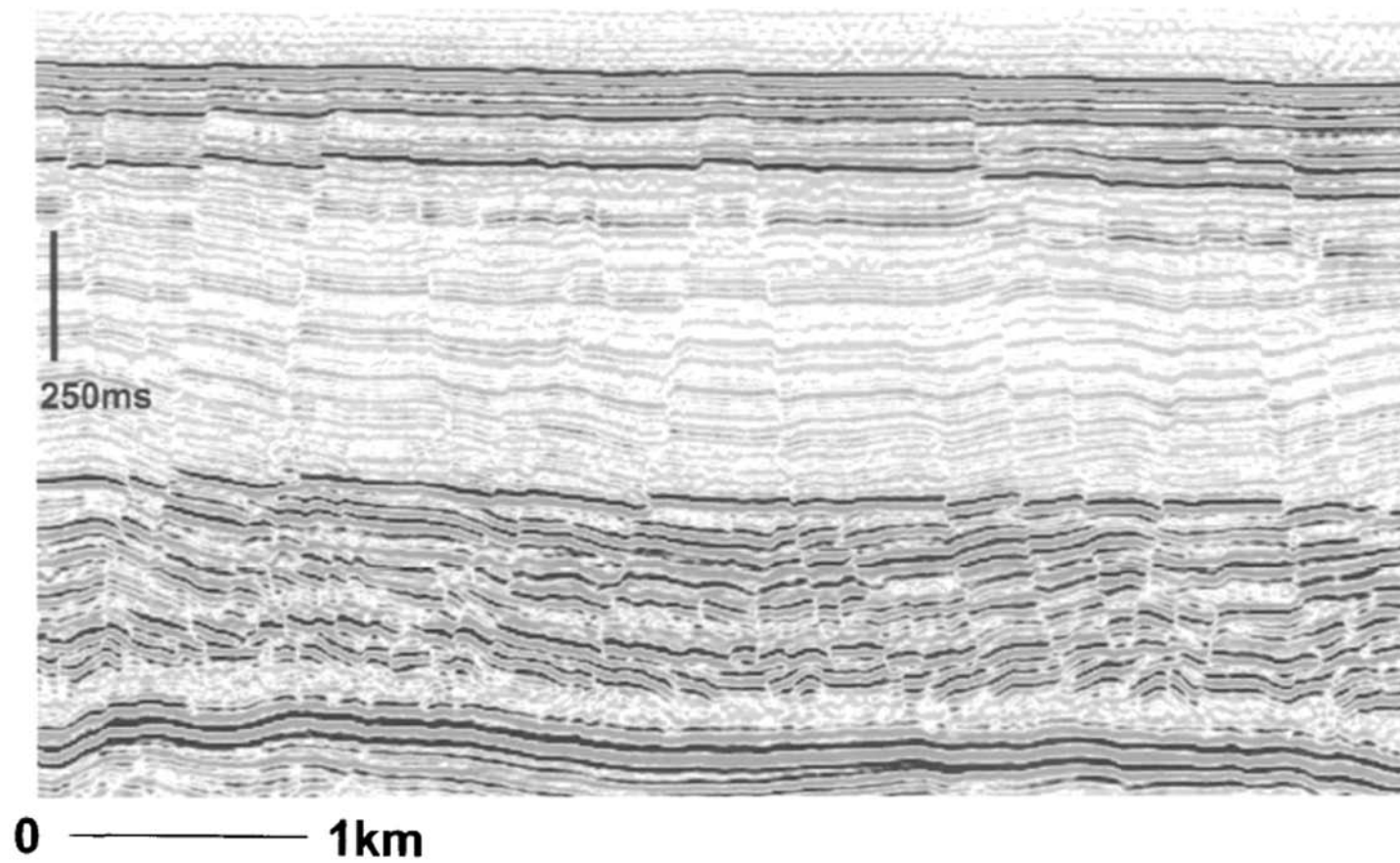
# Polygonal Faults

'an array of layer-bound extensional faults within a mainly fine-grained stratigraphic interval that exhibit a diverse range of fault strikes which partially or fully intersect to form a polygonal pattern in map view'

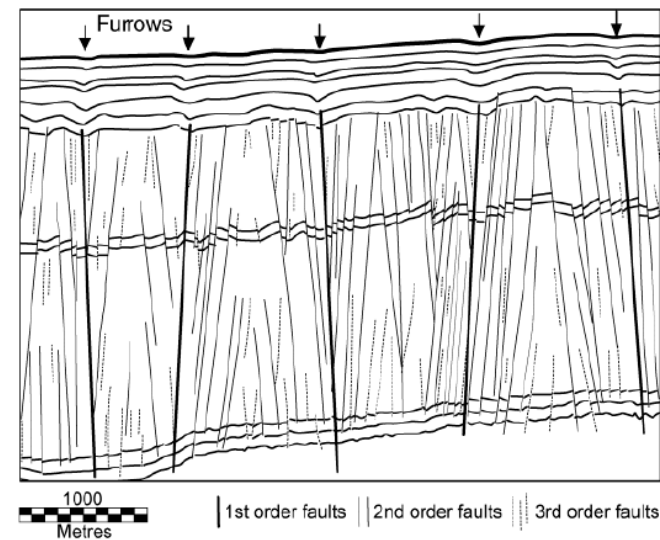
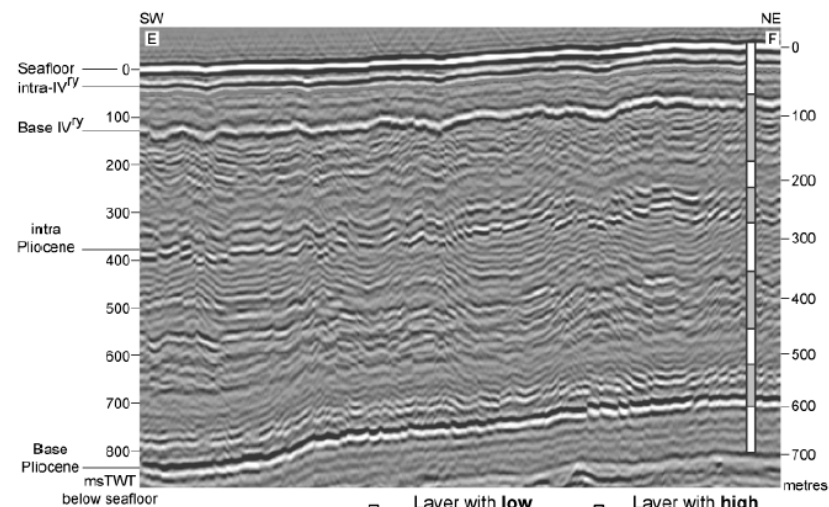
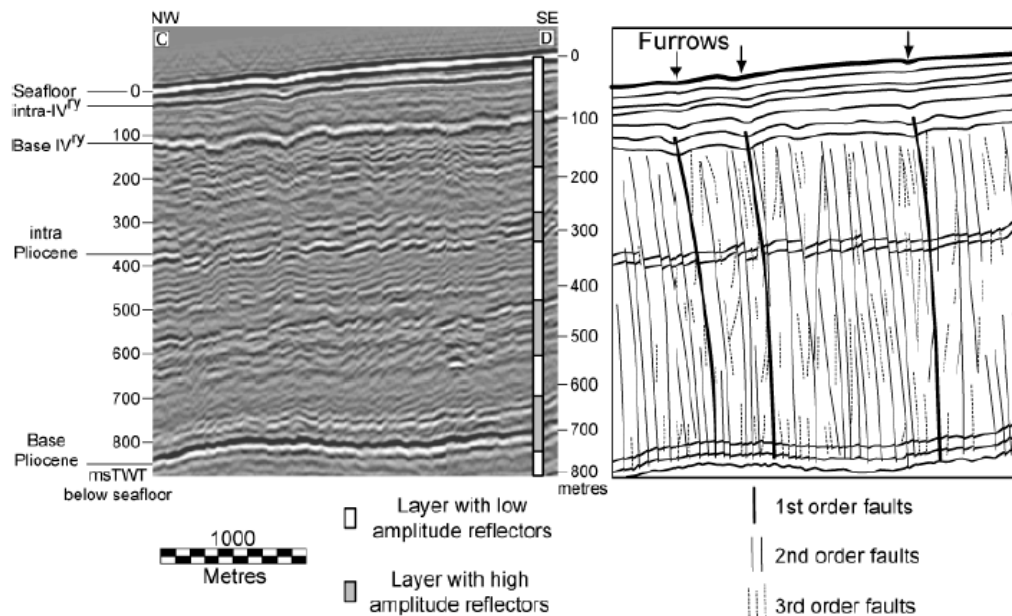
- This type of fault has only been recognized in packages that are predominately composed of fine-grained sediments.
- The local stress regime operative at the time when polygonal faults grow can exert a significant influence on strike and on the organisation of the fault array as a whole.

