Istituto Nazionale
di Oceanografia
e di Geofisica
Sperimentale

# Università degli studi di Trieste

## LAUREA MAGISTRALE IN GEOSCIENZE

**Classe Scienze e Tecnologie Geologiche**

## Curriculum: Esplorazione Geologica

**Anno accademico 2022 - 2023**

# Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: **Michele Rebesco**

| ***Module*** | **Topic** | **Teacher** | **Date** |
|---|---|---|---|
| ***1.1*** | Introduction to the course | Rebesco | 03/10/22 |
| ***1.2*** | Methods (geophysics, but not only) | Volpi/Rebesco | 06/10/22 |
| ***6.1*** | Visit to the icebreaker Laura Bassi (along with Geologia Marina) | Rebesco | 10/10/22 |
| ***1.3*** | Mechanisms of basin formation (geodynamics, tectonics…) | Lodolo | 13/10/22 |
| ***1.4*** | Seismic interpretation, facies and primary structures | Rebesco | 17/10/22 |
| | No lesson: 20th October | | |
| ***2.1*** | Sedimentary processes in river & deltas | Rebesco | 24/10/22 |
| | No lesson: 27th | | |
| ***2.2*** | Action of tides and waves, wind and ice | Rebesco | 31/10/22 |
| | No lesson: 3rd November | | |
| ***2.3*** | Density currents, bottom currents and mass transport | Lucchi/Rebesco | 07/11/22 |
| ***1.5*** | Energy storage & CCUS | Volpi/Donda | 10/10/22 |
| ***3.1*** | Alluvial deposits, lakes and deserts | Rebesco | 11/11/22 |
| | No lesson: 14th November | | |
| ***3.2*** | Barrier systems and incised valleys | Rebesco | 17/11/22 |
| ***3.3*** | Continental shelves (wases, storms, tsunamis) | Rebesco | 21/11/22 |
| ***3.4*** | Mass transport deposits | Ford | 24/11/22 |
| ***3.5*** | Abyssal plains (hemipelagic fallout) and continental margins | Rebesco | 28/11/22 |
| ***3.6*** | Submarine fans (gravity flows on the continental slope) | Lucchi | 01/12/22 |
| ***3.7*** | Sediment drifts (bottom currents along the continental slope) | Rebesco | 05/12/22 |
| | No lesson on Thursday 8 th December | | |
| ***3.8*** | Glacial depositional systems | De Santis | 12/12/22 |
| ***3.9*** | Carbonatic environments, faults, volcans | Rebesco | 15/12/22 |
| ***4.1*** | Sequence stratigraphy: introduction | Rebesco | 19/12/22 |
| | No lessons from 23 rd December to 8 th January | | |
| ***4.2*** | Sequence stratigraphy: closer view | Rebesco | 09/01/23 |
| ***4.3*** | Sequence stratigraphy: applications (e.g. hydrocarbon reservoirs) | Rebesco | 12/01/23 |
| ***5*** | Excercise | Rebesco | 13/01/?? |
| ***6.2*** | Visit to OGS and SEISLAB (along with Geologia Marina) | Rebesco | 20/01/?? |
| ***6.3*** | Visit to CoreLoggingLAB (along with Geologia Marina) | Rebesco | 24/02/?? |

# Modulo 3.1

# Abyssal plains and (hemi)pelagites

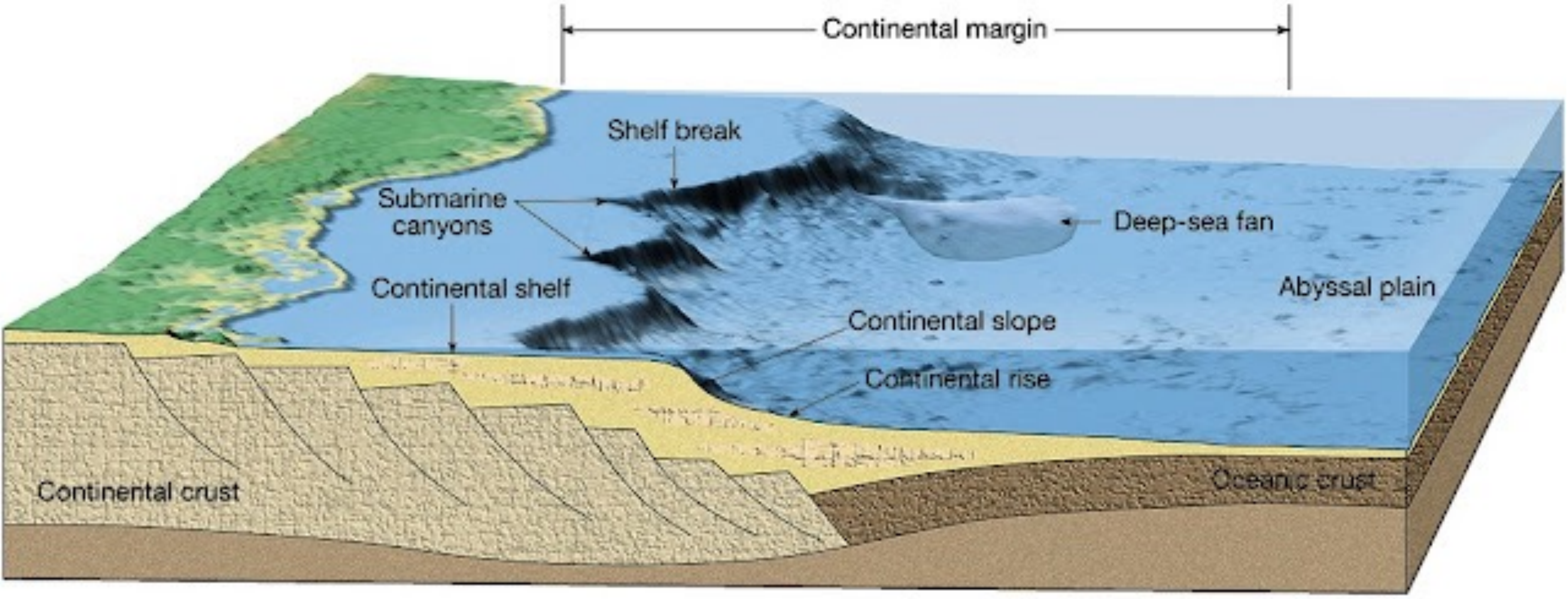
Outline:

- Basin physiography
- Deep sea interacting processes
- Pelagic sediments
- Hemipelagic facies model
- Echo and seismic facies

# Physiographic provinces

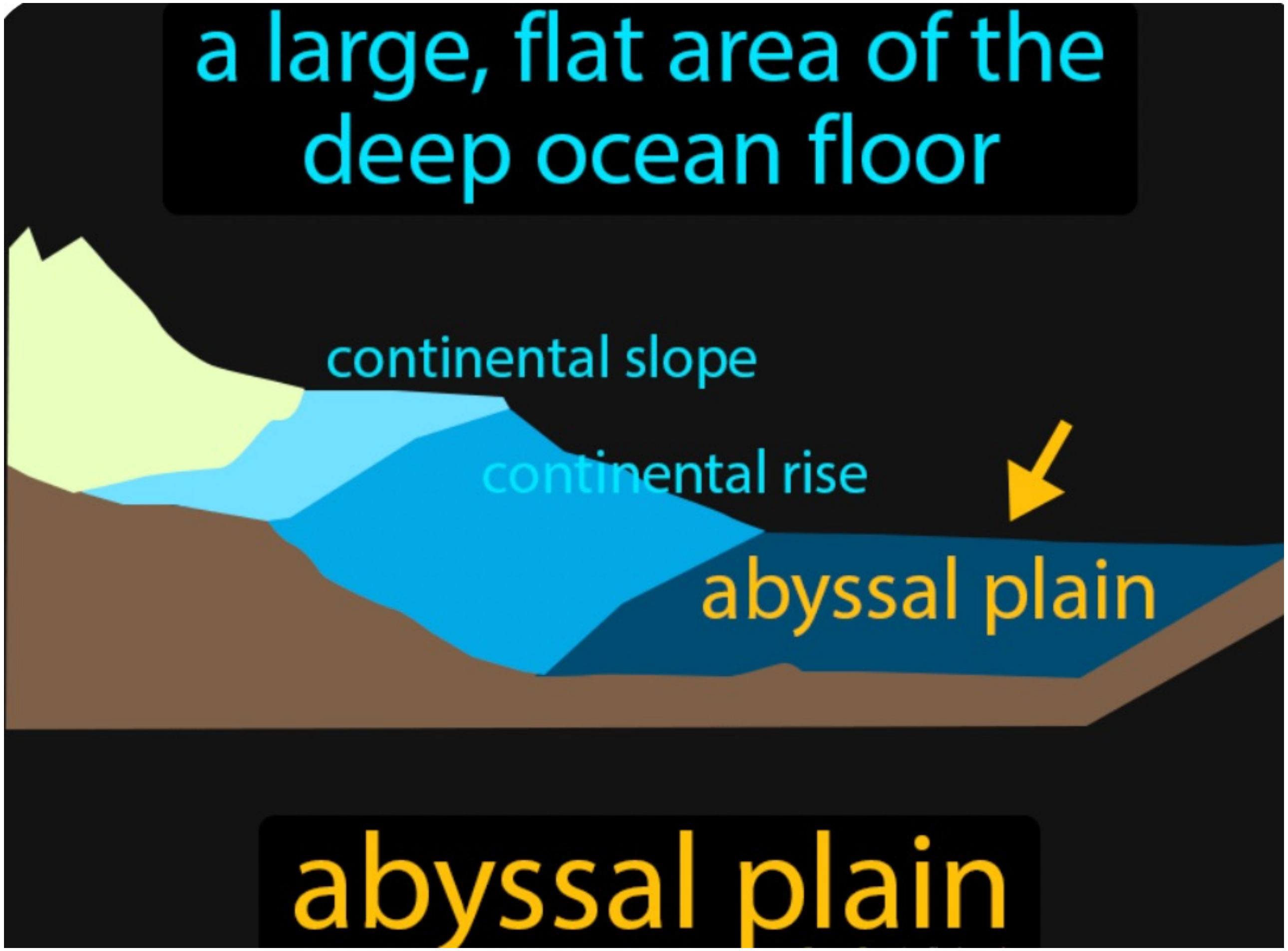
Continental shelf > November 24
Shelf break
Continental slope > November 16
Continental rise > November 17
Abyssal plain > Today

Abyssal hill province
Mid-ocean ridge
Hydrothermal vents
Polymetallic nodules
Mud volcanoes



# Abyssal Plain

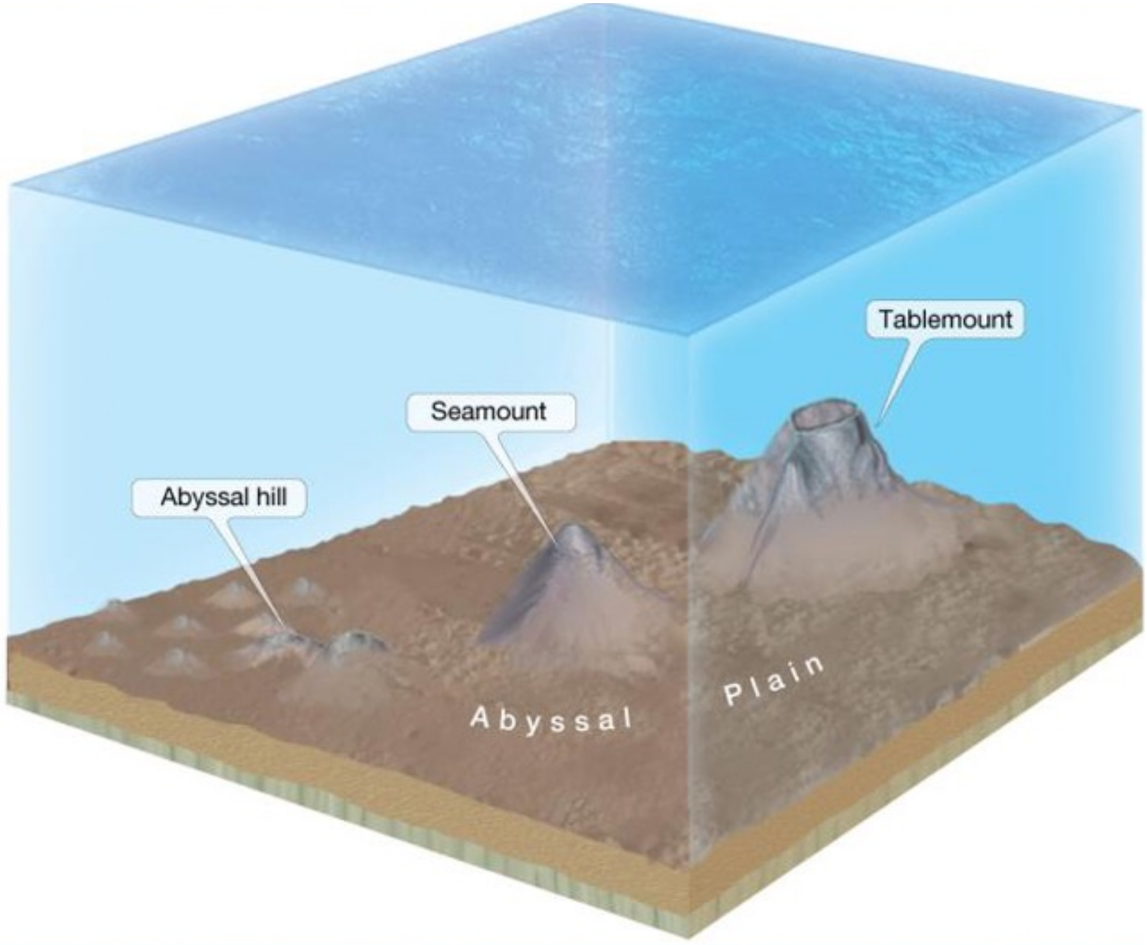
The term ‘abyssal plain’ refers to a flat region of the ocean floor, usually at the base of a continental rise, where slope is less than 1:1000. It covers more than half of the Earth's surface and represents the deepest part of the ocean floor lying between 4000 and 6500 m deep.



A more general term ‘basin plain’ is commonly used in referring to ancient examples. Being adjacent to continental rises, they act frequently as the terminus of turbidity currents, which deposit thin turbidites with usually very fine grains interbedded with the most common **pelagites and hemipelagites**.

# Abyssal hill

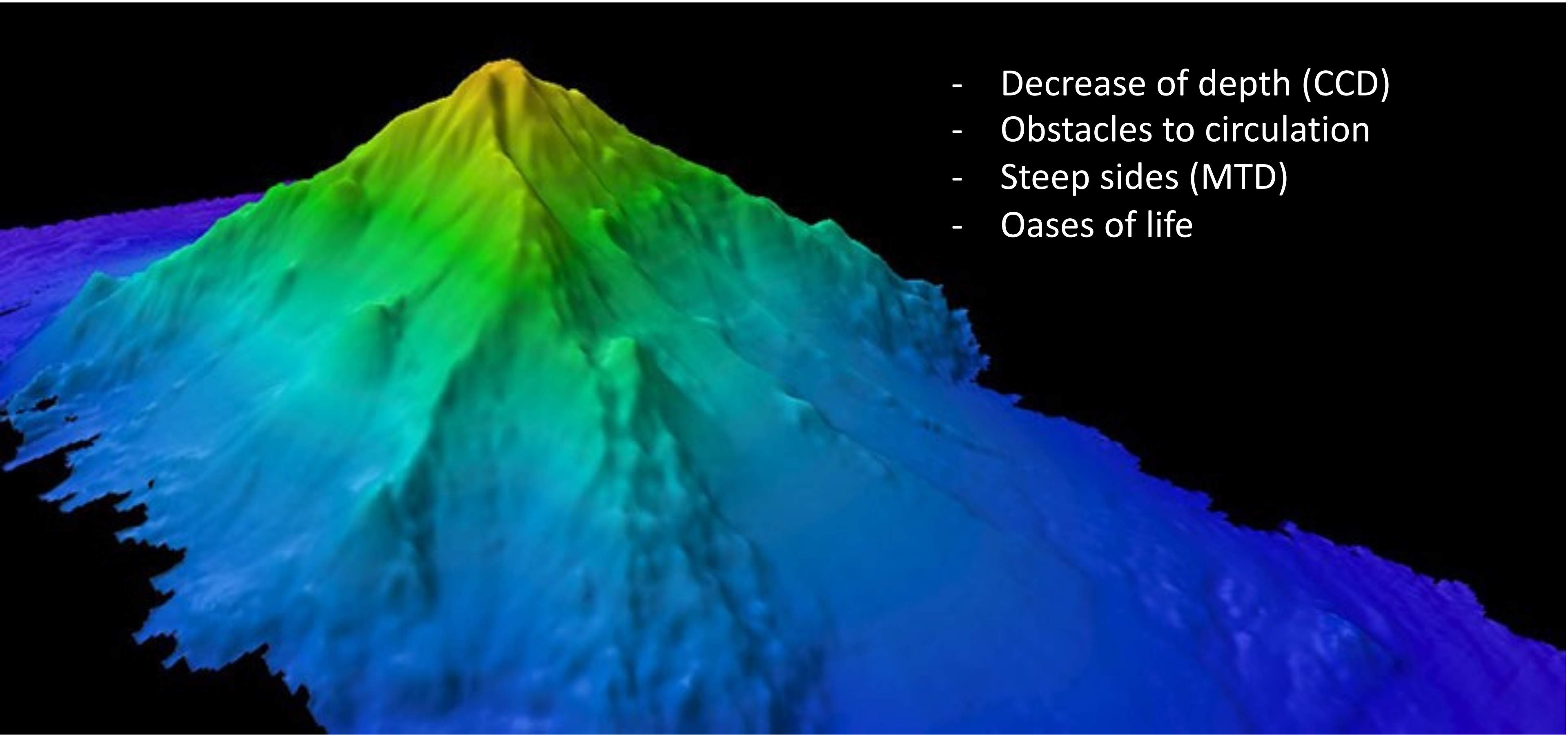
An abyssal hill is a small hill that rises from the floor of an abyssal plain. They are the most abundant geomorphic structures on the planet Earth, covering more than 30% of the ocean floors.