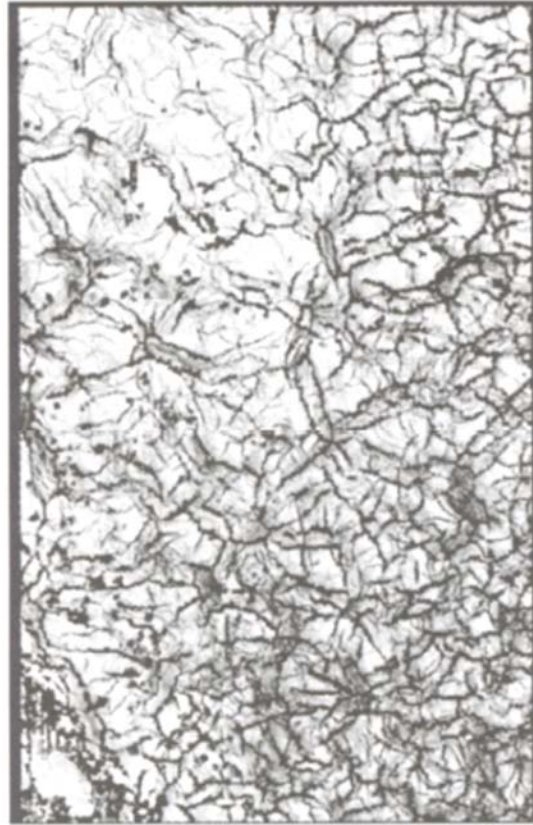
# Polygonal Faults. Geometry

- Polygonal faults systems develop in tiers. Faults in one tier may partially interconnect with those in adjacent tiers by cross-propagation of a sub-set of the total fault population, but the majority of the faults in the separate tiers are contained wholly within individual tiers.
- They range in fault trace length from 100 m to several kilometres and extend vertically across discrete layers from a few tens of metres to over one kilometre in thickness.
- Polygonal faults can be planar or listric
- Faults are characterized by a large range of fault strikes. Where strikes are almost randomly oriented, a classical polygonal plan form geometry results.  
*Variations in the basic polygonal plan form can arise from regional slope, tectonic context, or basement topography, or from intrinsic variation in the physical properties or the thickness of the deforming interval.*
- Three-dimensional geometry of polygonal fault systems is invariably complex and difficult to appreciate from simple 2D cross-sections.

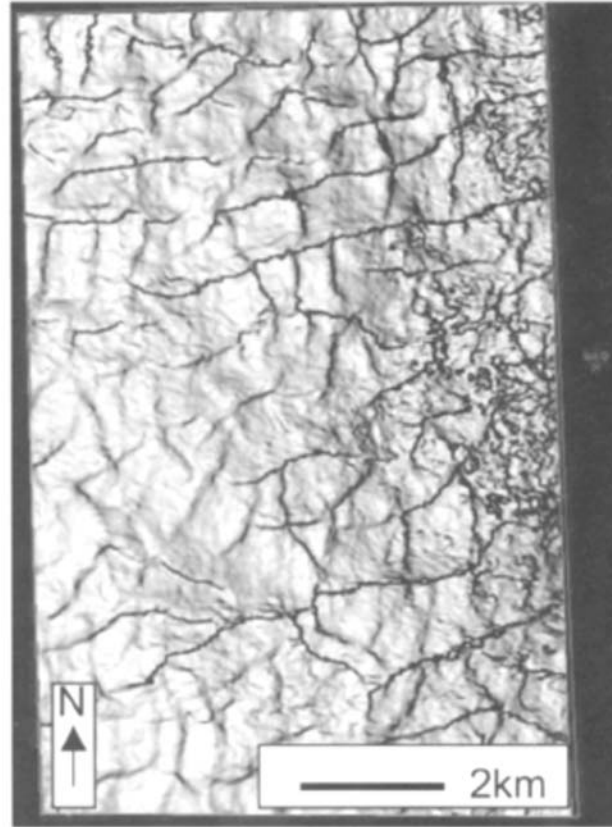




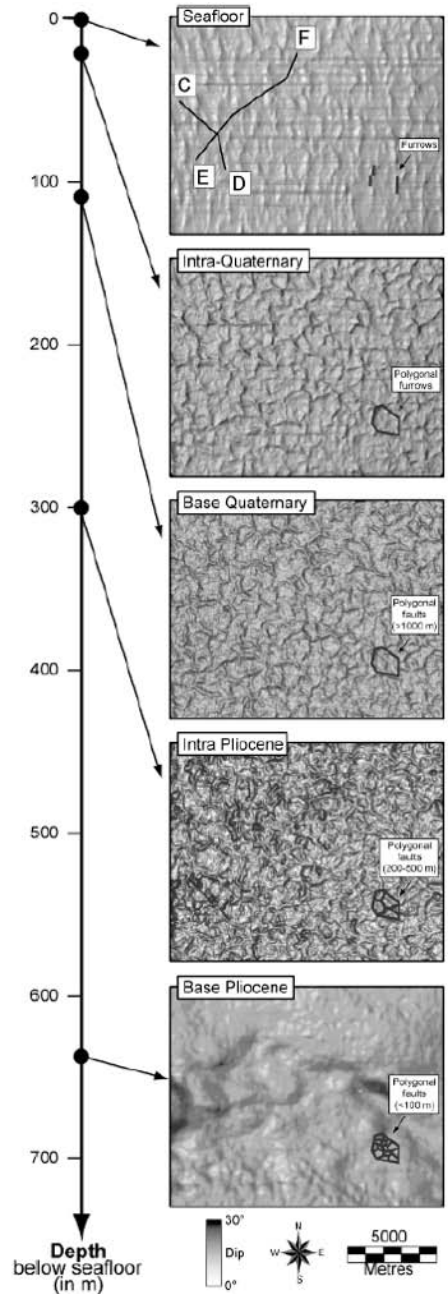




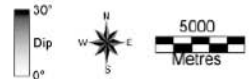
0 ————— 3 km

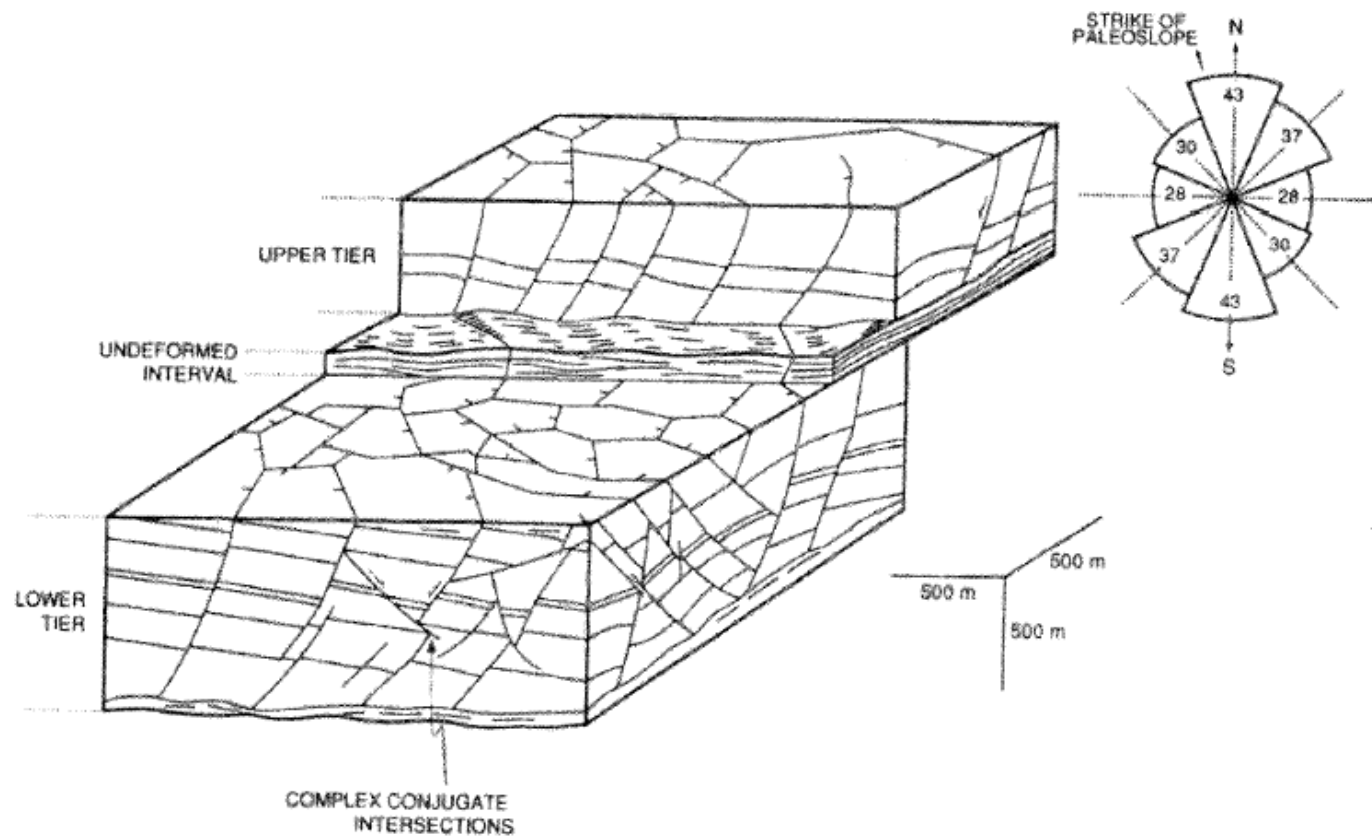


2km



Depth below seafloor (in m)





# Polygonal Faults. Genetic mechanisms

## *Gravity sliding-collapse NO*

Sliding down a slope, with a basal detachment at the boundary would imply iso-orientation, and basal contraction.