Abyssal hills have relatively sharply defined edges and climb to heights of no more than a few hundred meters. They can be from a few hundred meters to kilometers in width. A region of the abyssal plain that is covered in such hill structures is termed an "abyssal-hills province". However, abyssal hills can also appear in small groups or in isolation

# Seamounts

A seamount is an underwater mountain with steep sides rising from the seafloor.

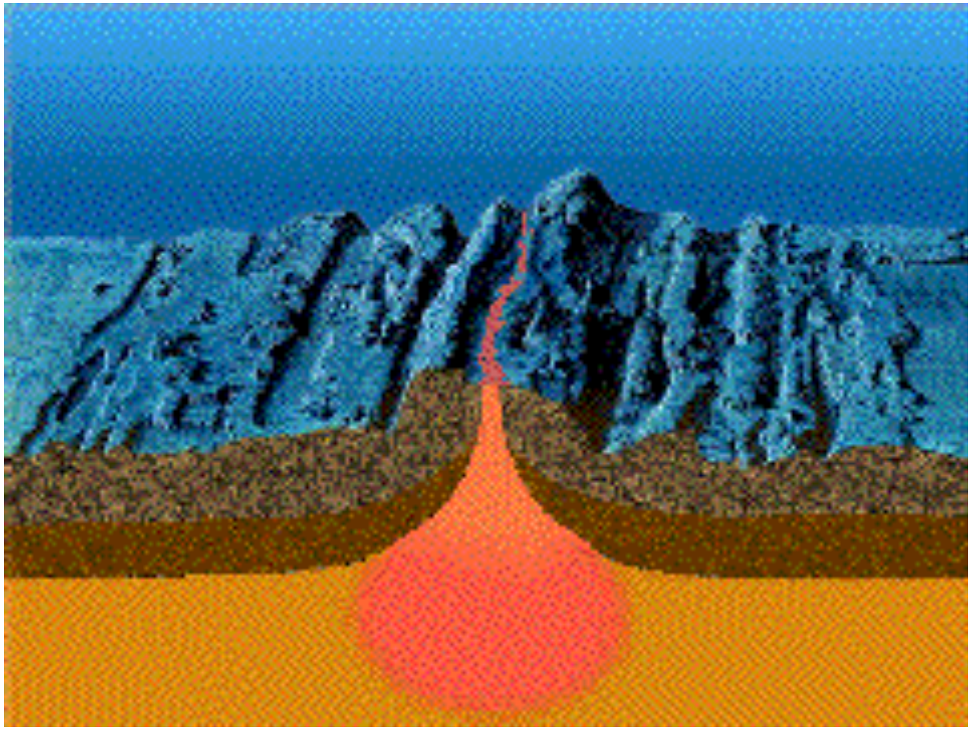


- Decrease of depth (CCD)
- Obstacles to circulation
- Steep sides (MTD)
- Oases of life

A ~4,200-meter high seamount mapped during the Mountains in the Deep: Exploring the Central Pacific Basin expedition
(Image courtesy of the NOAA Office of Ocean Exploration and Research)

# Mid-ocean ridges

A mid-ocean ridge (MOR) is a seafloor mountain system formed by plate tectonics.



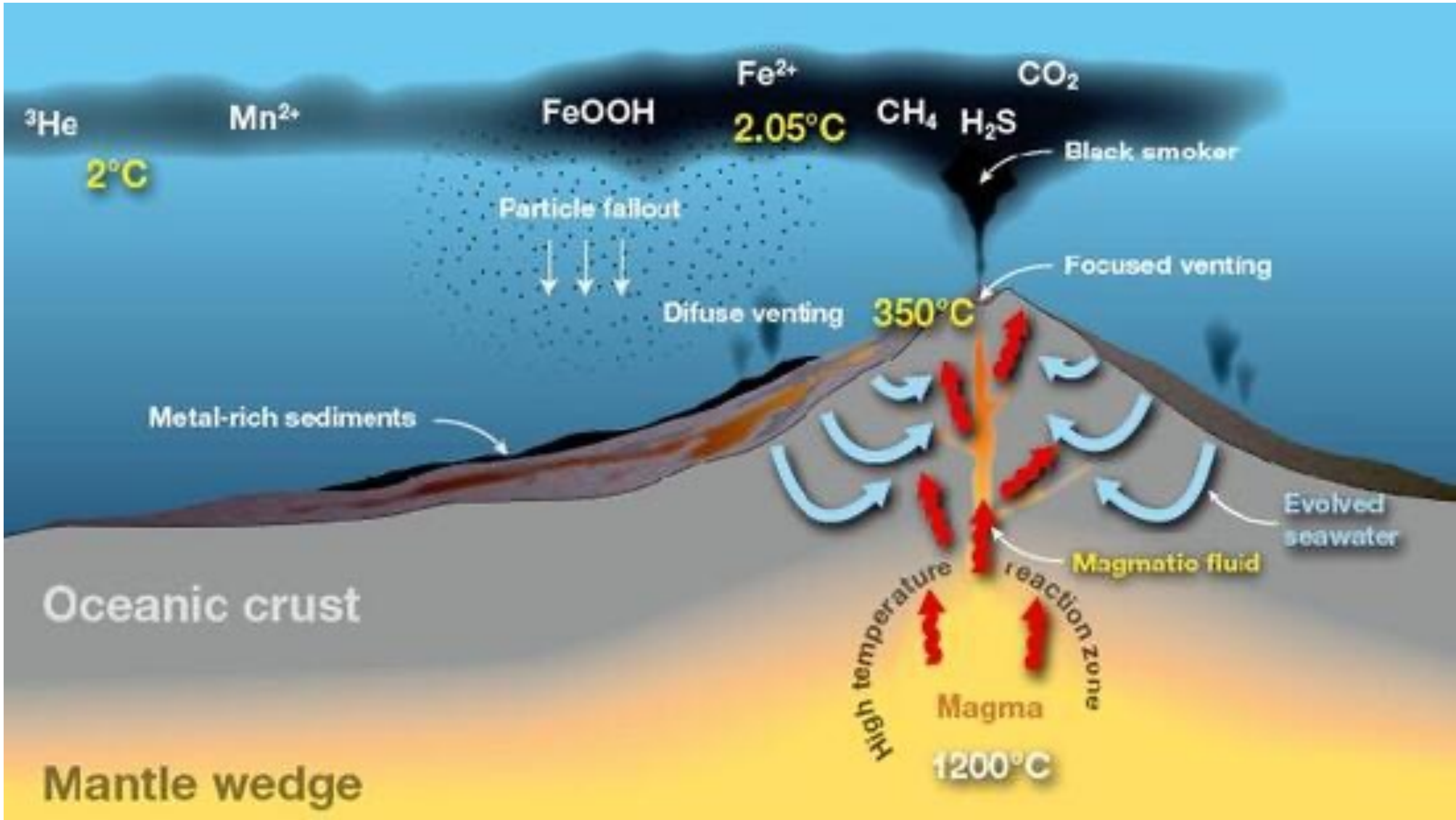
Sediment on ridge flanks commonly thicken with distance from the spreading axes, reflecting the increasing age of the volcanic seafloor. Complications to this simple picture occur where there is substantial sediment transport or varied dissolution of carbonate.

# Hydrothermal vents

A hydrothermal vent is an underwater hot spring found on the ocean floor

>100 vent fields documented along the 60,000-km global mid-ocean ridge system.

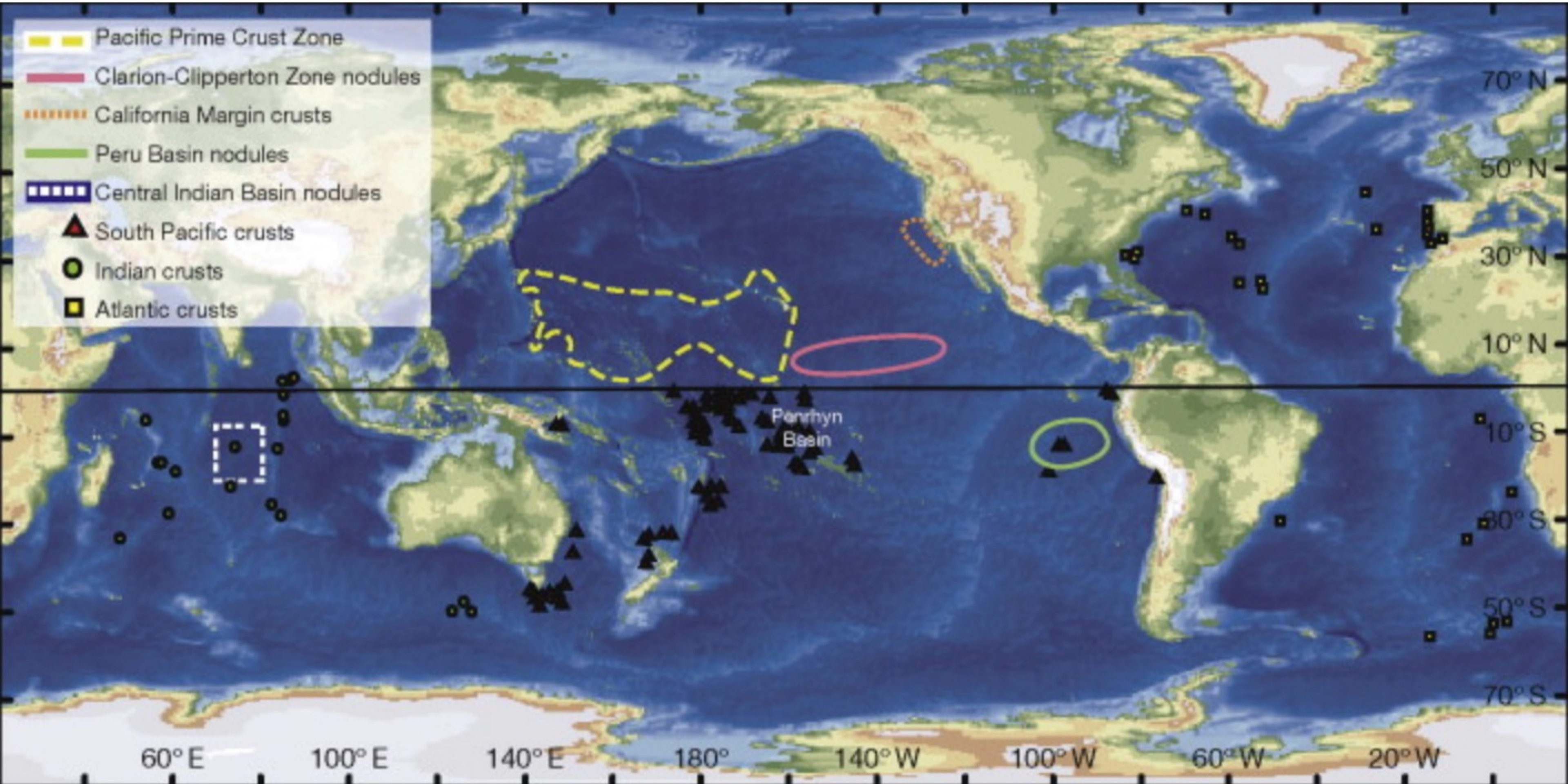
Commonly found near volcanically active places, areas where tectonic plates are moving apart, ocean basins, and hotspots, hydrothermal vents produce metal-rich chimneys, of interest in undersea prospecting, and provide an important environmental niche for life in the deep.



# Nodules

Hein & Koschinsky, Geochemistry of Mineral Deposits, 2014

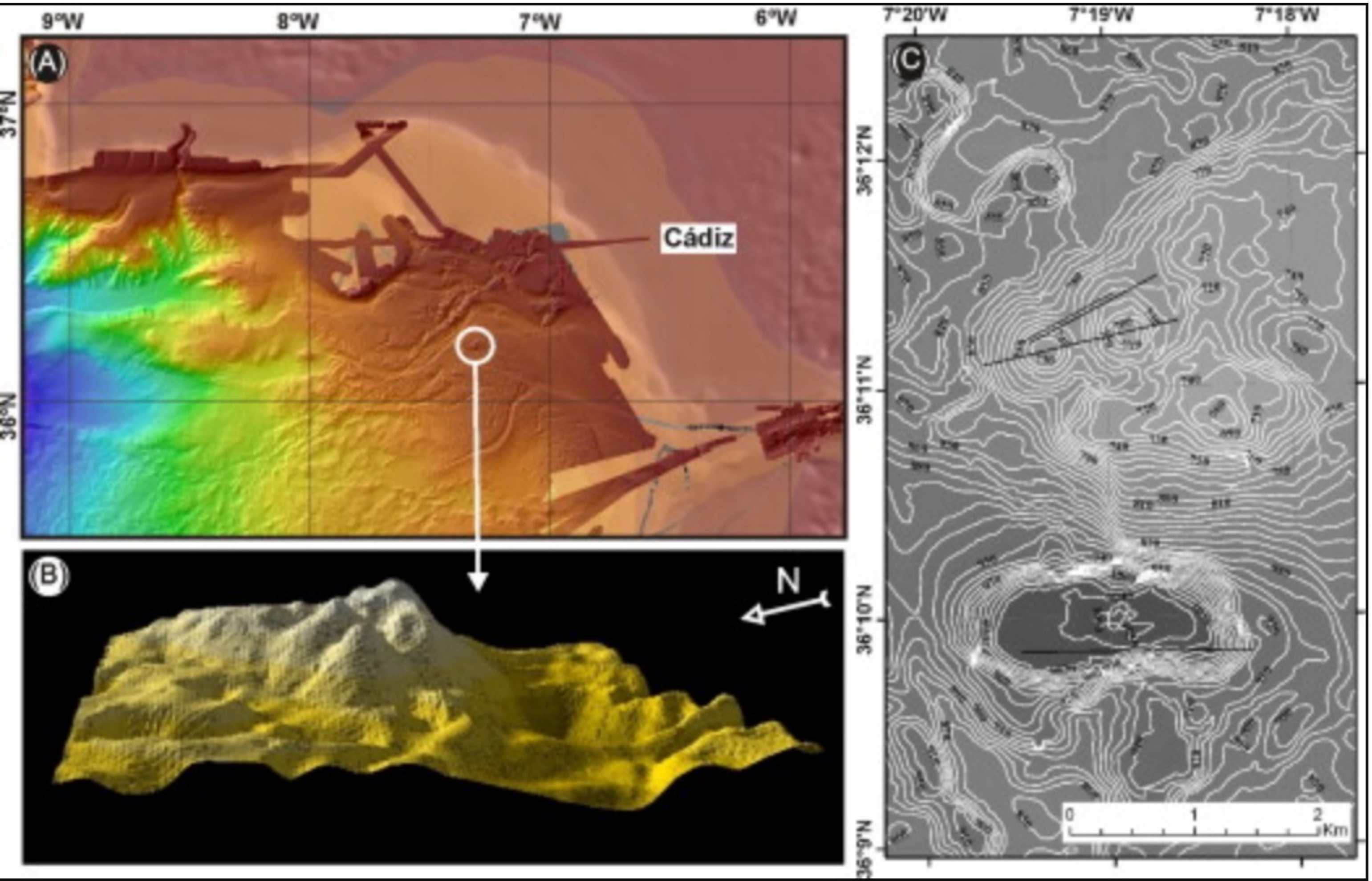
Fe–Mn nodules typically occur on sediment-covered abyssal plains where sediment accumulation rates are low (<10 mm/ky). Nodule coverage is more than 50% over large areas of the Pacific and Central Indian Ocean Basin. Although nodules are known to occur on abyssal plains in the Atlantic and polar oceans, their distribution is not well known.