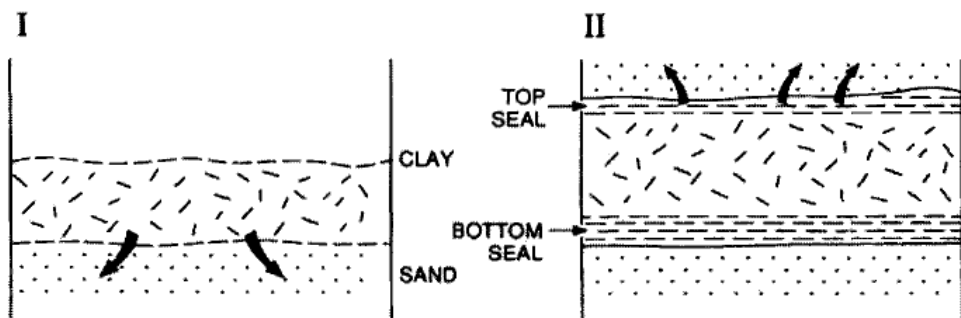
## *Density Inversion (Such as Henriët)*

Density inversion should produce folding (like in salt diapirs), which are not always observed.

## *Syneresis*

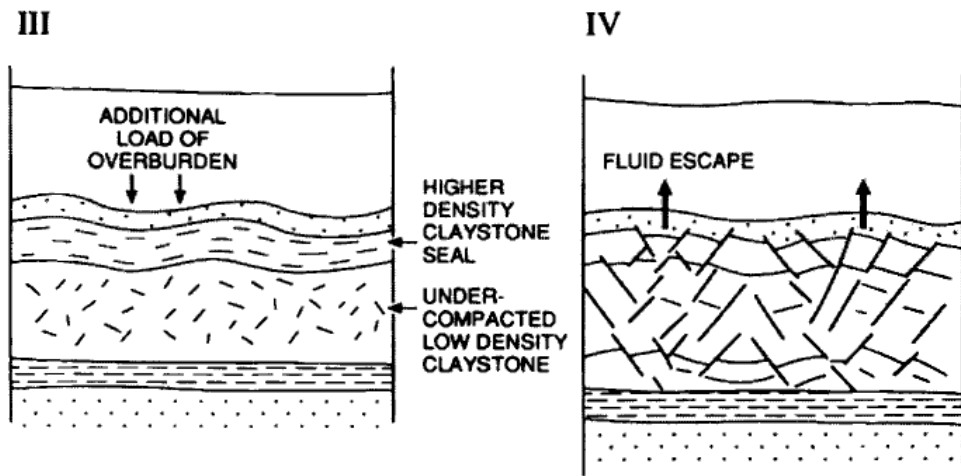
- Syneresis is a spontaneous contraction (shrinkage) without evaporation, but is a process that is specifically restricted to gels.
- Gels are a framework of colloidal particles, and the primary condition for gel formation is the very fine size range of the constituent particles (clay size range).
- Ultra-fine grained sediments in which all polygonal fault systems form, fall into the range of colloidal materials

# Density inversion model For polygonal fault systems Henriet et al., 1989.



Deposition of clays  
Downward flow into aquifer

Formation of top and bottom seals by preferential compaction adjacent to sands



Density inversion –  
Pressure build-up –  
Rayleigh-Taylor instability

Overpressure relaxation  
hydrofracturing  
Roof faulting of top seal  
Collapse  
Undercompacted claystone becomes compacted

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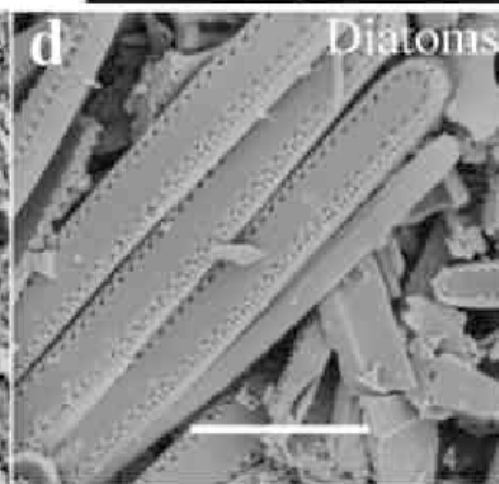
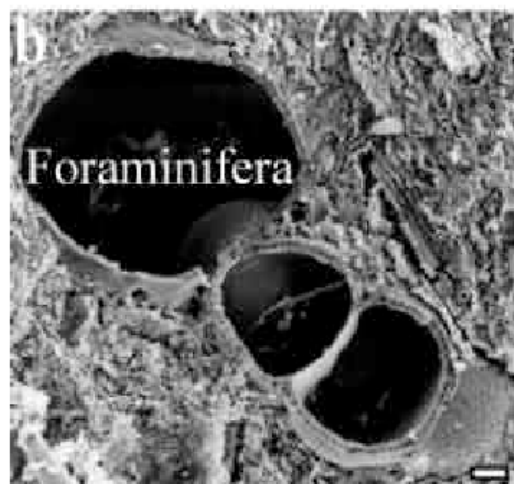
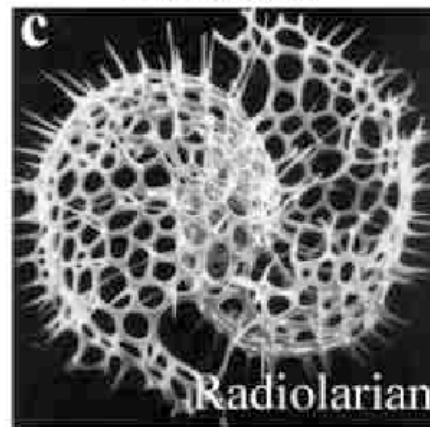
## **FOSSILIFEROUS SOILS**

- They trap water and introduce a significant bias on index properties, and diatoms microfossils in particular can play a significant role on physico-chemical properties of soil because of their potentially large specific surface area.
- They can provide delayed compressibility or a sudden increase in compressibility once the yield strength of the microfossil is exceeded.
- They influence the frictional behavior of soils by their size and shape.