# Mud volcanoes

Mud volcanoes are conduits for fluid venting and consequent carbonate precipitation within the sediments or at the seafloor.

Around 1100 mud volcanoes have so far been found on land and in shallow water. It is believed that more than 10,000 mud volcanoes may exist on continental slopes and abyssal plains.

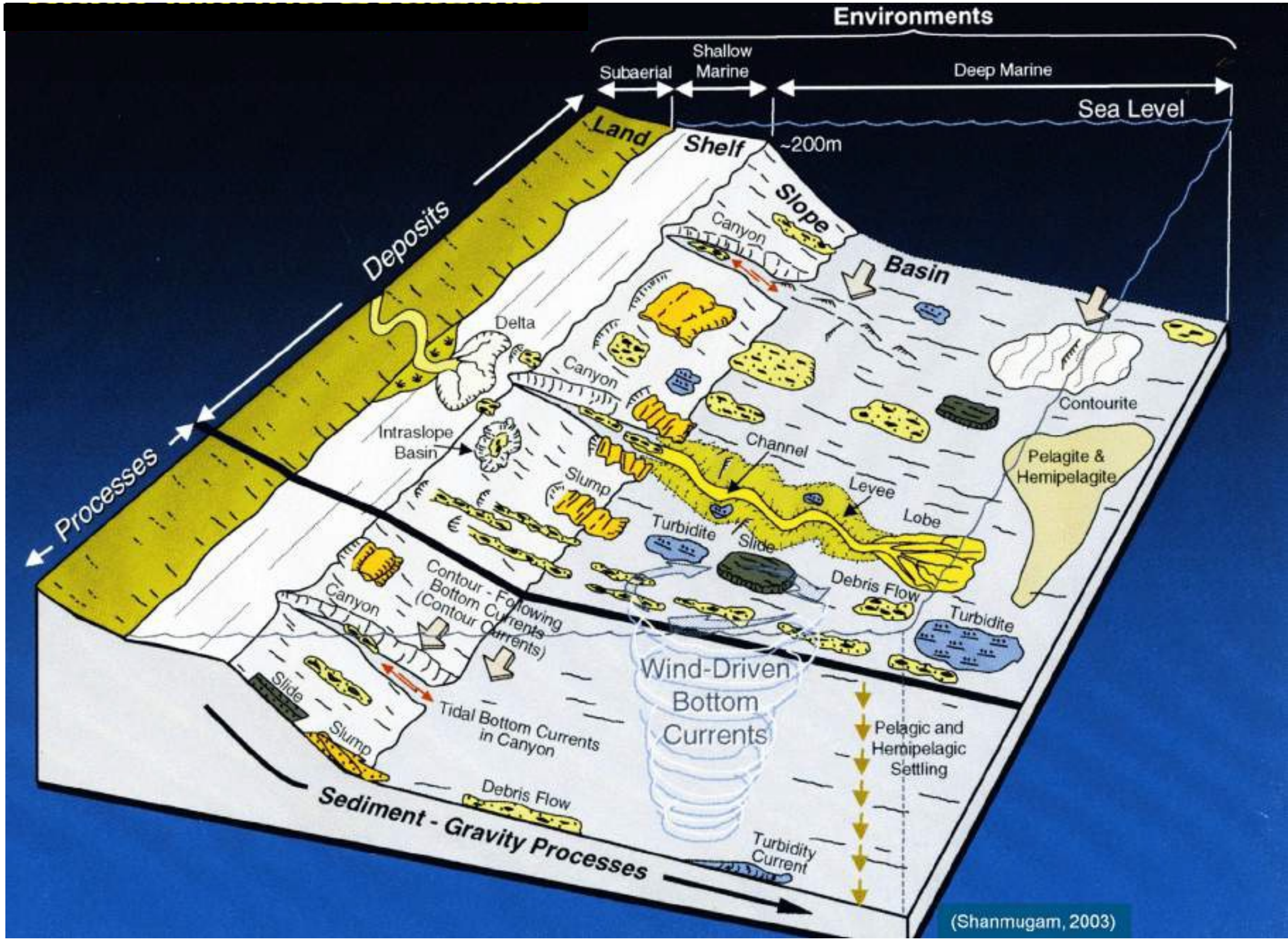


Rueda et al., 2012, in Seafloor Geomorphology as Benthic Habitat

# Deep sea depositional processes

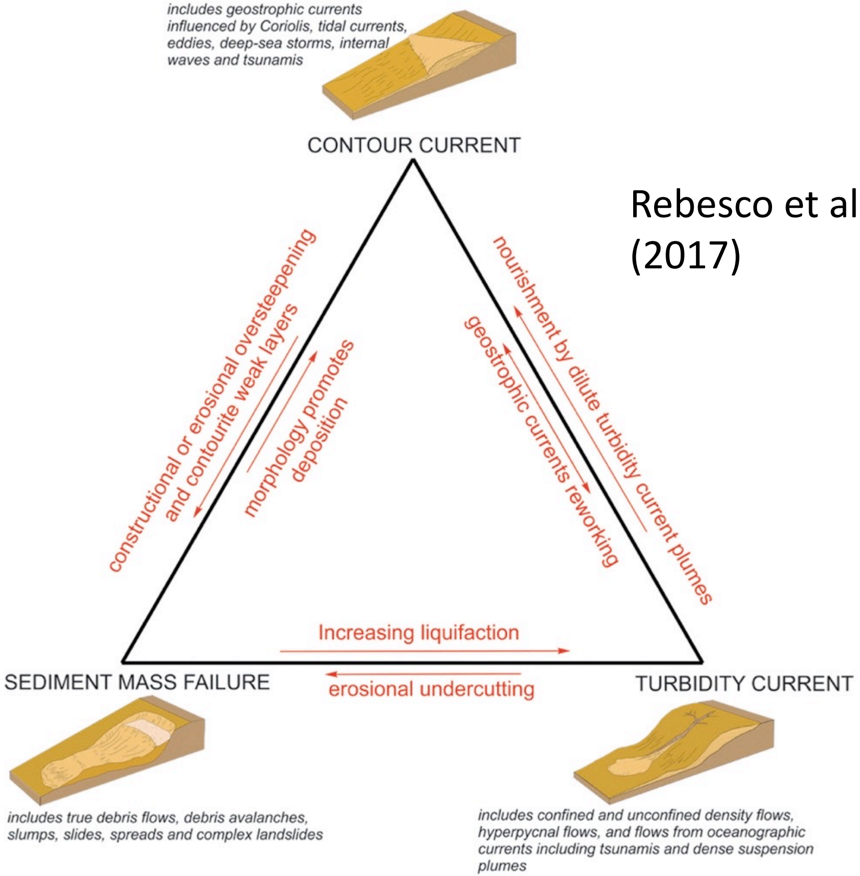
Sediment transport in deep-marine (slope and basin) environments is characterized by gravity-driven downslope processes, such as mass transport (i.e., slides, slumps, and debris flows), and turbidity currents.

Bottom currents, composed of thermohaline contour-following currents, wind-driven currents and up and down tidal bottom currents in submarine canyons.

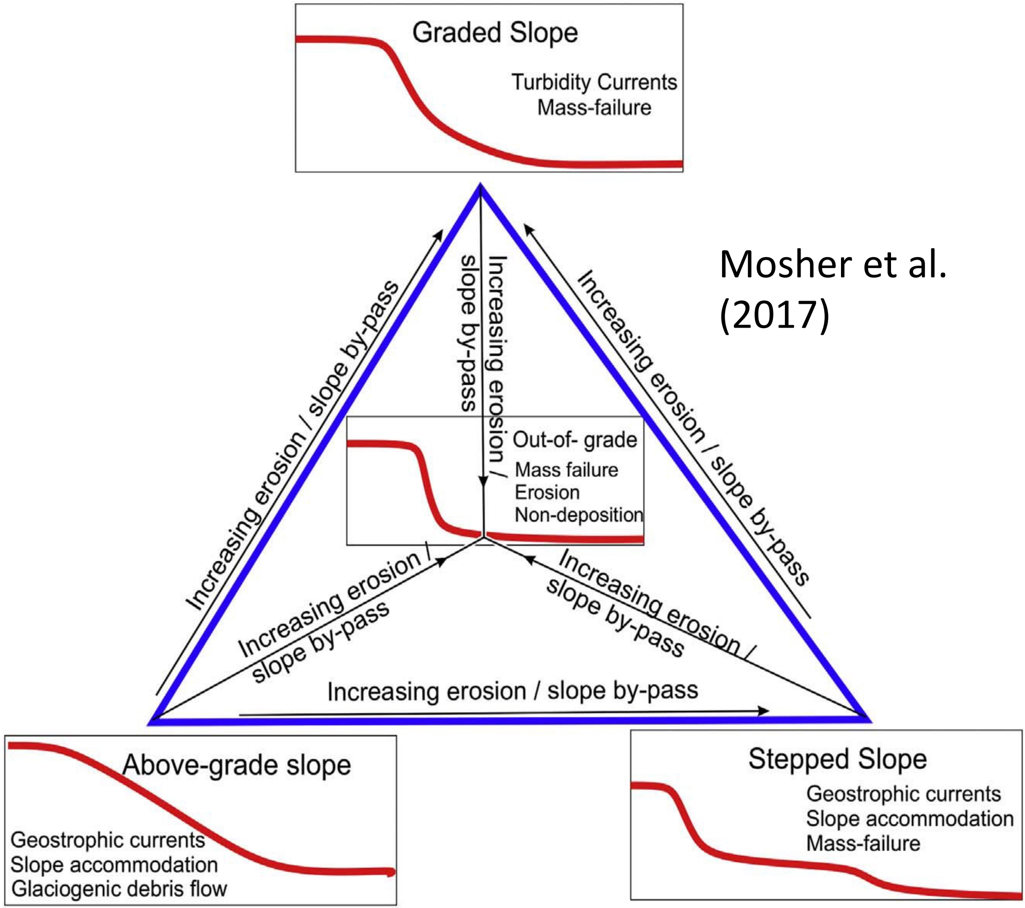


(Shanmugam, 2003)

# Clastic sedimentary processes on continental margins and morphotypes



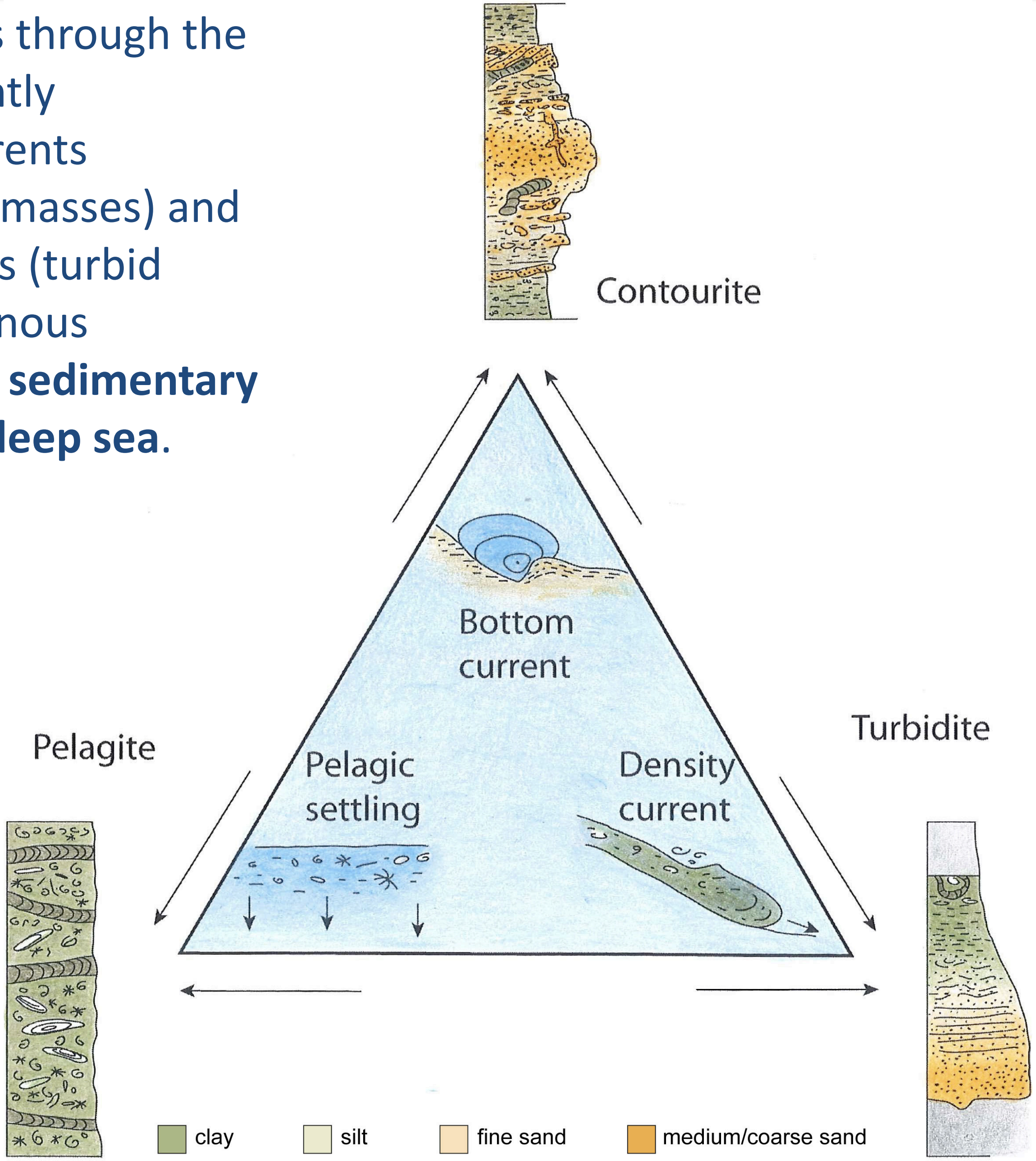
Rebesco et al. (2017)



Mosher et al. (2017)

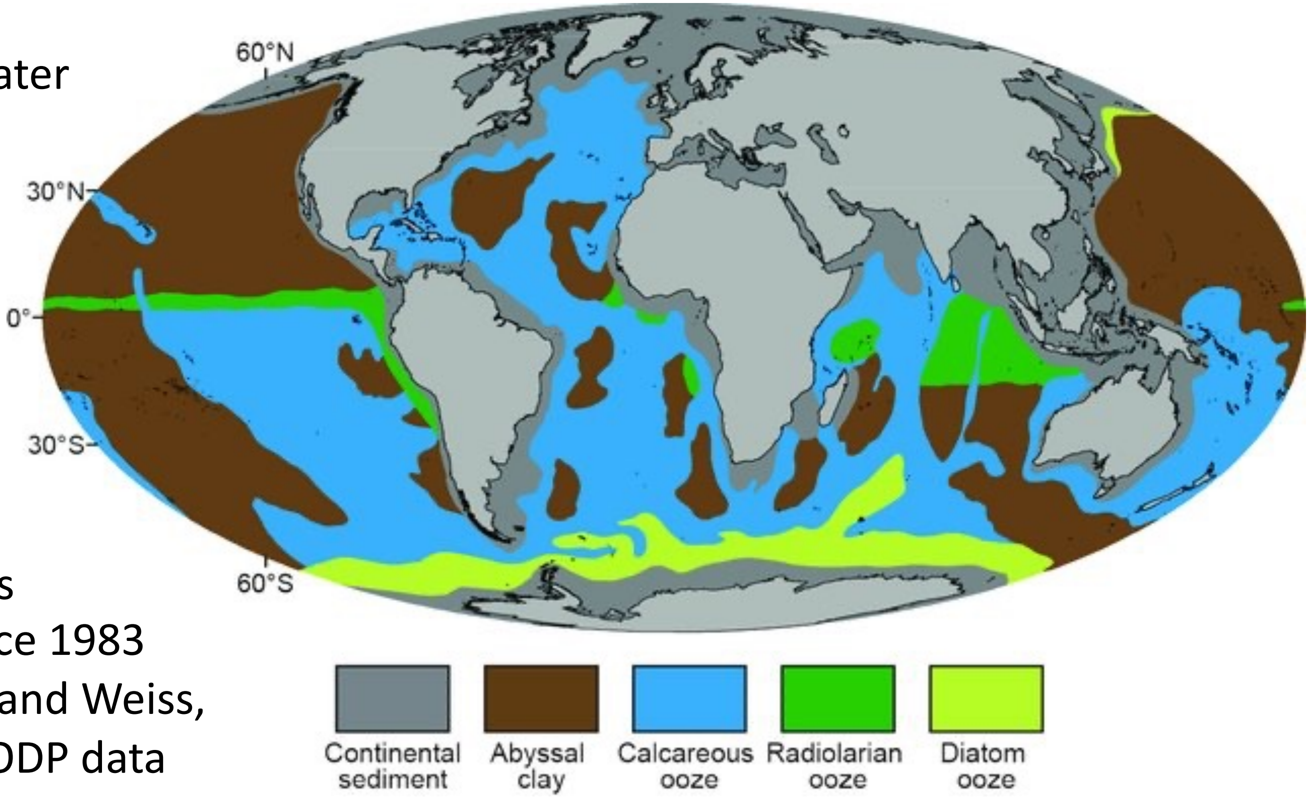
The settling of pelagic particles through the water column, the predominantly alongslope flow of bottom currents (relatively clean bottom water masses) and the downslope density currents (turbid flows of predominantly terrigenous sediments) are **the three main sedimentary processes taking place in the deep sea**.