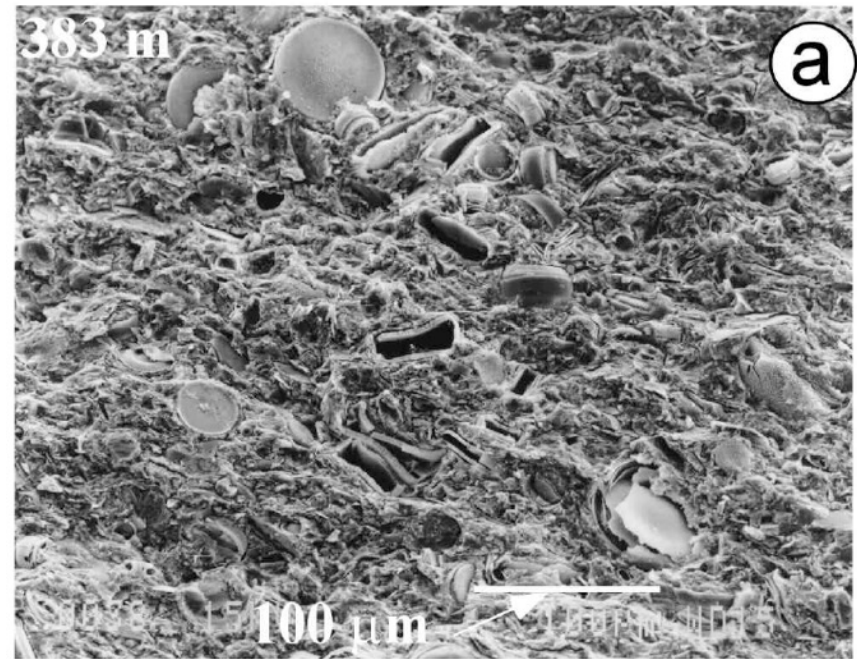
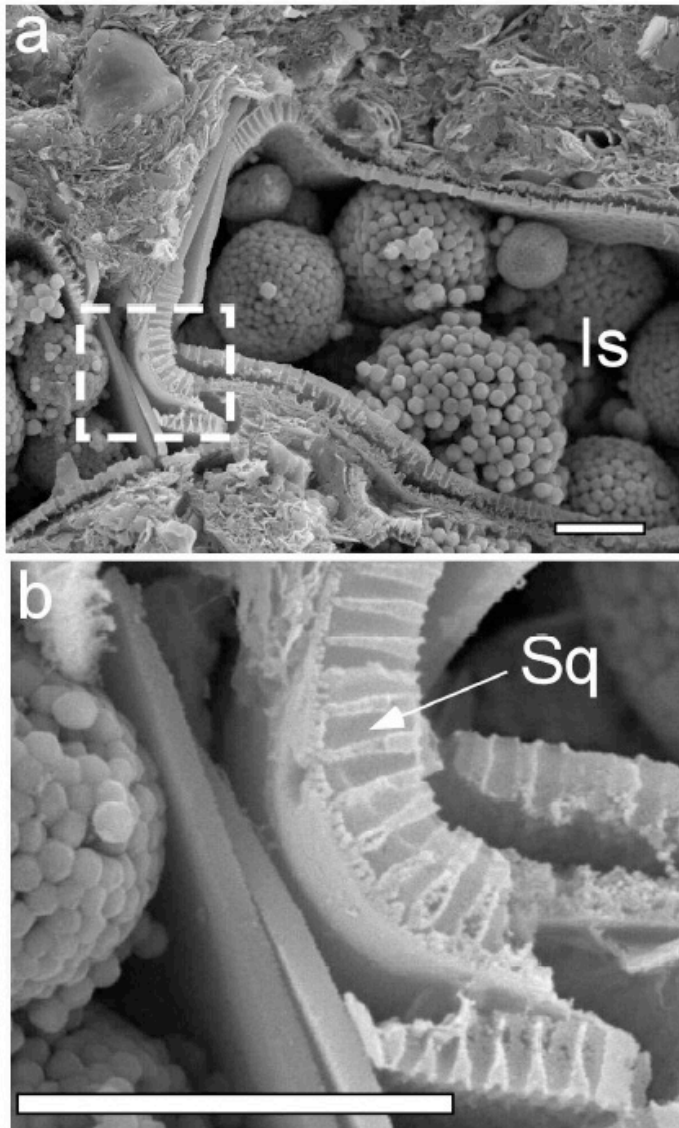
Calcareous



Siliceous

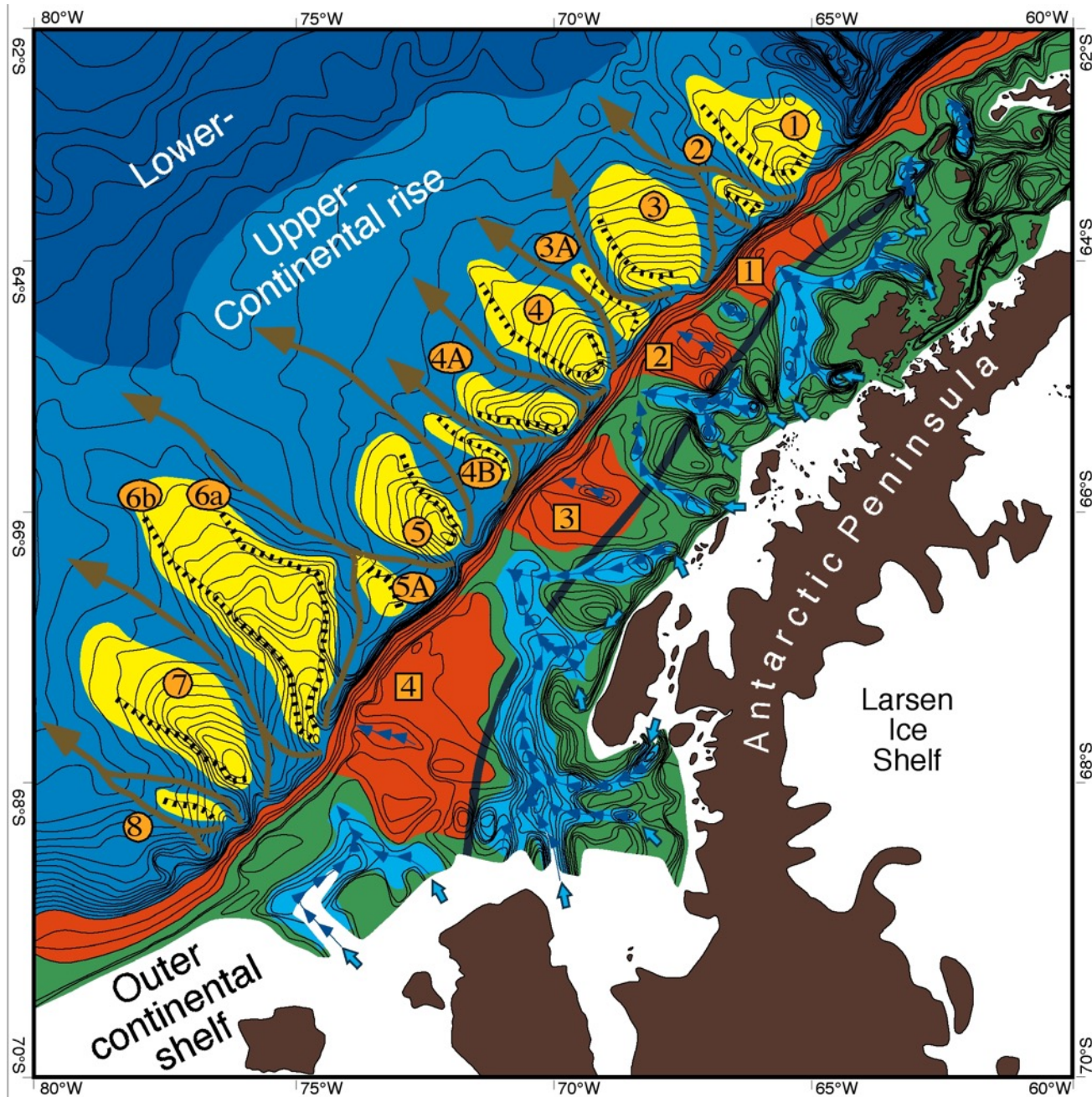




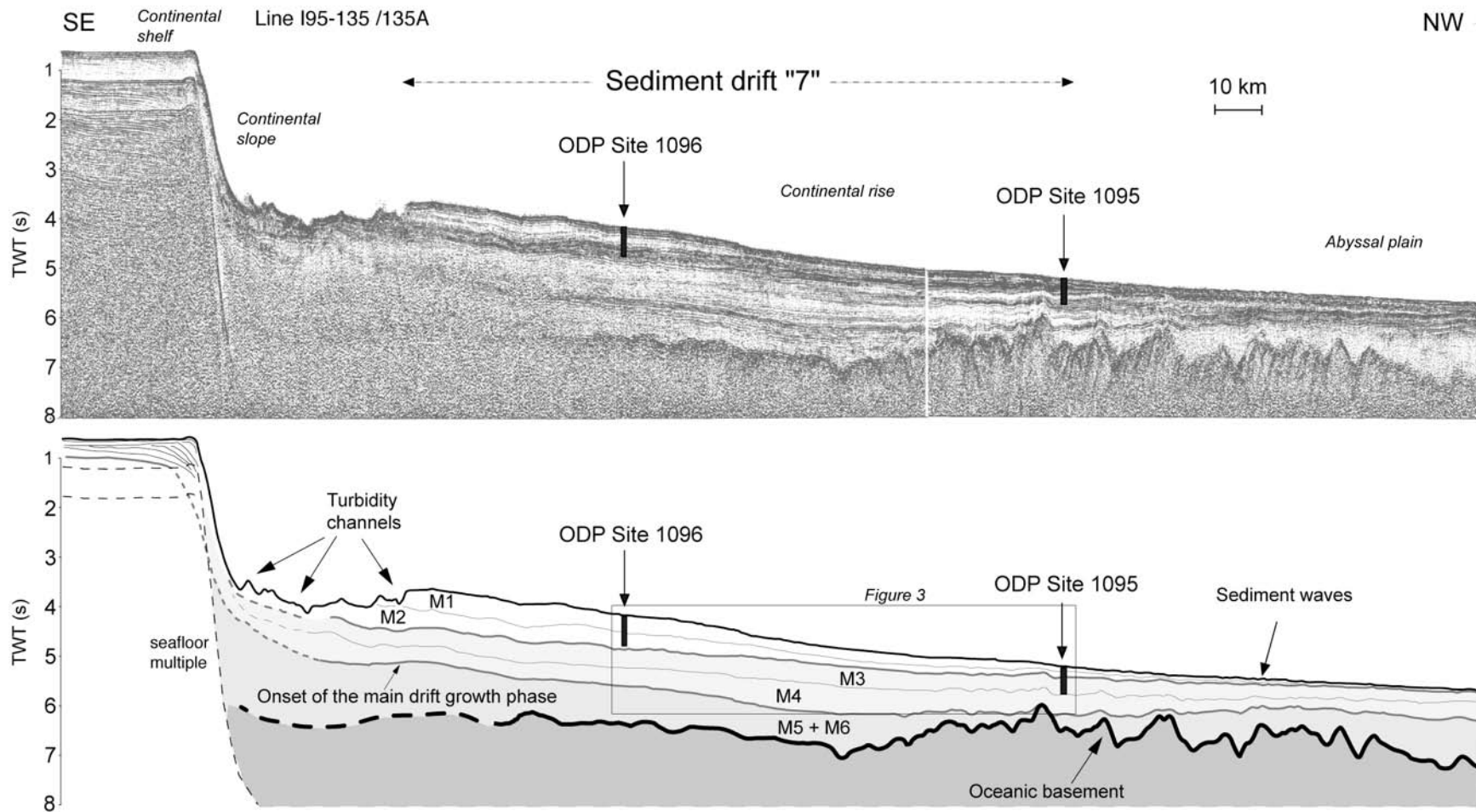


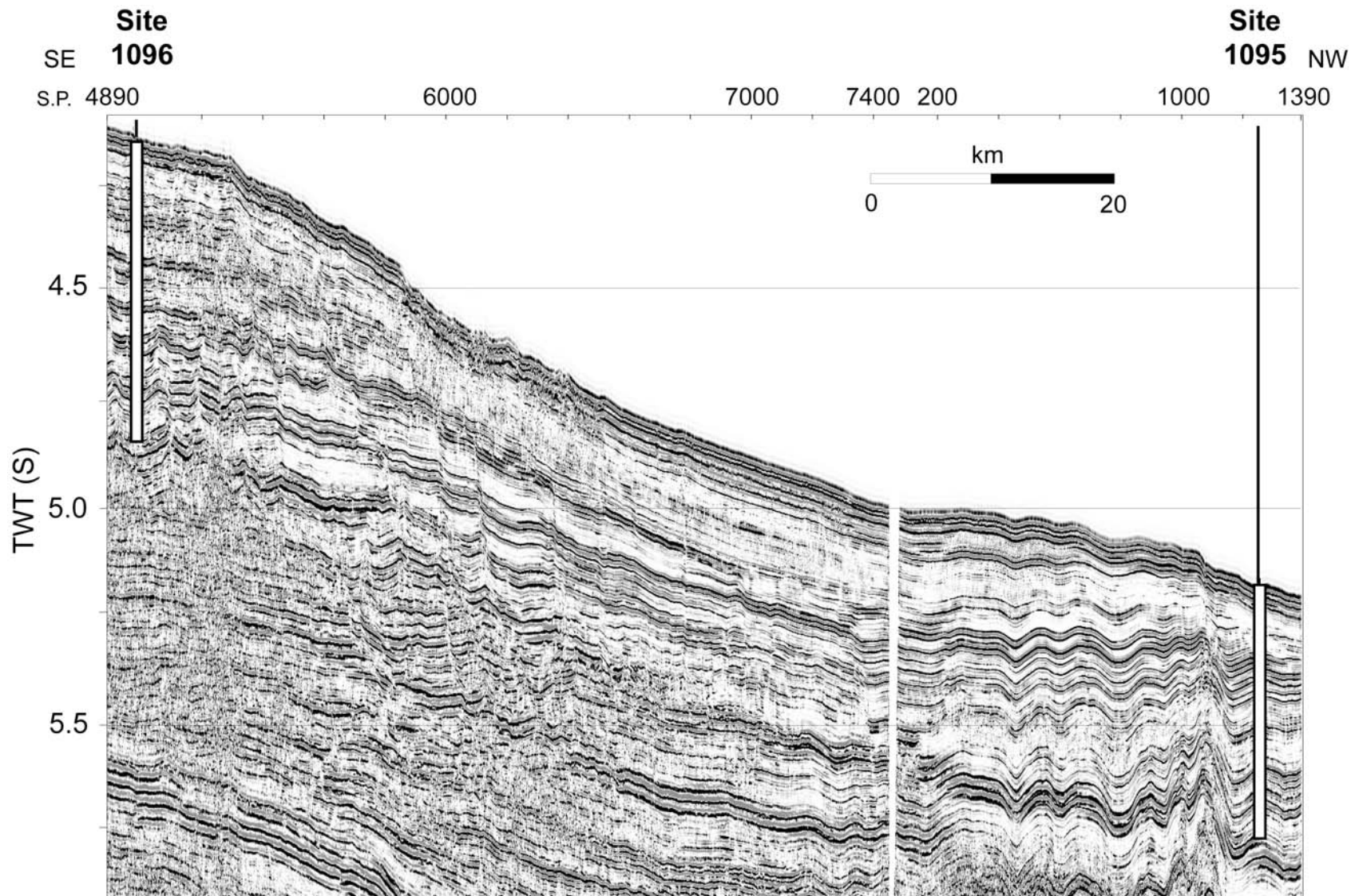
Distribution of diatoms in a consolidated sediment taken at a depth of 383 m at the site of Kansai airport.

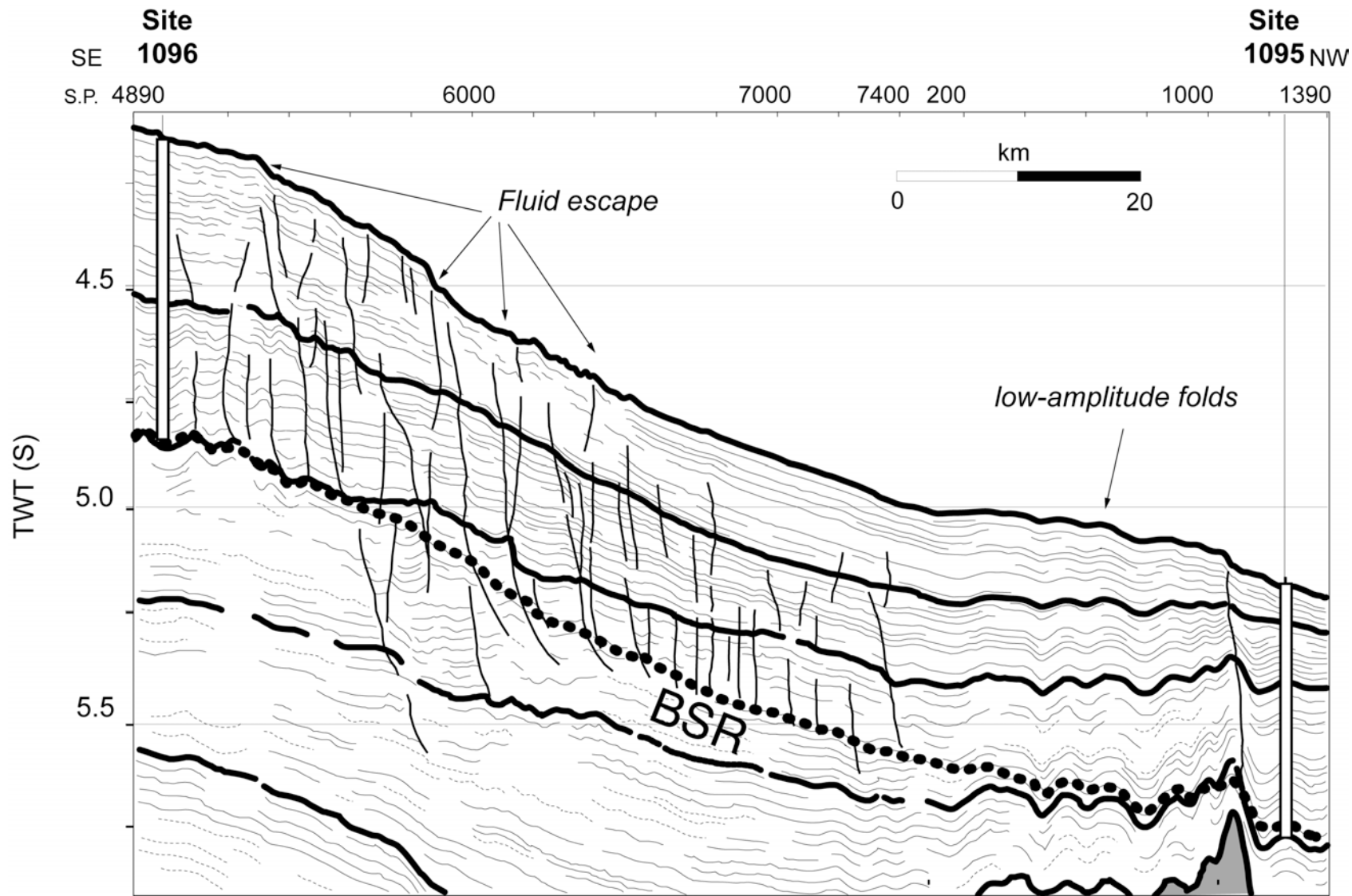
Intra-skeletal (Is, a) and skeletal (Sq, b) porosity of microfossils.