While the first two represent a "background" process that is dominant only in very remote abyssal areas, episodic, high-energy density flows are commonly superposed to the two other permanent processes on many continental margins.



# Pelagic sediment

Half of the Earth's surface is covered by pelagic sediment, yet study of its sedimentology is challenging because of its slow sedimentation rates and intense bioturbation. Some 47% of the pelagic realm is floored by foraminiferal ooze, 15% by siliceous ooze (mostly diatom ooze around Antarctica), and 38% by abyssal brown clay, in areas where there is total dissolution of biogenic material.

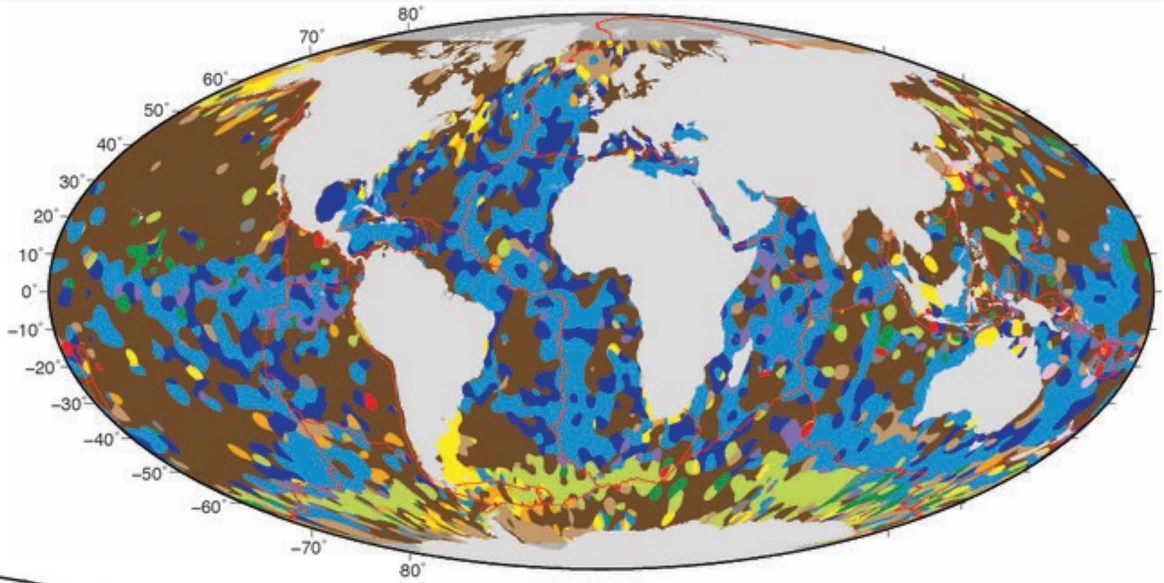


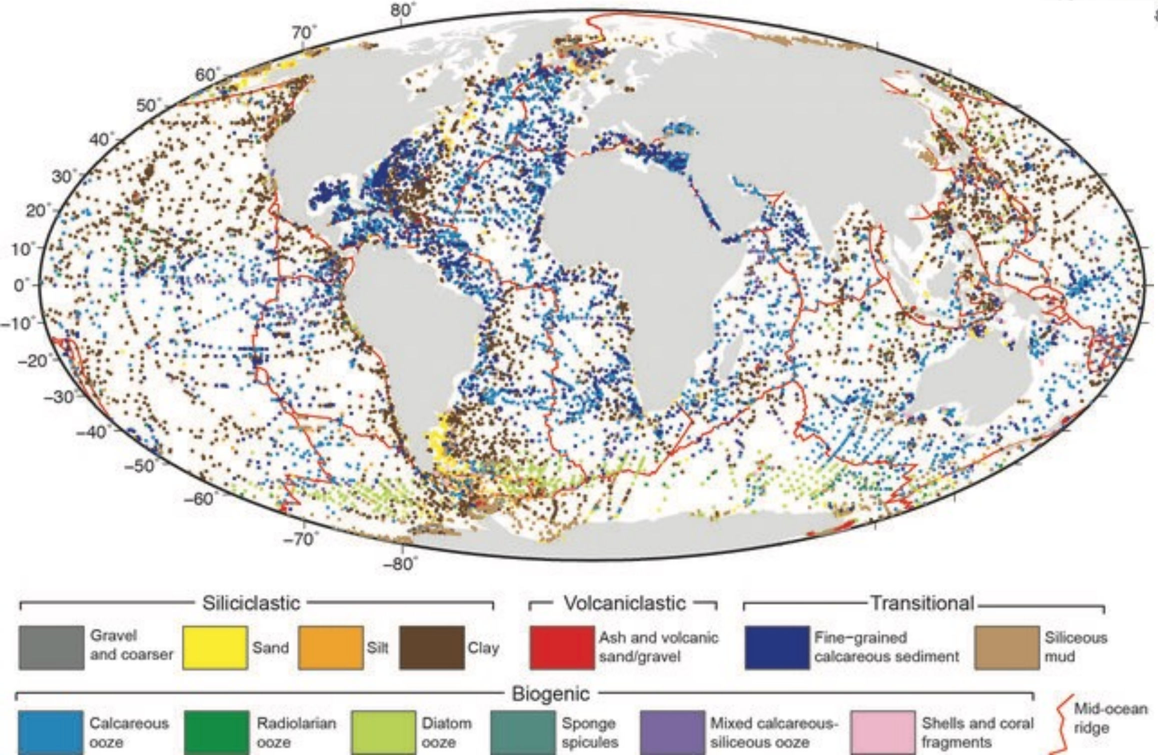
D.J.W. Piper, 2005, Deep Water Processes and Deposits. in Encyclopedia of Geology

This hand-drawn map has remained unchanged since 1983 and is based on Bershad and Weiss, 1974, supplemented by ODP data

# Seafloor sediments

Dutkiewicz et al., 2015.
Census of seafloor sediments in the world's ocean.
Geology 43(9):795-798



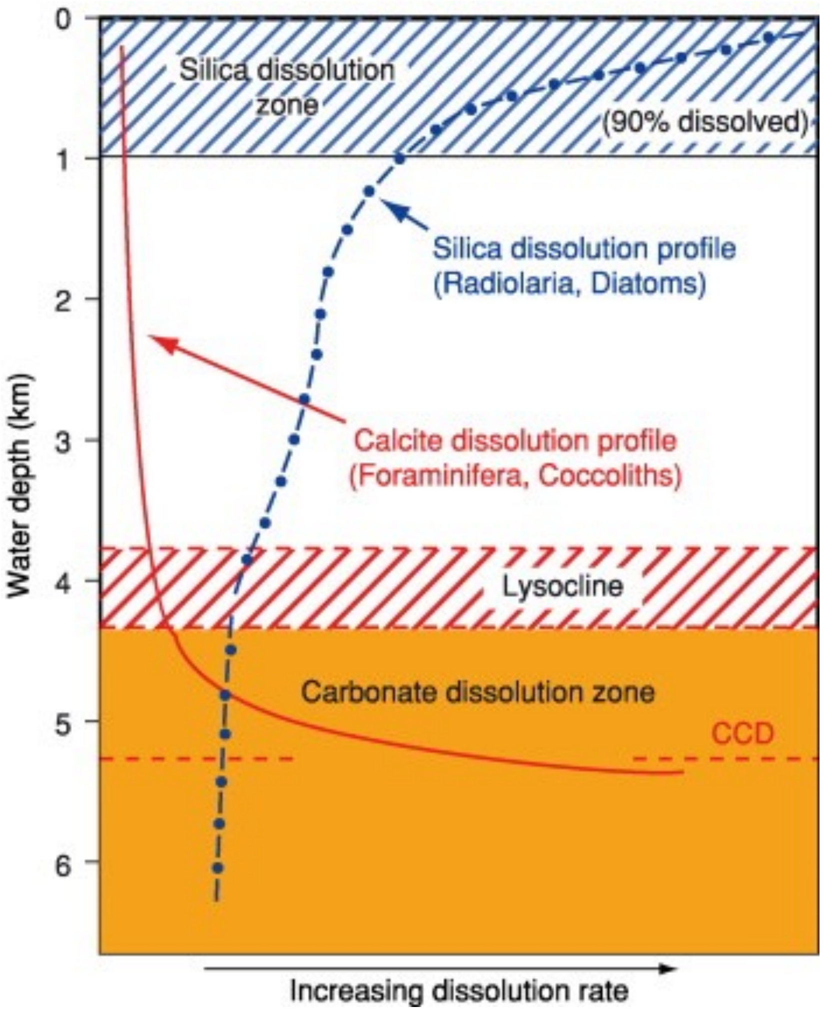


digital map of seafloor lithologies based on descriptions of nearly 14,500 samples from original cruise reports, interpolated using a support vector machine algorithm

# calcite compensation depth

It controls of the distribution of pelagic deposits

Pelagic sediments are defined as those formed of settled material that has fallen through the water column; their distribution is controlled by three main factors, distance from major landmasses, water depth, and ocean fertility. Pelagic sediments are composed largely of the calcareous or siliceous remains of planktonic micro-organisms or wind-derived material or mixtures of these. The distribution of pelagic sediment types is strongly controlled by the calcite compensation depth (CCD), which is that depth at which the rate of supply of biogenic calcite equals its rate of dissolution. Therefoe, below the CCD, only carbonate-free sediments accumulate. Thus the calcite compensation depth marks a major boundary defining the deposition of pelagic clays and calcareous sediments.

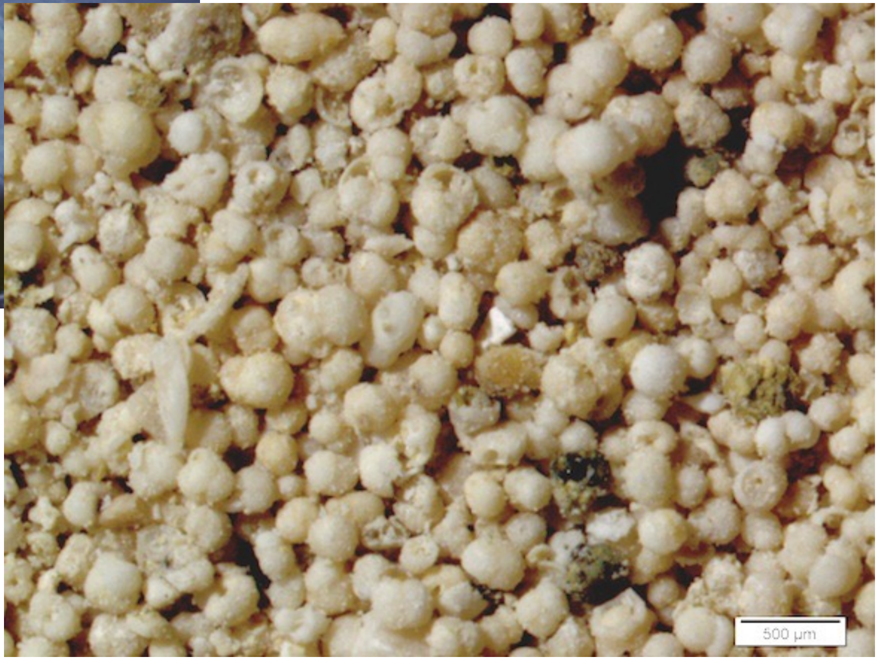


R.G. Rothwell, 2005. Deep Ocean Pelagic Oozes. in Encyclopedia of Geology

# Foraminiferal ooze

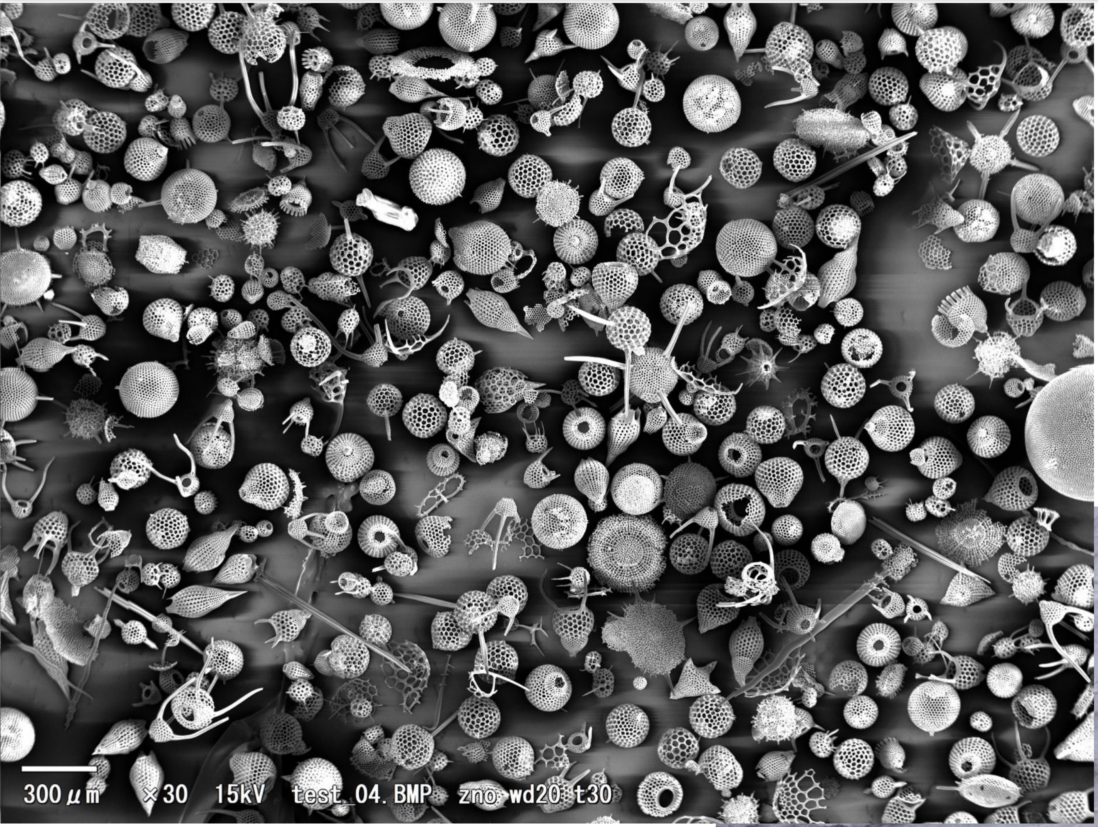
Calcareous foram ooze of the ocean floor viewed from the submersible Alvin in the Oceanographer Fracture Zone, central North Atlantic (~35N, 35W).