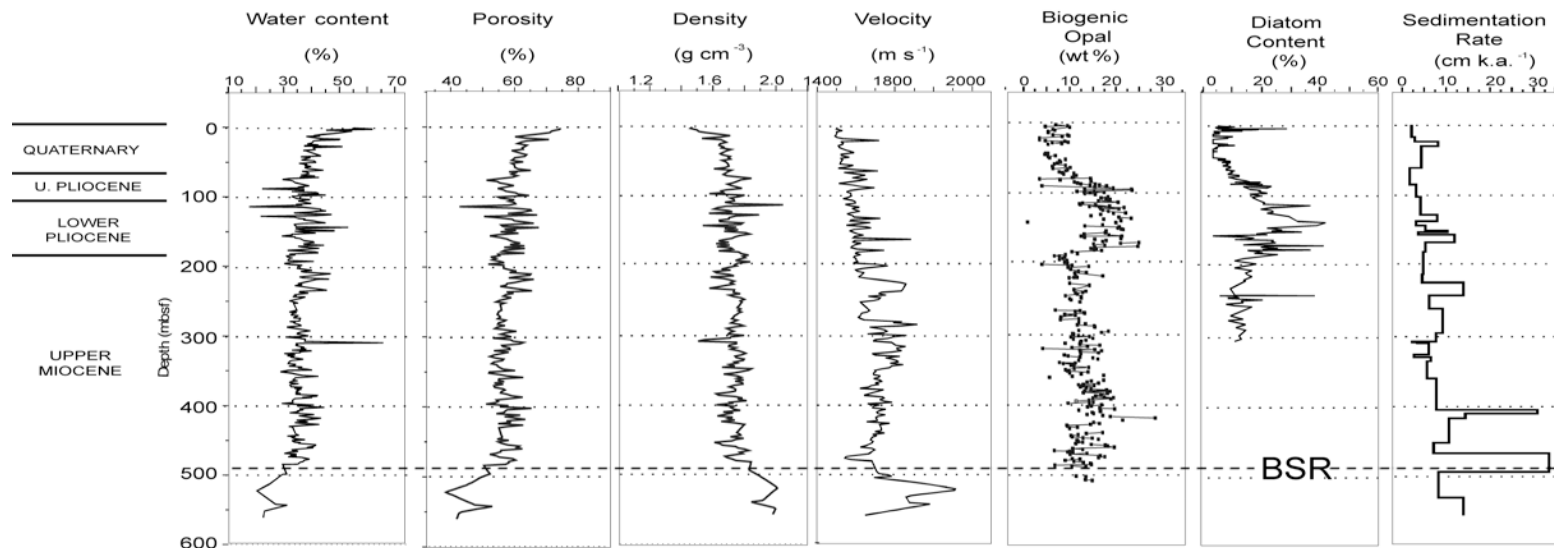
Rebesco et al. (1998),  
*Terra Antarctica*, 5(4),  
715-725



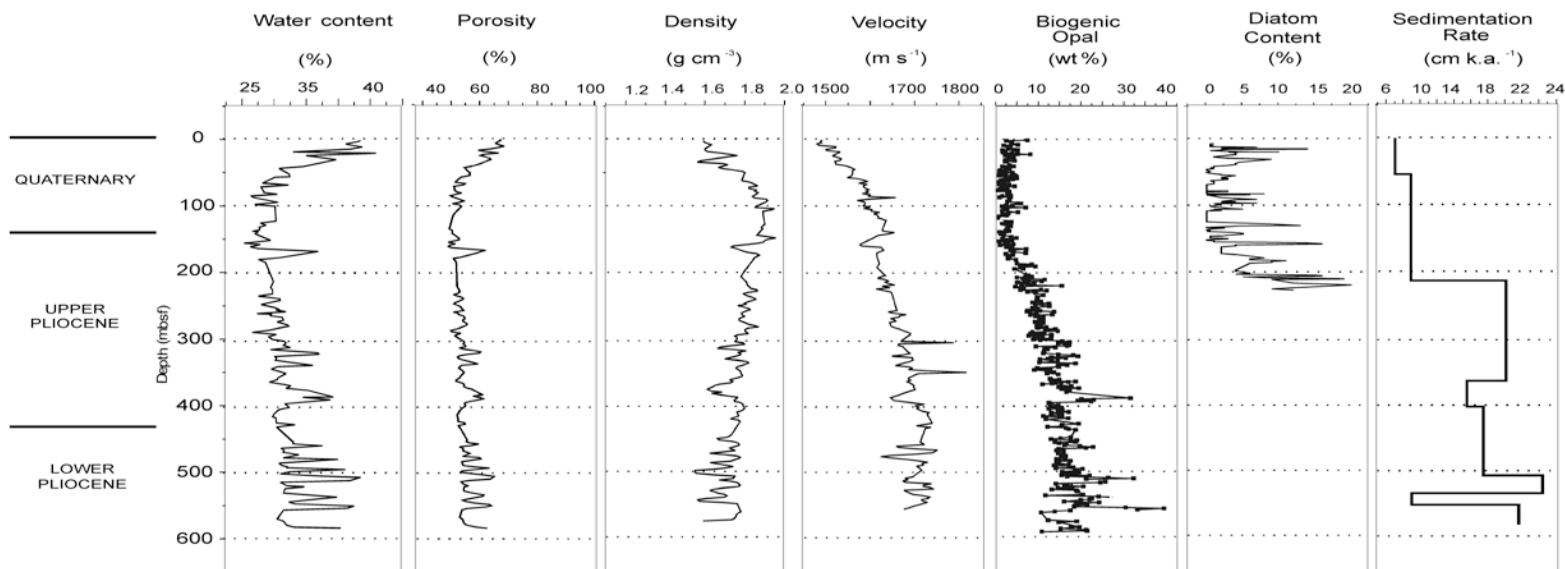


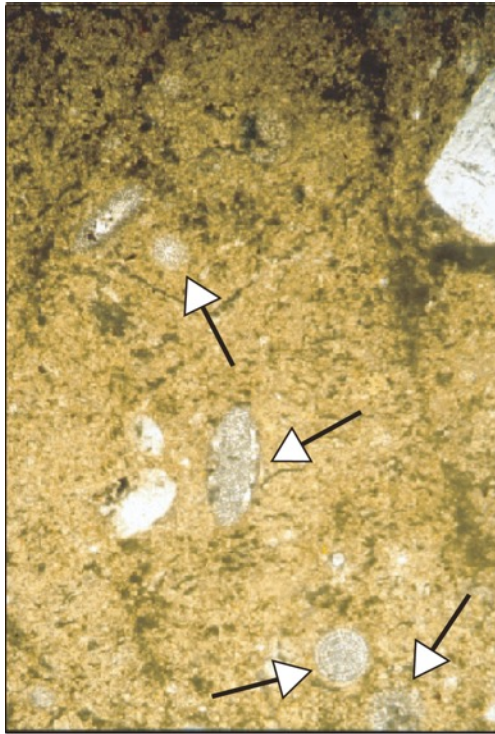


SITE 1095



SITE 1096

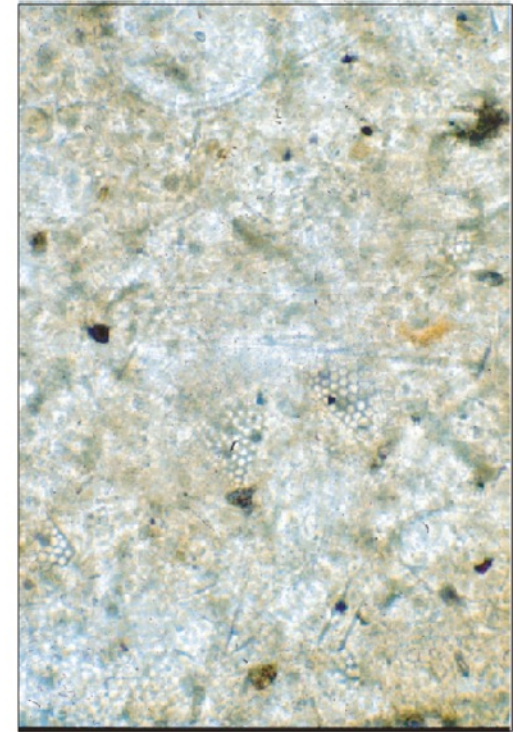




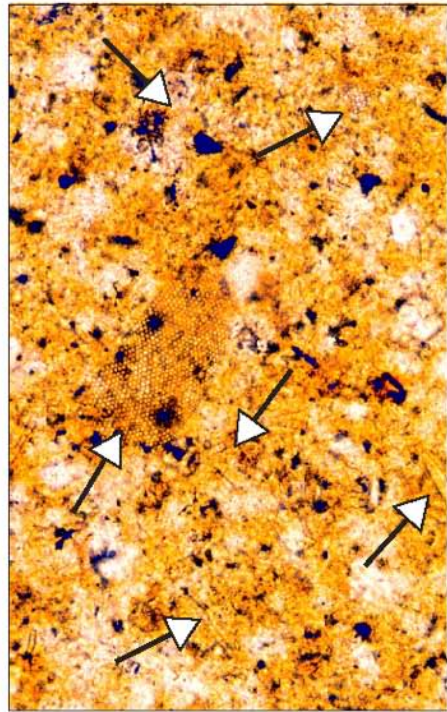
— 0,1 mm



— 10 μm

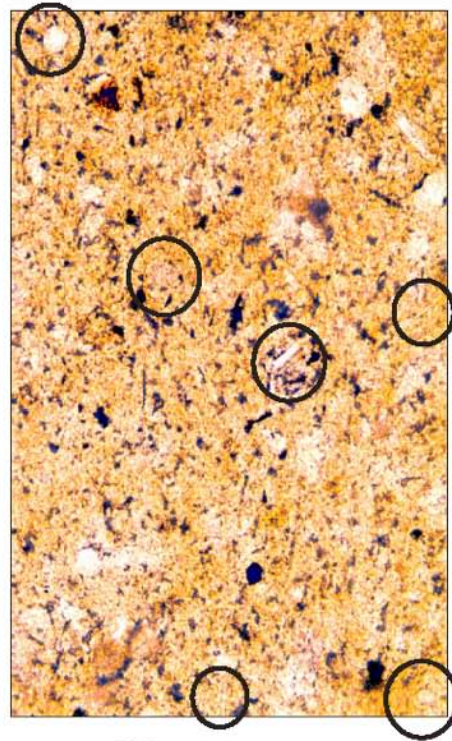


— 40 μm



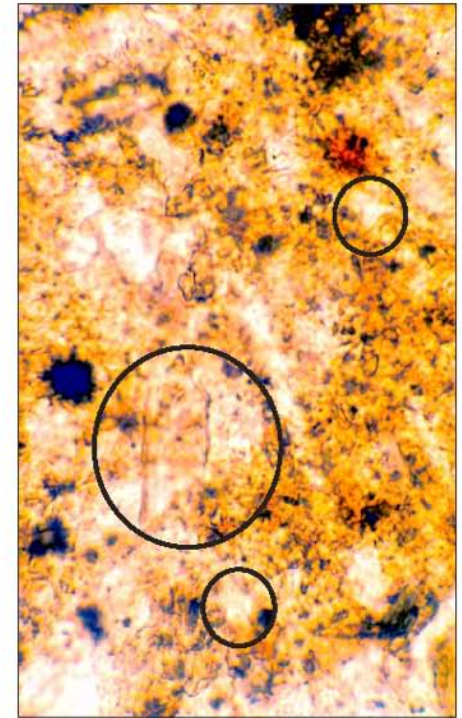
— 50  $\mu\text{m}$

A



— 50  $\mu\text{m}$

B

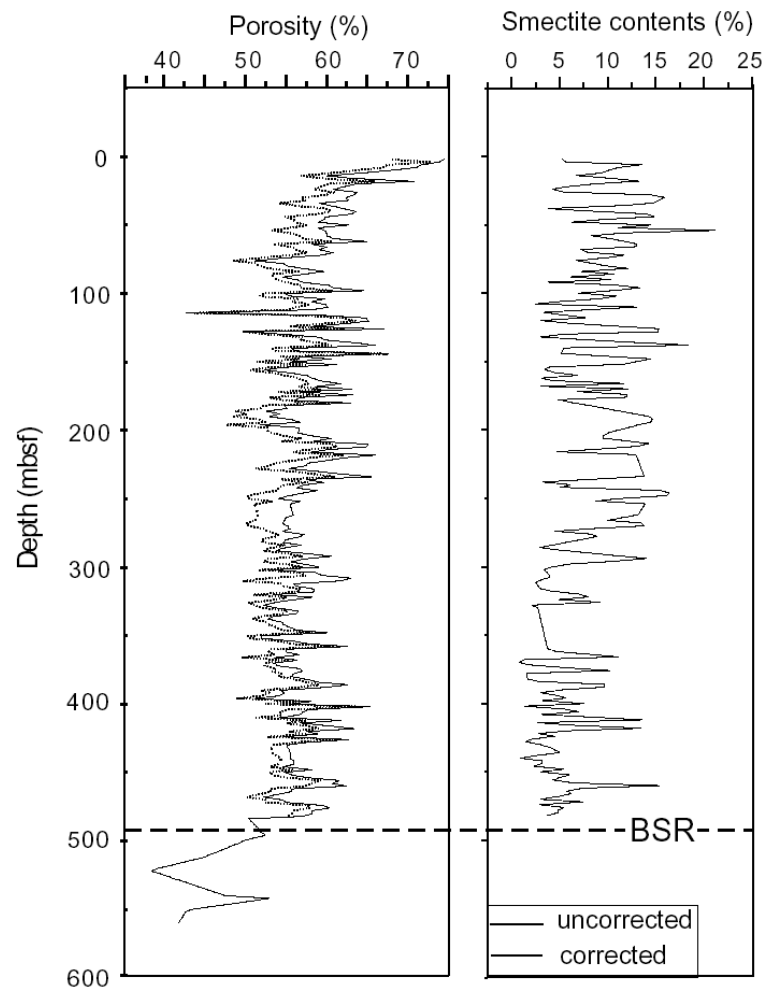


— 10  $\mu\text{m}$

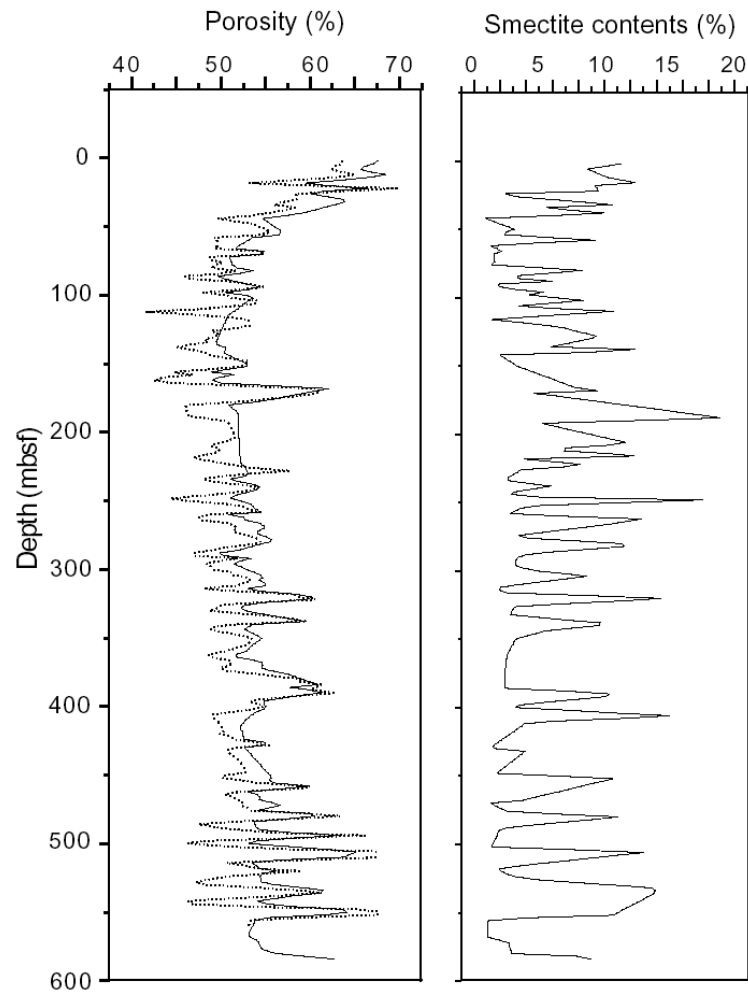
C

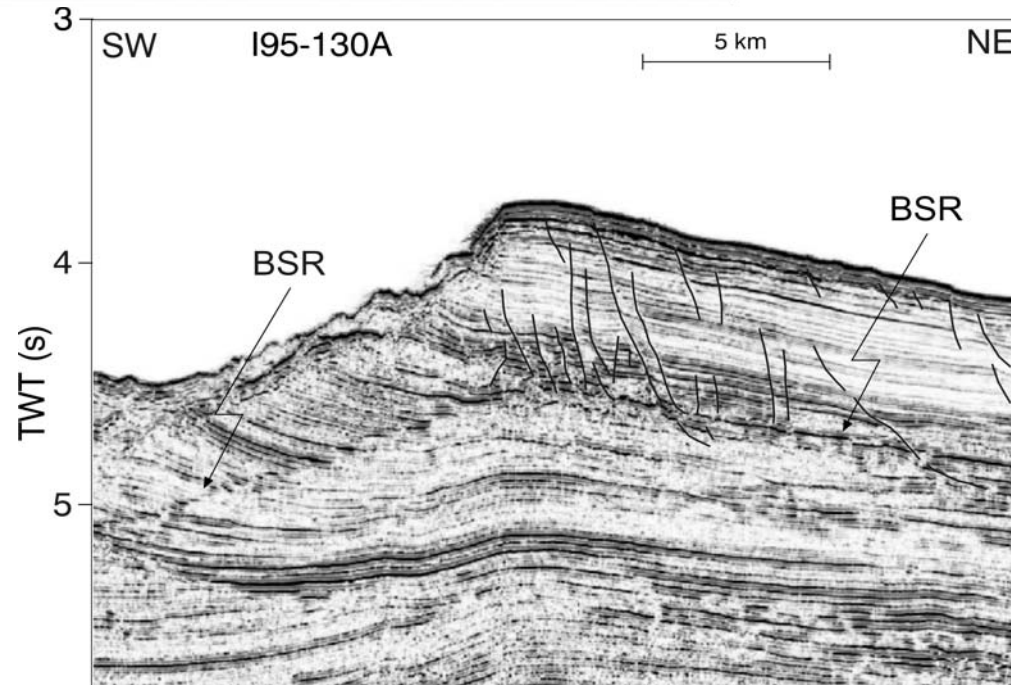
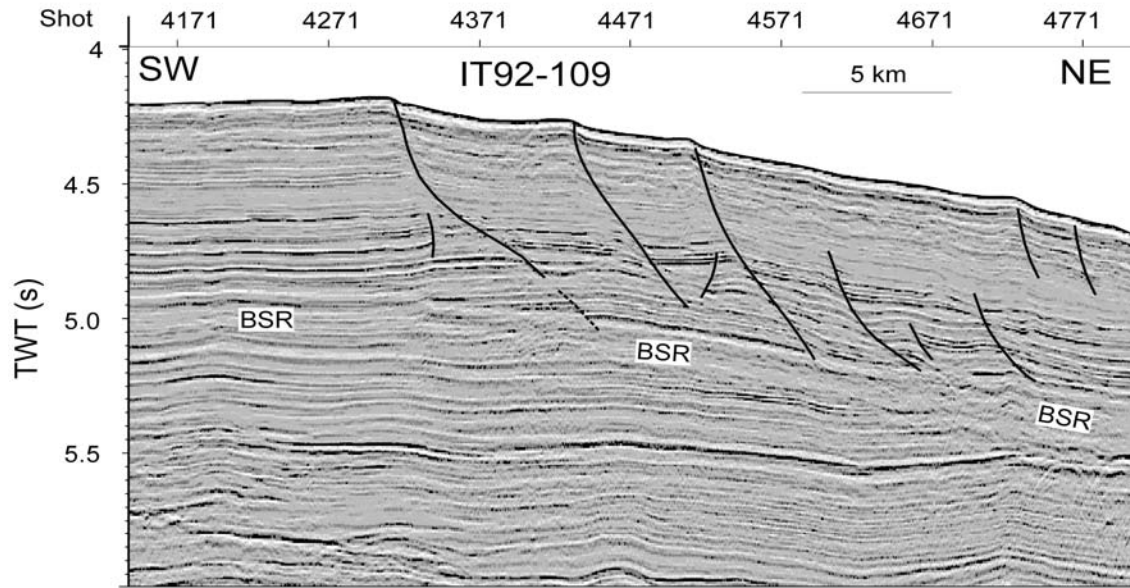


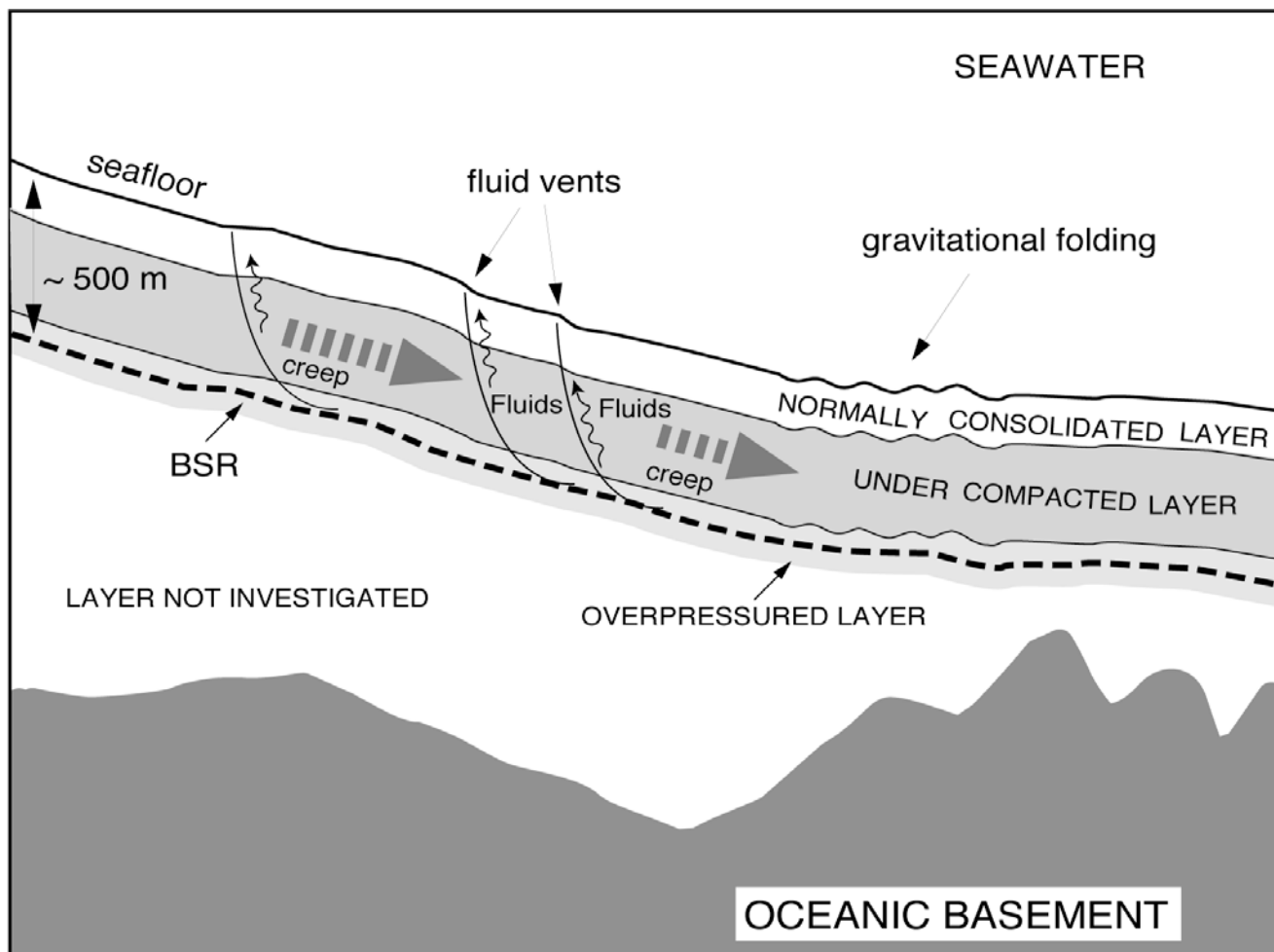
Site 1095



Site 1096







## Conclusions:

- Due to their shape and strengths, microfossils affect significantly the physical properties and mechanical behavior of marine sediments:
  - Microfossil-rich sediments retain porosity with depth.
- They resist consolidation until a threshold value of applied stress, exceeded which the rigid structure of the sediment collapses.
- Micro-structural collapse may trigger overpressure in the pore fluids, and weakness of the sediment (decreased effective stress).
  - Diagenesis may act in two ways:
    - \_ Cementation contributed to strengthening of the sediment.
    - \_ Opal A to C/T transformation acts as a micro-structural collapse
- Microfossil rich sediments, and oozes in particular, are candidate sediments to provide weakness surfaces in submarine slopes.

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