It consists almost entirely of tests (skeletons) of foraminiferans known as Globorotalia inflata.



Above is the outcrop of the "Yellow Calcareous Marls" at Cala Sant'Antonino from which the left samples were collected. The rock is very soft and powdery to the touch.

# Siliceous ooze



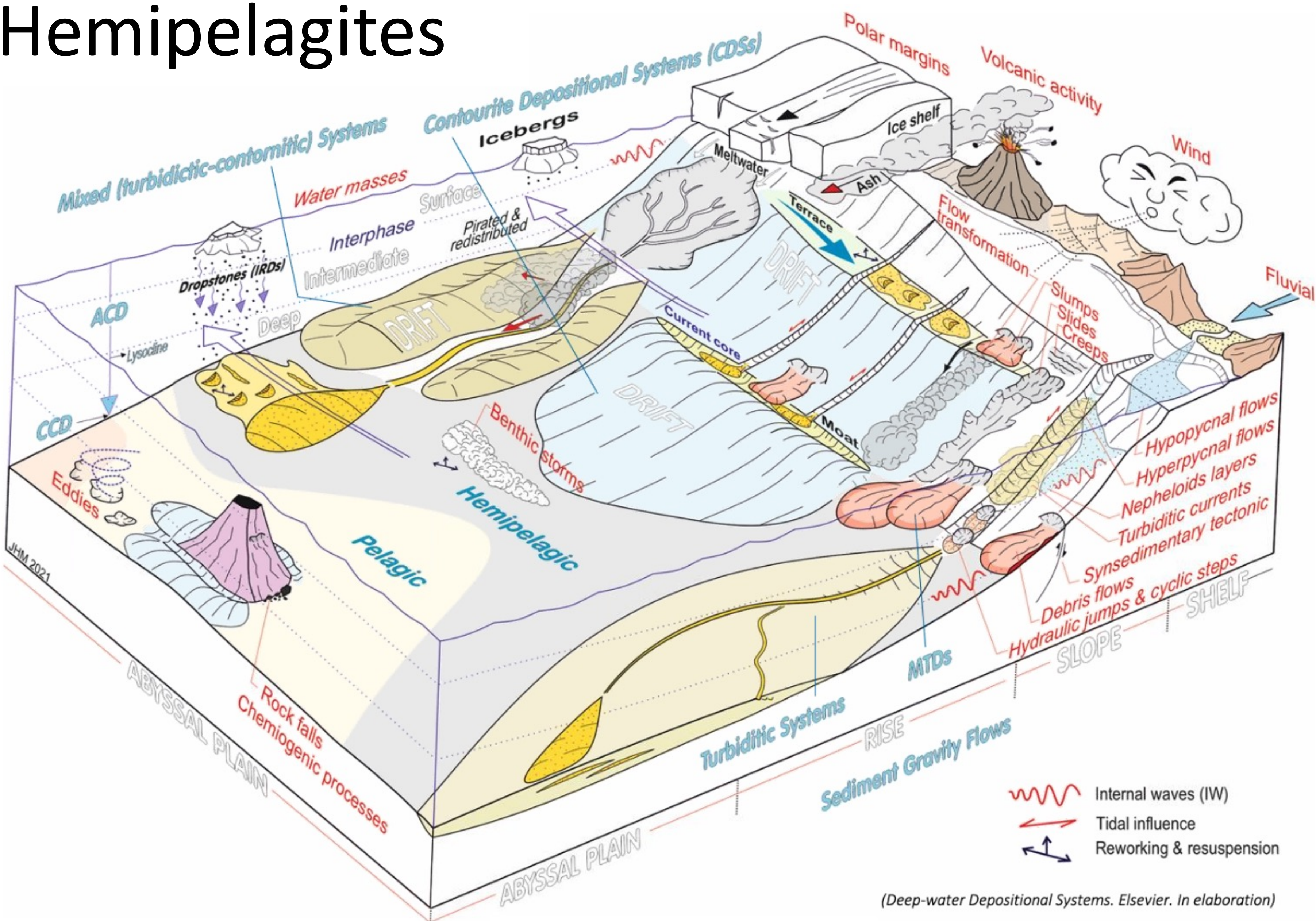
Eocene radiolarian ooze seen at the Scanning Electron Microscope. Credit: Yasuhiro Hata

Nodules of chert (yellowish, in relief) within a crinoid-bearing limestone of the Buttle Lake Group, Vancouver, Canada. Photo courtesy MarkuMark.

# Pelagic red clays

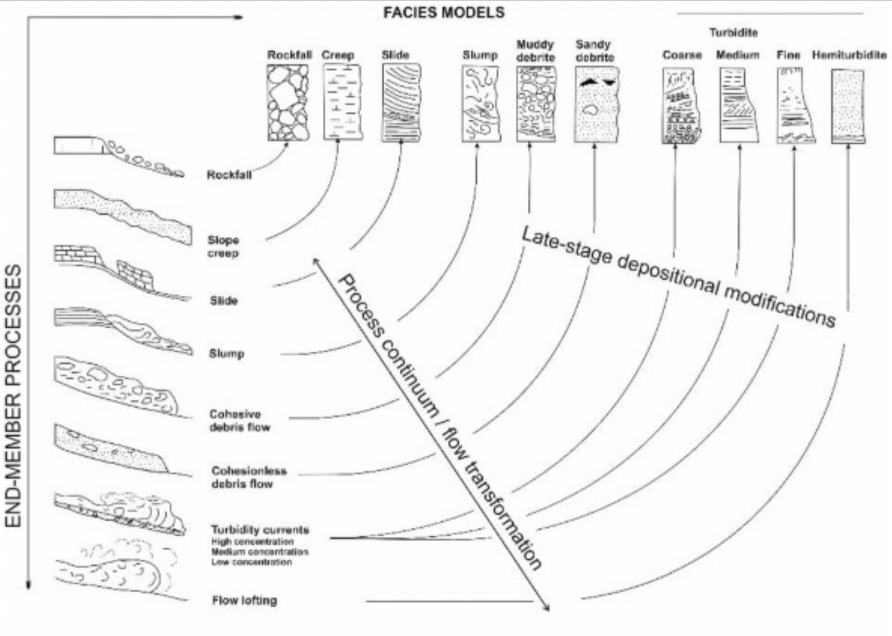
For example *Rosso ammonitico*, deposits typical of pelagic highlands, in conditions of good oxygenation and therefore water exchange.

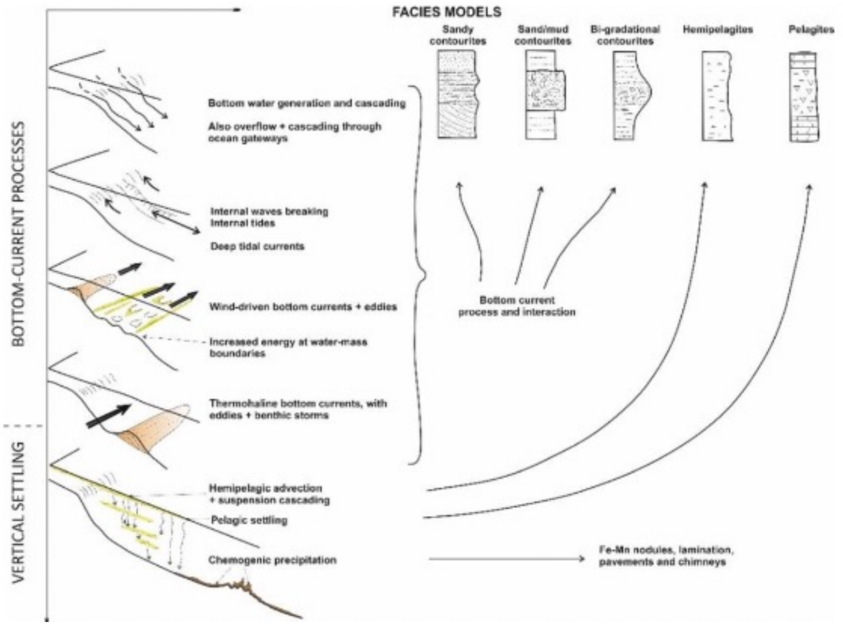
# Hemipelagites



(Deep-water Depositional Systems. Elsevier. In elaboration)

# Distinguishing between Deep-Water Sediment Facies





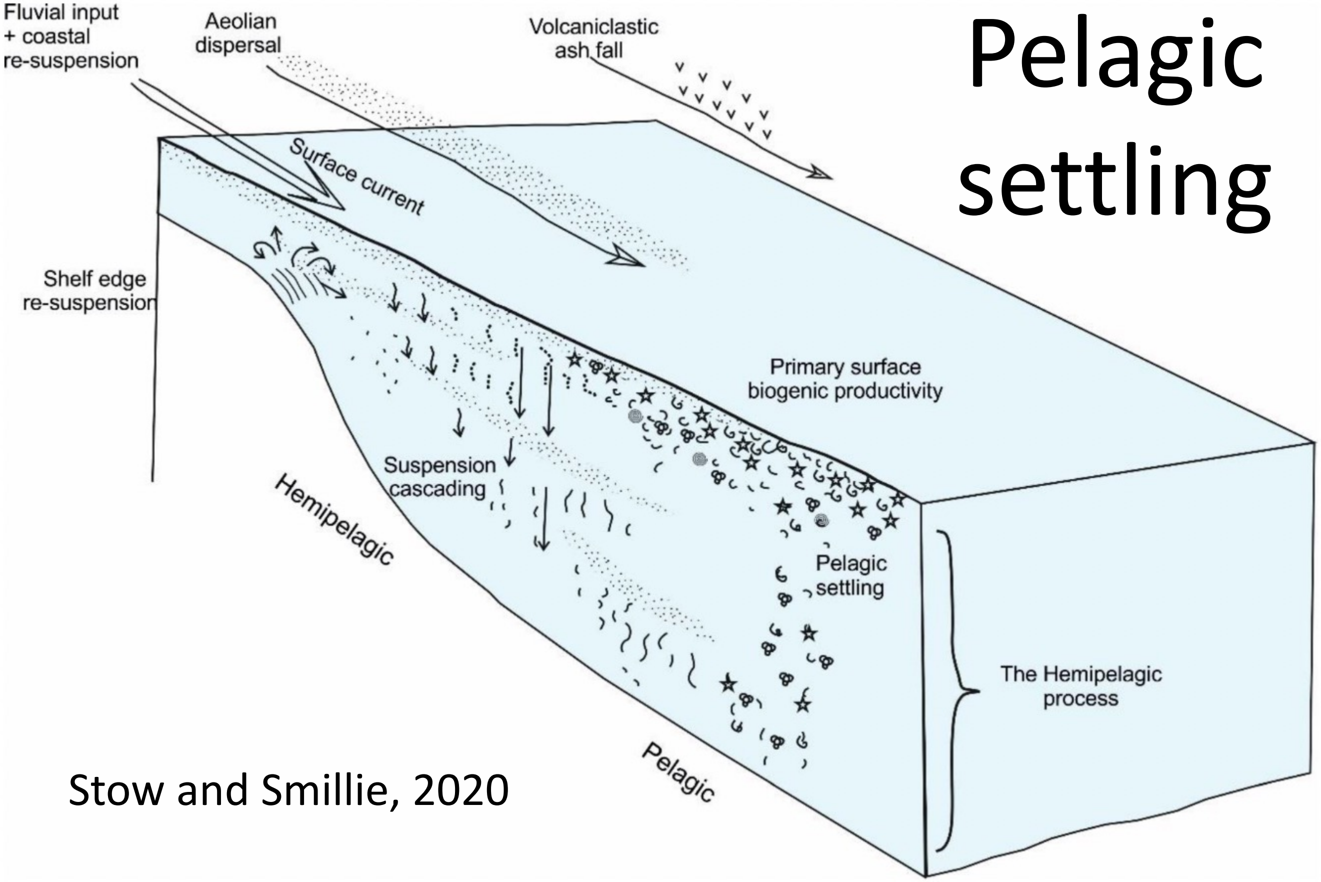
Pelagic or hemipelagic sedimentation dominates where other processes are absent or rare, but all trace of these deposits can be removed where turbidites dominate or where strong bottom currents have prevented deposition. It is in part for these reasons that the distinction between turbidites, contourites and hemipelagites has long been a matter of controversy. Anyone whose work involves deep-water systems and their sediments should be aware of these differences in opinion.

Hemiturbiditic sedimentation involves flow lofting and upward dispersion from a dilute turbidity current during its final stages of deposition. The fine-grained material carried by the turbidity current disperses beyond the final deposit of the normal turbidite, mixes with any background pelagic or hemipelagic material, and deposits slowly by vertical settling.

Stow and Smillie, 2020. Geosciences 10, 68

Pelagic settling is a process of vertical settling under the influence of gravity by which primary biogenic material and very fine-grained terrigenous or other detritus in the surface waters fall slowly to the seafloor. The rate of fall and hence of sediment accumulation is increased by both flocculation and by organic pelletisation, especially in high productive areas. In oligotrophic open-ocean systems, the process is quite continuous and accumulation is typically very slow, i.e., < 1 cm ka−1.

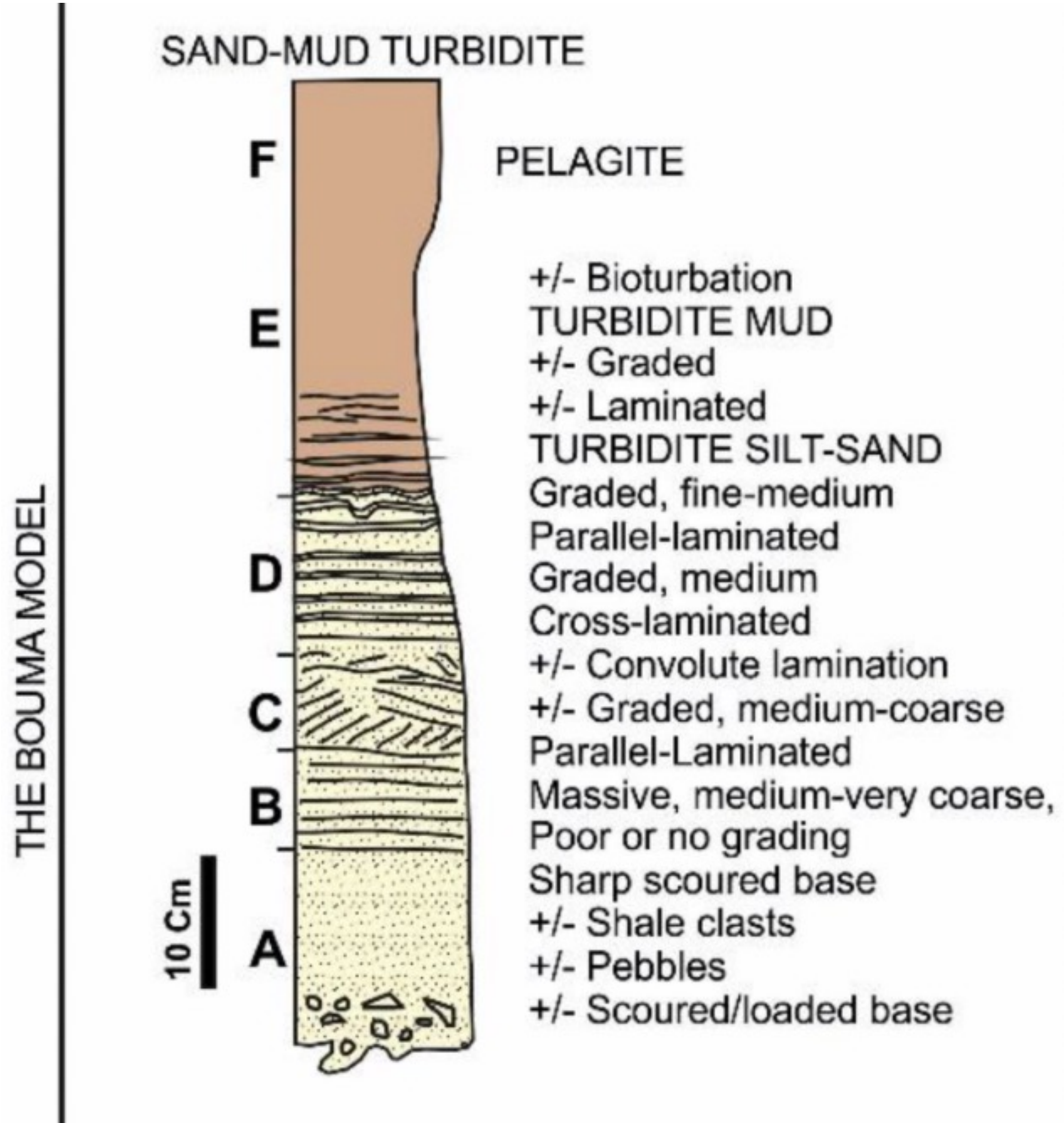
# Pelagic settling



Stow and Smillie, 2020

Hemipelagic deposition is a complex process involving both vertical settling and slow lateral advection through the water column. The driving forces behind this lateral advection include the inertia of river plumes, glacial meltwater diffusion, turbid layer plumes, internal tides and waves and other slowly moving midwater currents.

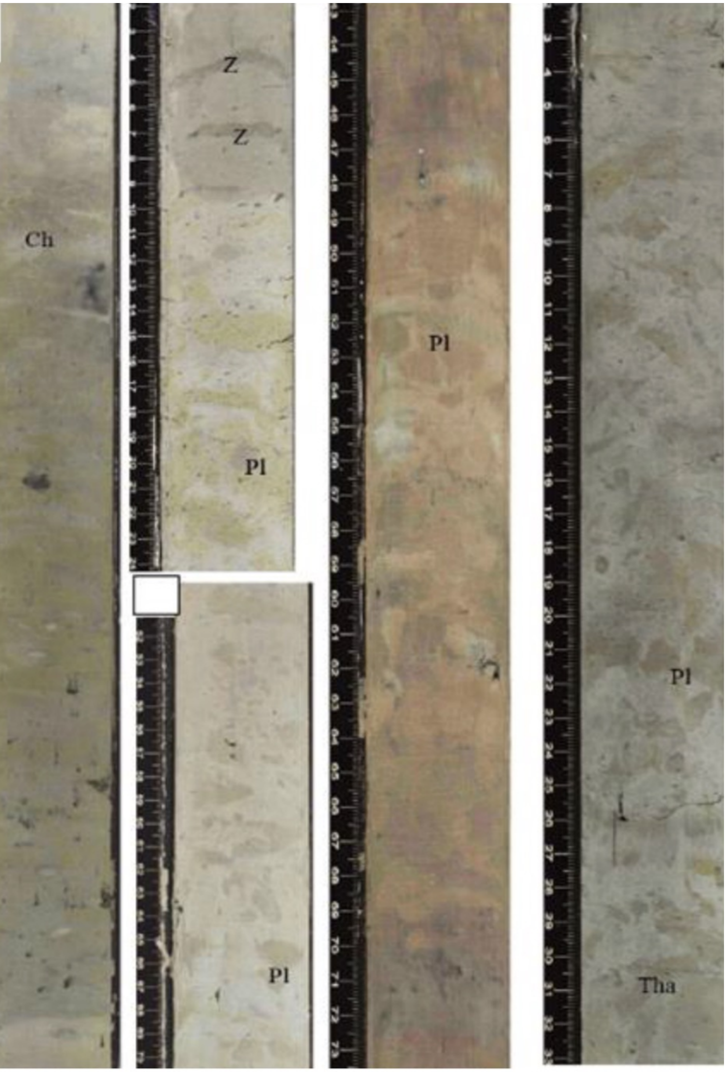
# Process Interaction



Close interaction between different processes is also common. Both turbidity currents and bottom currents will directly affect the slow settling of hemipelagic material, incorporating this fine-grained, often biogenic, material into their deposits. Bottom currents will similarly pirate the fine suspended load of distal turbidity currents and of the upper parts of flows that have over-spilled channel levees. The sudden introduction of turbidity current material into bottom currents will affect the nature and concentration of the flow as well as the composition of the deposit. Both interbedded and hybrid facies will result.

Stow and Smillie, 2020

# Bedding

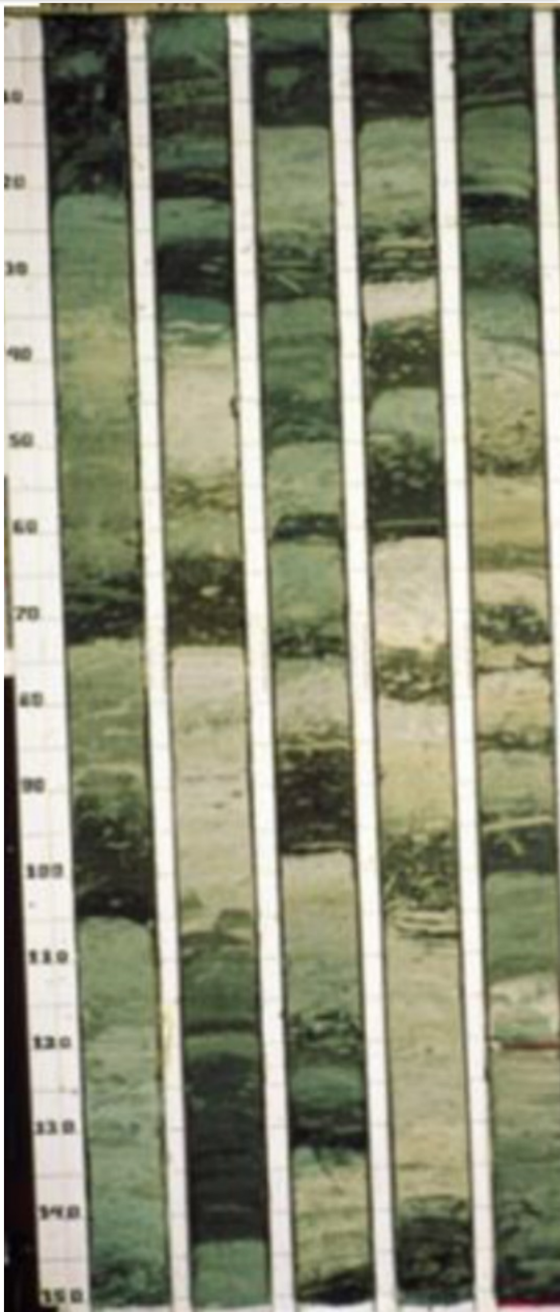


Stow and Smillie, 2020

Typical bioturbated and colour-varied hemipelagites, IODP Site 1385 (Expedition 339), offshore SW Portugal.

There is an absence or indistinctness of beds in thick successions of modern hemipelagites, where the subtle, often cyclic, variation in composition can lead to a cyclic colour bedding.

Bioturbated hemipelagites–pelagites (whitish) interbedded with graded mud turbidites (dark brown), Plio-Pleistocene, DSDP Site 530, SE Angola Basin, S Atlantic



# Structures

Stow and Smillie, 2020

Primary sedimentary structures are completely absent in those hemipelagites deposited in oxygenated water. There is no current activity and a complete bioturbational overturn has served to homogenise the sediment. Where bottom waters are low in oxygen, then parallel lamination may be preserved, with low to absent bioturbation. This is most typically a fissile lamination with laminae showing a sub-parallel, wavy, anastomosing pattern.

Pelagite (micritic limestone), Eocene, Petra tou Romiou, southern Cyprus. Some evidence for interbedding with fine calcareous contourites, i.e., small bi-gradational sequence from calcilutite to calcisiltite and back to calcilutite (marked with a black line).

# Bioturbation

Bioturbation. Pervasive, high-intensity and diverse bioturbation is typical for hemipelagites deposited under normal oxygenated conditions.
Trace fossil zonation, with multiple tiering, is most evident in more rapidly deposited hemipelagites, especially where they are interbedded with turbidites. Complete bioturbational mottling is more common under slow rates of deposition.

Detail from the bioturbated hemipelagites–pelagites interbedded with graded mud turbidites of DSDP Site 530 in SE Angola Basin: hemipelagite over turbidite with intense bioturbation.

Stow and Smillie, 2020

# Texture and fabric

Hemipelagites are characterised by random to semi-random silt and clay fabrics further accentuated by the presence of isolated large grains as well as by intense bioturbation.

Grain size characteristics of hemipelagites are strongly influenced by their composition as well as by distance from source. They are mostly fine-grained (mean 5–35 µm) and poorly sorted. Coarser grains are introduced, in particular, by ice rafting at high latitudes and by volcaniclastic activity.

Hemipelagite (pale) interbedded and inter-bioturbated with volcaniclastic ash layers (dark). Miocene Misaki Formation, Miura, Japan.

# Composition

Hemipelagites, by definition, have a mixed composition, with biogenic components dominated by open ocean planktonic microfossils and terrigenous components depending on the source area and supply. Total organic carbon content, although generally very low, may be significantly higher (1–10%) in upwelling zones and areas of low bottom-water oxygenation.

Pelagites: interbedded limestone (white) and organic-rich chert (black) beds, Cretaceous, central Umbria, Italy

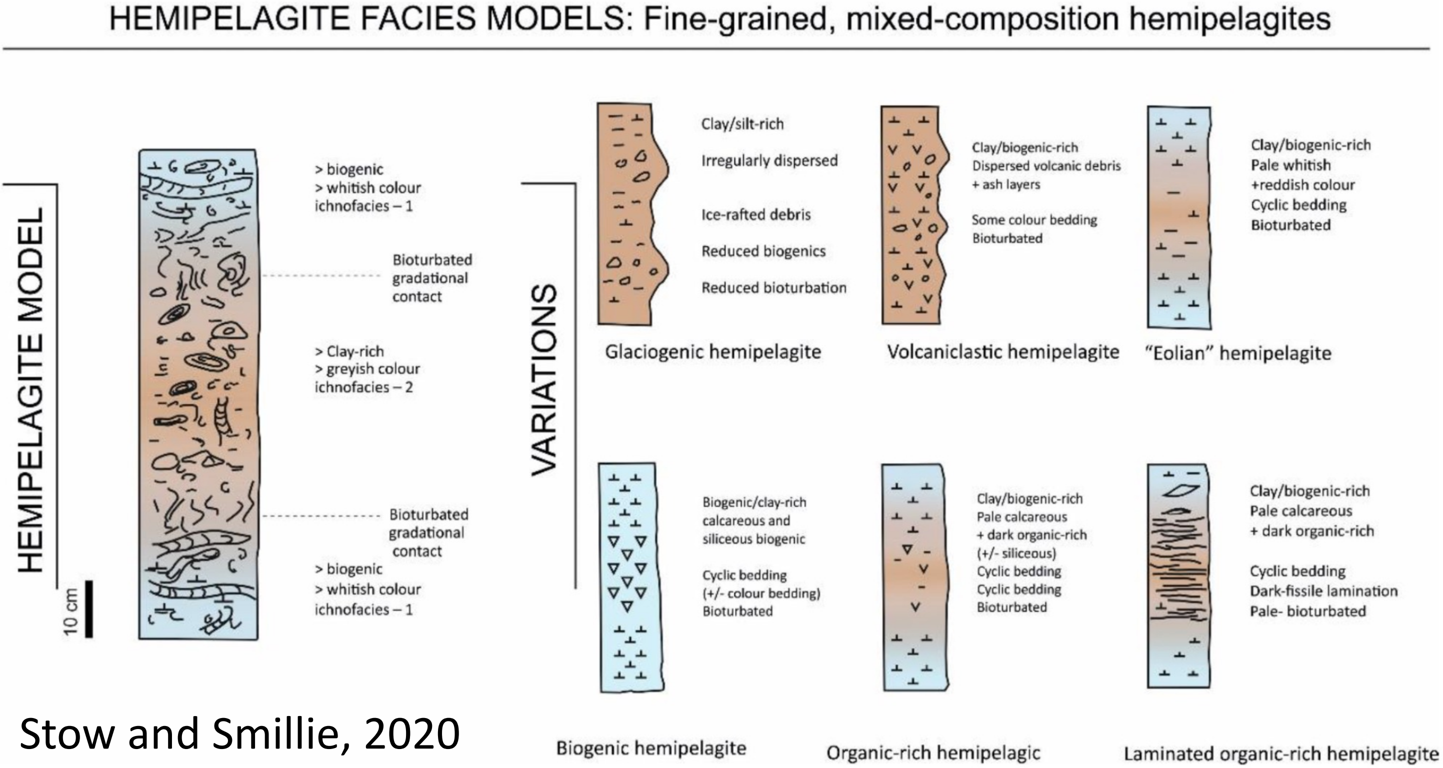
Stow and Smillie, 2020

# Hemipelagic Facies Models

Hemipelagite is often considered to be a rather elusive sediment facies and almost a bucket-term for a wide range of sediment types that form background deposits in many basins.

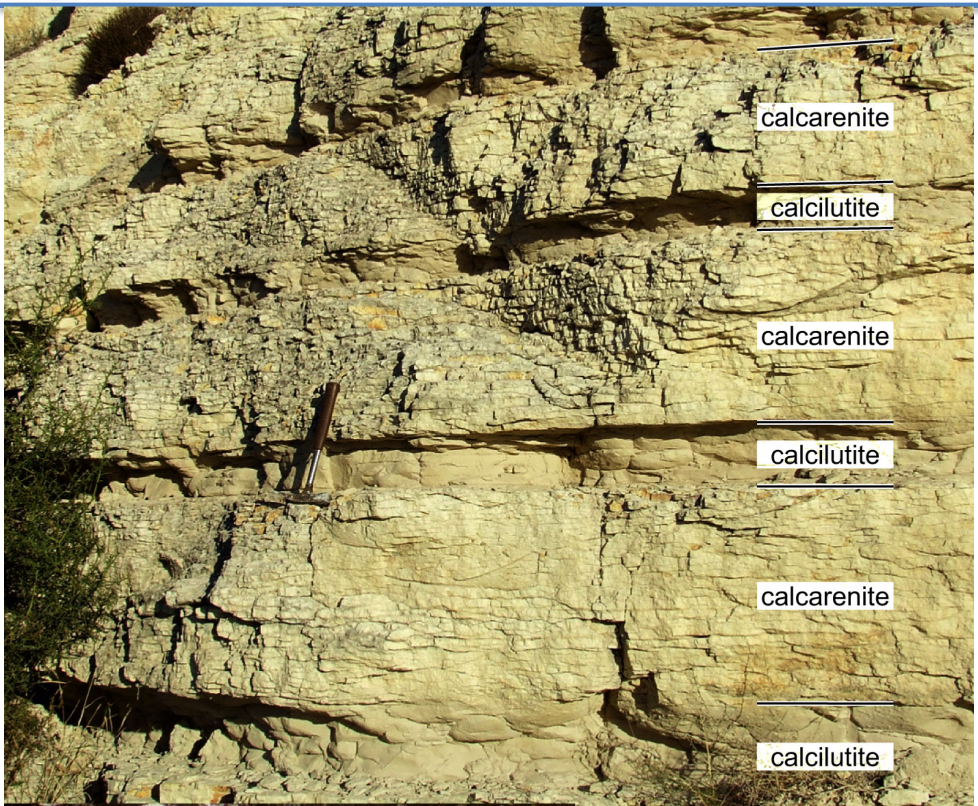
An estimated 15–20% of the present-day seafloor is composed of hemipelagites. Limestone-marl cyclic sedimentation is commonly reported from ancient successions in which the marlstone units are hemipelagic and the limestones pelagic in nature.

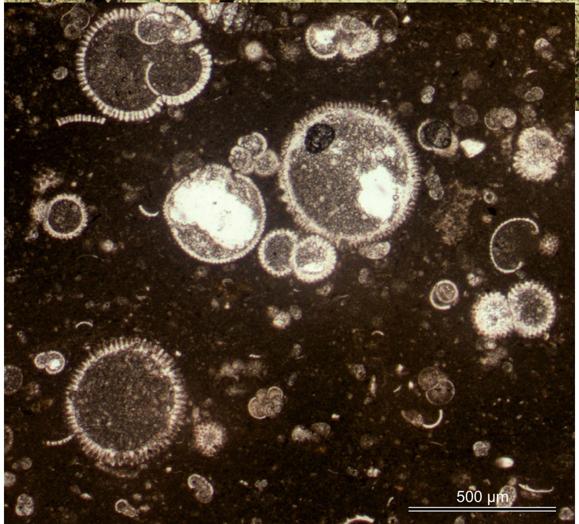
The standard facies model shows indistinct bedding. Compaction, burial and diagenesis commonly yield a more well-bedded succession. There are no primary sedimentary structures but a pervasive bioturbation. The mean size is fine (5–35 µm) and the sediment poorly sorted. The microfabric is random. Composition is mixed biogenic and terrigenous.



Stow and Smillie, 2020

# Diagnostic criteria using microfacies for calcareous contourites, turbidites and pelagites





Hüneke et al.,2021. Sedimentology

The distinction of pelagic oozes from muddy calcareous contourites is difficult, since all of these fine-grained sediments form relatively uniform records showing indistinct bedding based on subtle compositional variation. In pelagic environments, this longer-duration compositional variation typically results from biogenic productivity fluctuations and alternating seafloor redox conditions

The key point is that sediment re-location and mixing from different sources occurs only in bottom-current controlled environments. Within pelagic sediments, by contrast, shells are empty or filled with mud that is identical to the overall matrix.

# echo-character types

Llave et al., 2018, Geomorphological and sedimentary processes of the glacially influenced northwestern Iberian continental margin and abyssal plains, Geomorphology 312, 60-85

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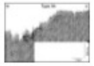
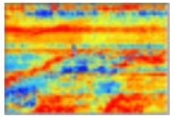
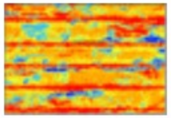
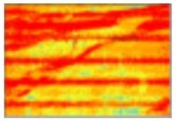
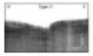
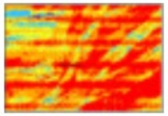
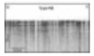
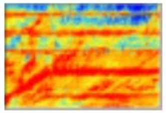
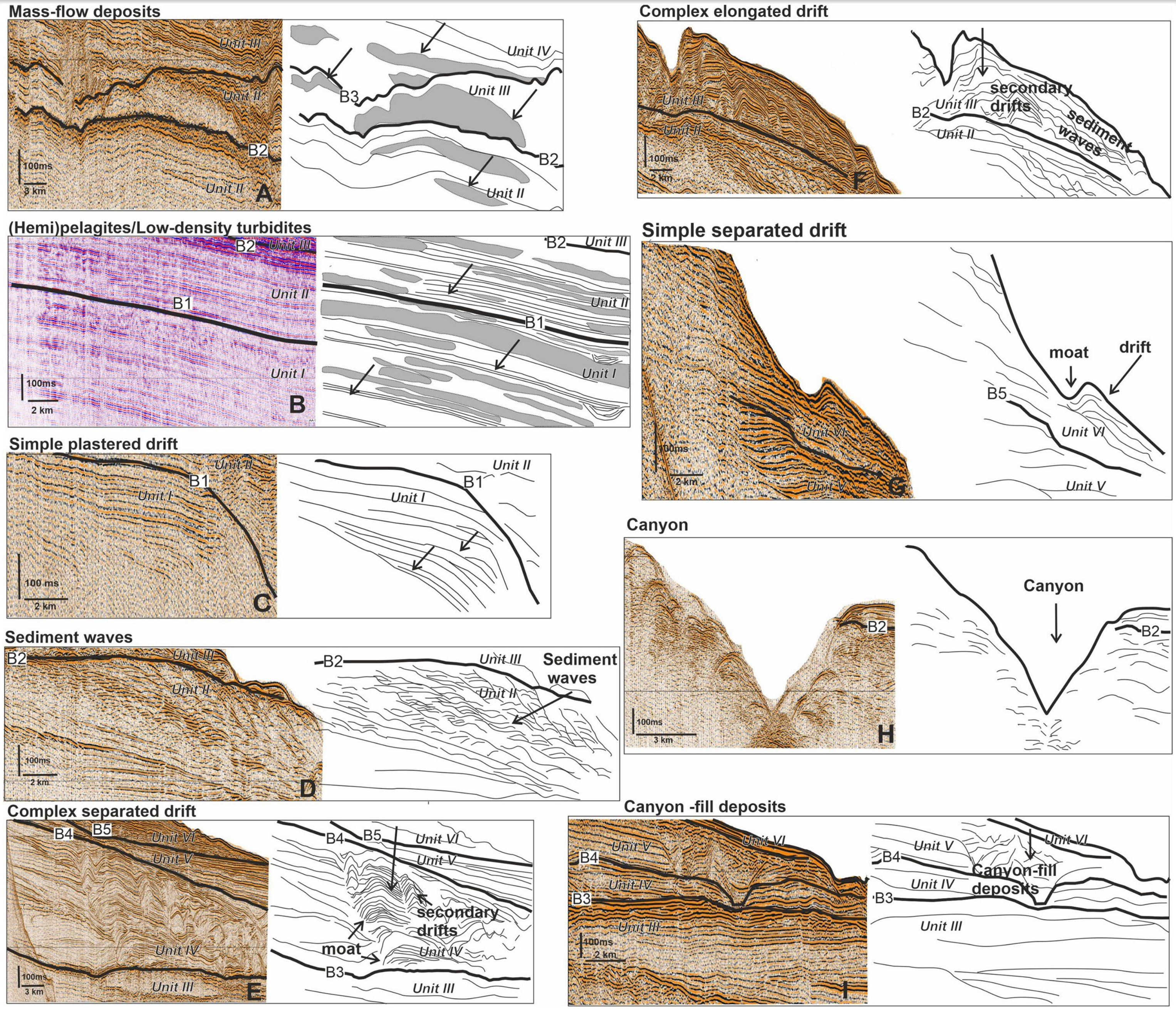
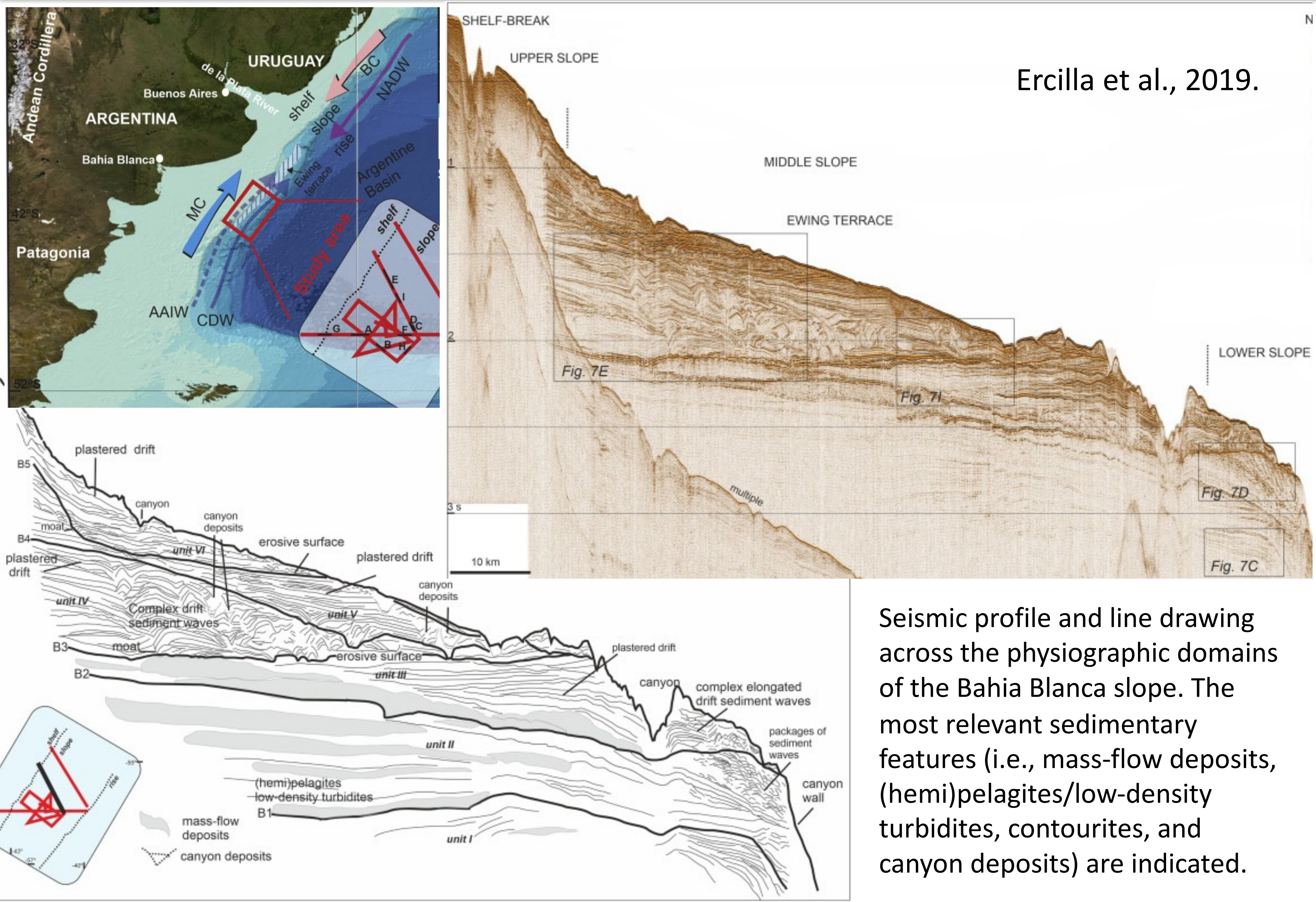
|---|---|---|---|---|---|
|  | Irregular hyperbolae overlapping with varying vertex elevations | Continental slope and abyssal plain |  | Erosion or outcrop | Erosive gravitational process or basement outcrop |
|  | Continuous echo with transparent fill | Abyssal plain |  | Debrite | Depositional mass flow process |
|  | Continuous echo and no sub-bottom reflectors in the first few meters followed by zones of parallel sub-bottom reflectors and intermittent transparent layers | Abyssal plain |  | Channel Infill | Depositional pelagic/hemipelagic process |
|  | Erosive bottom surface with parallel and truncated sub-bottom reflectors | Abyssal plain |  | Channel | Erosive turbiditic process |
|  | Wavy echo with no parallel sub-bottom reflectors | Abyssal plain |  | Sediment waves | Depositional turbiditic process |

# Main morphological and seismic characteristics

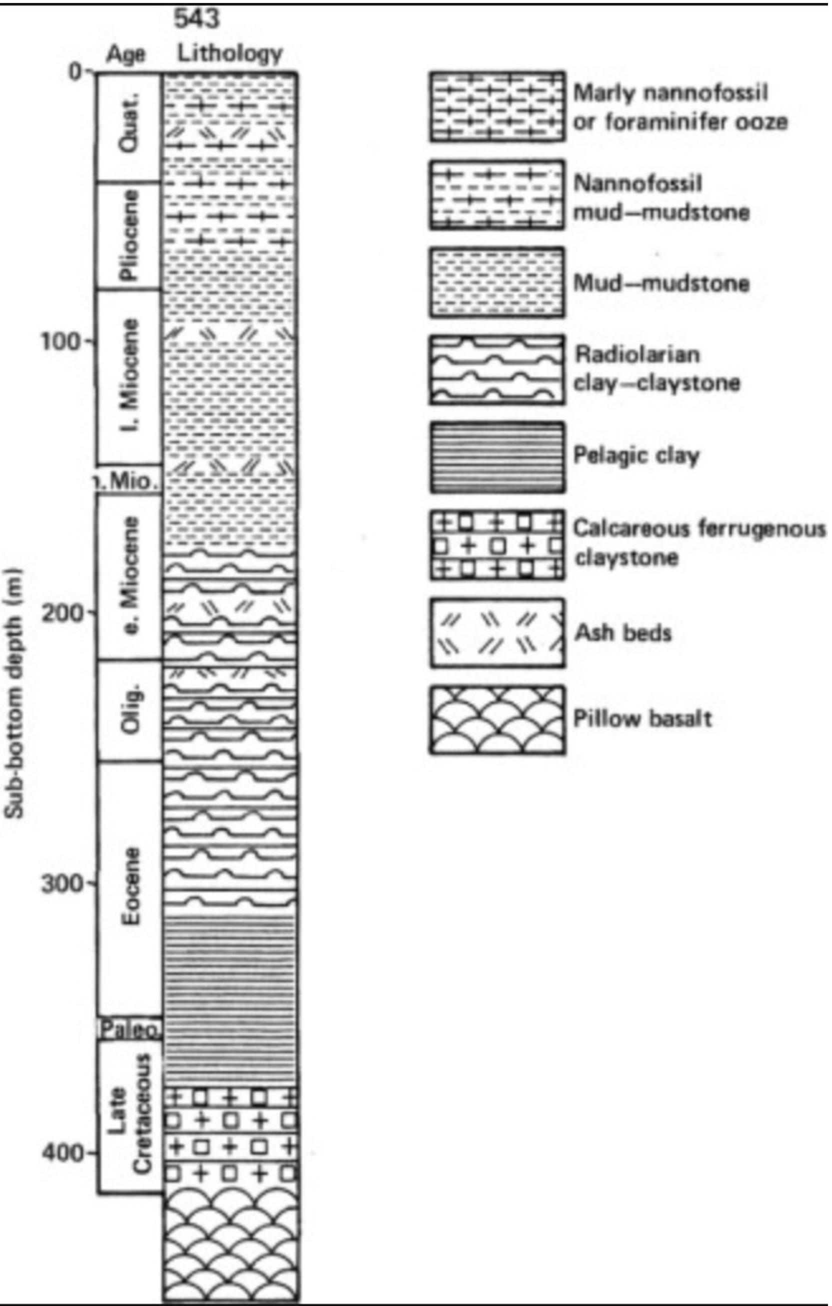


Ercilla et al., 2019. Cenozoic sedimentary history of the northern Argentine continental slope, off Bahia Blanca, the location of the Ewing Terrace: Palaeogeodynamic and palaeoceanographic implications. Marine Geology 417, 106028

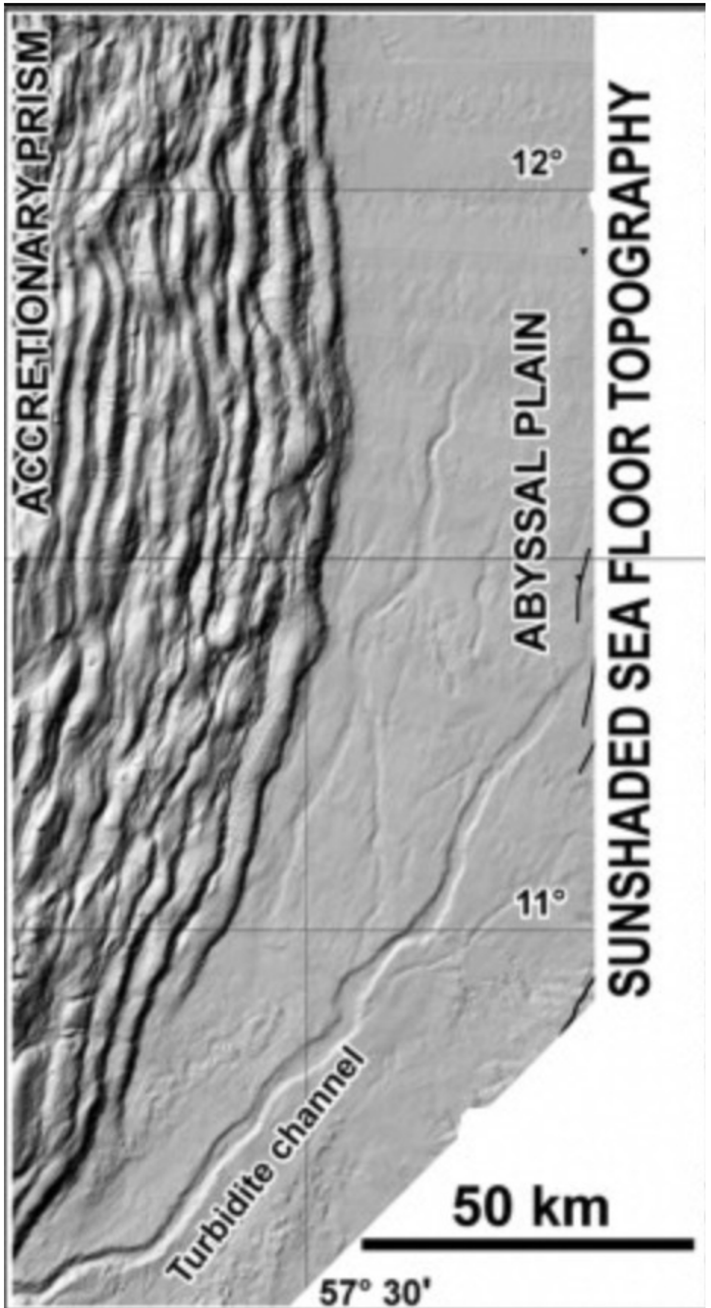


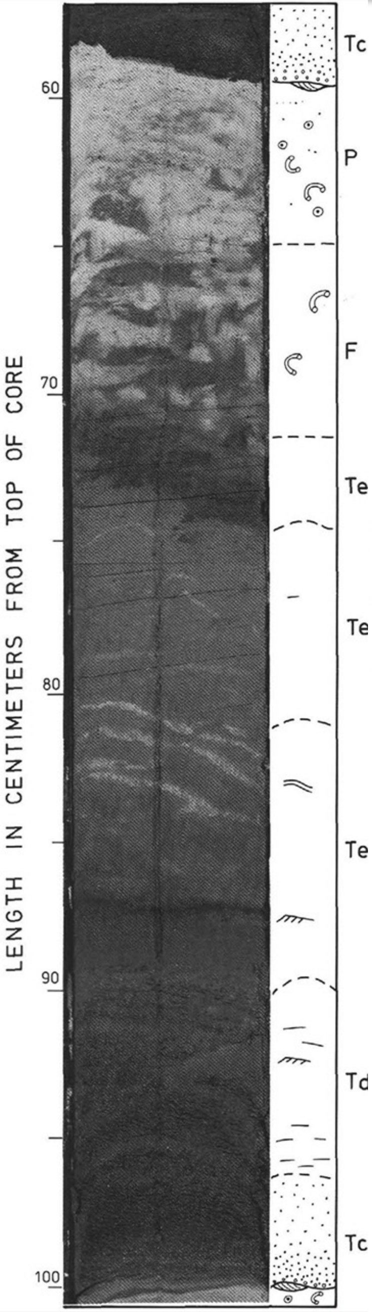
Ercilla et al., 2019.

Seismic profile and line drawing across the physiographic domains of the Bahia Blanca slope. The most relevant sedimentary features (i.e., mass-flow deposits, (hemi)pelagites/low-density turbidites, contourites, and canyon deposits) are indicated.



Deville & Mascle, 2012, The Atlantic abyssal plain: The Barbados ridge. in Regional Geology and Tectonics: Principles of Geologic Analysis

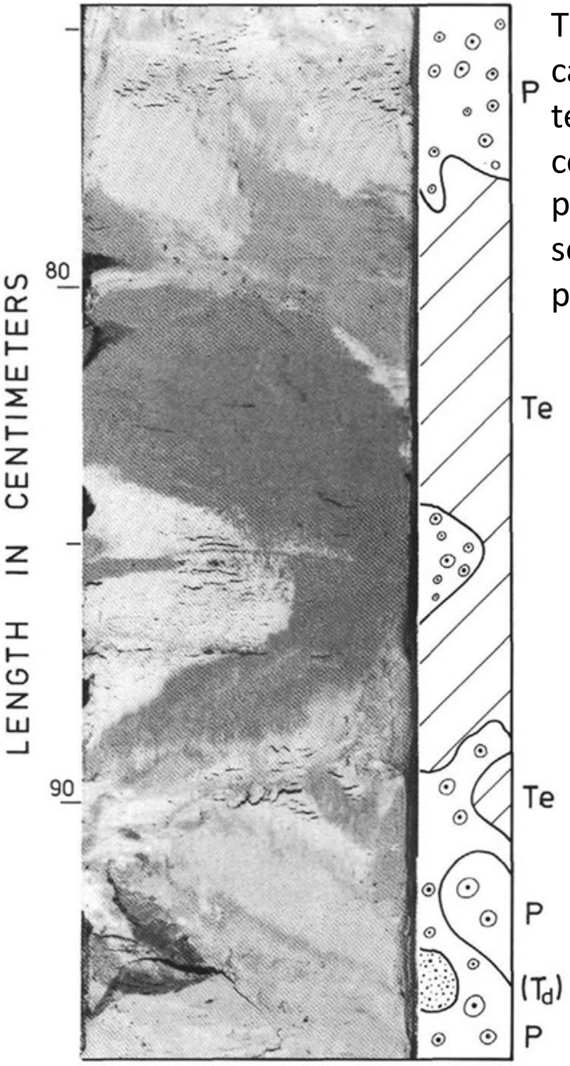




# Late Cenozoic sedimentary facies and processes in the Iberian Abyssal Plain.

Comas and Maldonado, 1988. ODP, Leg 103

The pelagic and hemipelagic facies type encompasses a wide spectrum of calcareous oozes and marls.

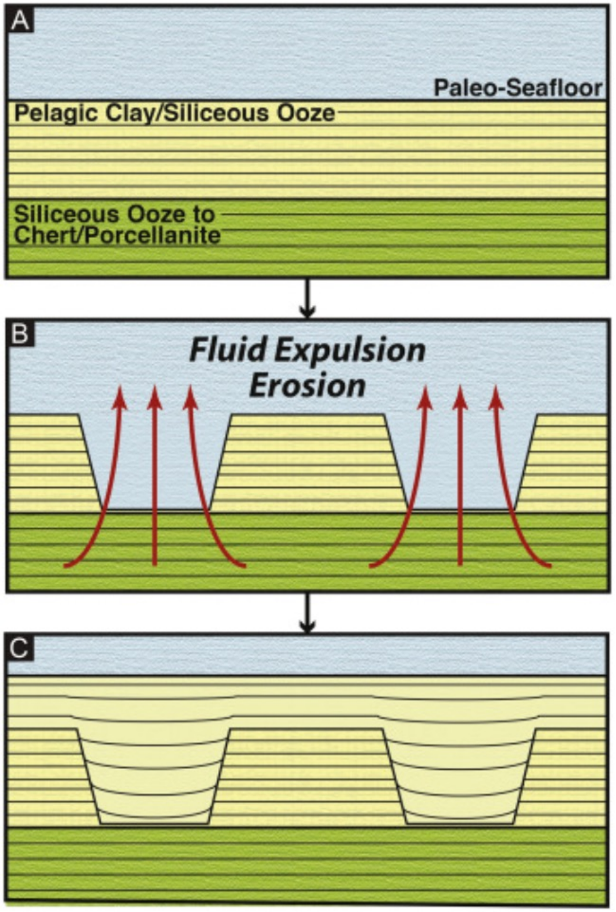


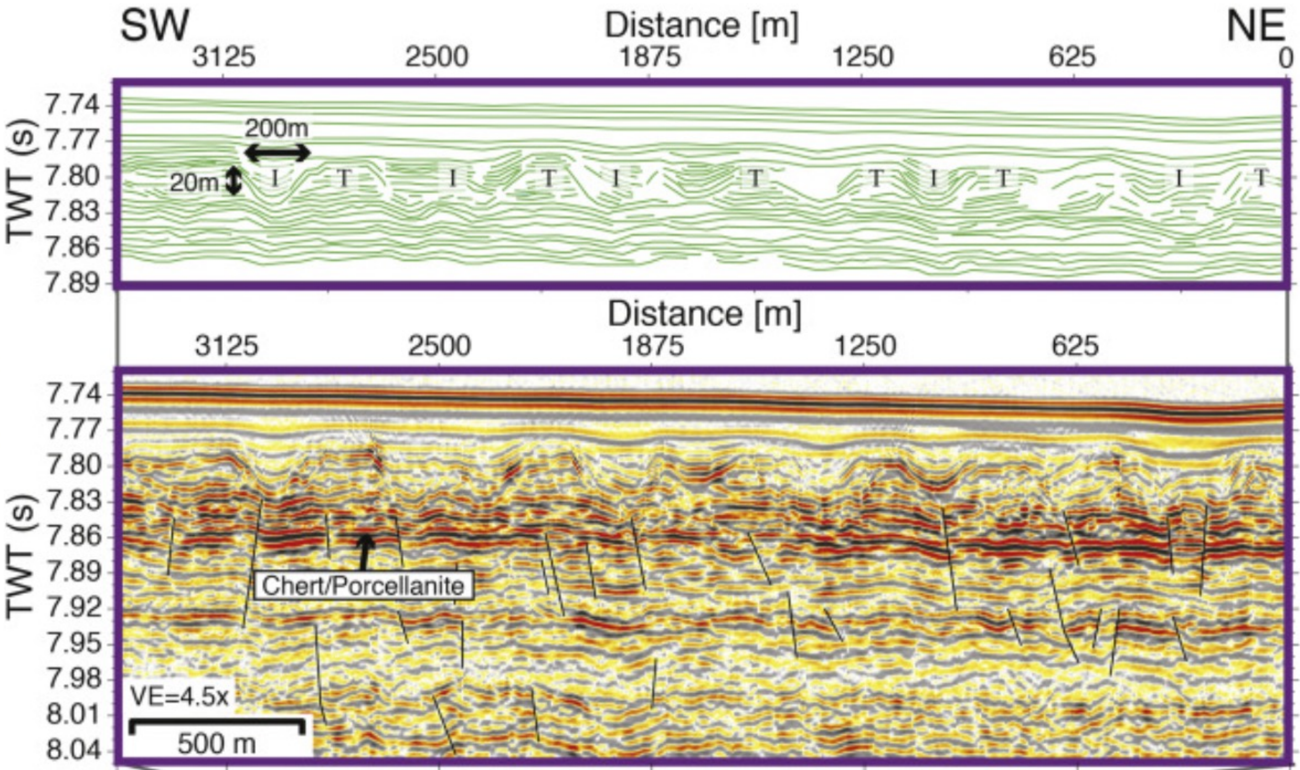
The more pelagic end-member of this facies consists of white calcareous, foraminifer-rich, nannofossil ooze. The mixed terrigenous-biogenic hemipelagic end-member includes light-colored, clayey, calcareous nannofossil ooze and marl. The primary source for these deposits is pelagic biogenic material; sedimentation represents a complex balance between primary productivity, terrigenous input, and dissolution.

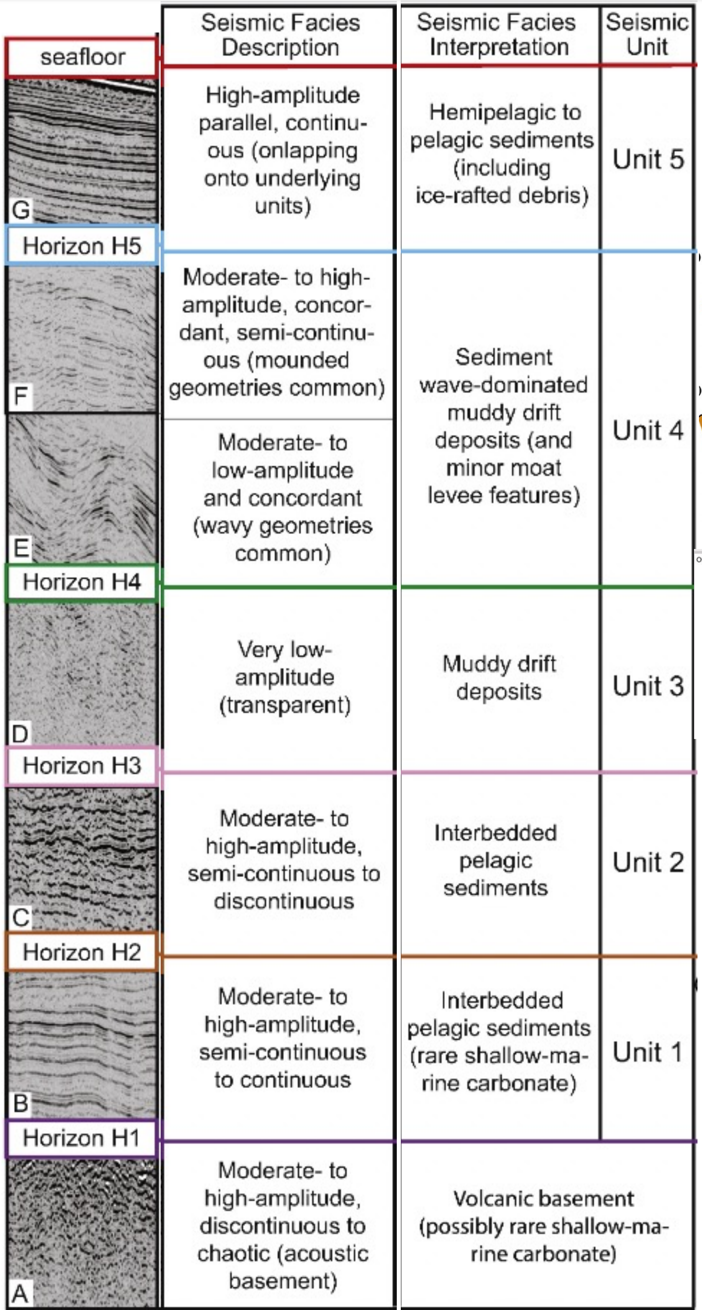
| Process | | Facies type symbol | Lithologic description |
|---|---|---|---|
| Pelagic-hemipelagic settling | Transition | P | Pelagic calcareous biogenic to transitional sediments: white (5Y 8/2) nannofossil-foraminifer oozes to light gray (5Y 7/1, 5Y 7/2) clayey nannofossil oozes and light gray (5Y 6/1), grayish green (5Y 5/2), and light olive gray (5Y 6/1) nannofossil marls |
| | | F | Transitional calcareous biogenic to terrigenous sediments: light olive gray to gray (5Y 6/2, 5Y 5/1), grayish green (5Y 5/2), and pale olive (5Y 6/3) nannofossil marls and grayish brown (2.5Y 5/2) and yellowish brown (10YR 5/4) calcareous clays |
| Turbidity currents | Transition | $T_{e3}$ | Terrigenous sediments: gray (5Y 5/2), brown (10YR 5/3), and olive gray (5GY 5/2) clays to silty clays (some calcareous) |
| | | $T_{e2}$ | Terrigenous sediments: olive to gray (5Y 5/1, 5Y 5/2, 5GY 5/2) and grayish brown (2.5Y 5/2) silty clays (some calcareous) |
| | | $T_{e1}$ | Terrigenous sediments: dark gray to gray (5Y 4/1, 5Y 5/1) and olive gray (5Y 5/2) silty clays to clayey silts (some calcareous) |
| | | $T_d$ | Terrigenous sediments: dark gray to gray (5Y 4/1, 5Y 5/1) and olive gray (5Y 5/2) clayey silt to sandy-clayey silts (some calcareous) |
| | | $T_c$ | Terrigenous sediments: dark gray to gray (5Y 4/1, 5Y 5/1) and dark olive gray (5Y 3/2) calcareous silty sand to sandy-clayey silts |
| Contour currents | | FC | Calcareous biogenic sediments: white (5Y 8/1, 5Y 7/1) foraminiferal sands to foraminifer-nannofossil oozes |
| | | SC | Terrigenous sediments: variegated yellowish brown (10YR 5/4, 10YR 6/4), dark grayish brown to grayish brown (2.5Y 4/2, 2.5Y 5/2) and pale brown (10YR 6/3) sand-rich clayey silts to sand-rich silty clays (some nannofossil rich) |
| | | MC | Terrigenous sediments: variegated dark grayish brown (10YR 4/2) and brown (10YR 6/3, 2.5Y 5/4) silty clays to clays (some nannofossil rich) |
| | | CC | Terrigenous sediments: light yellowish brown (10YR 6/4, 2.5Y 6/4) and pale brown (10YR 6/3, 10YR 5/4) clays |

# Deep-ocean paleo-seafloor erosion in the northwestern Pacific identified by high-resolution seismic images

Greene et al., 2020 . Marine Geology 429, 106330

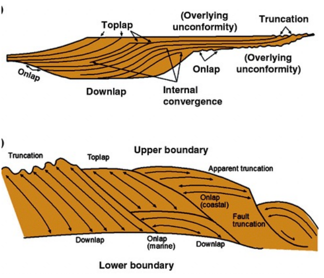


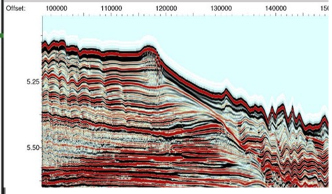




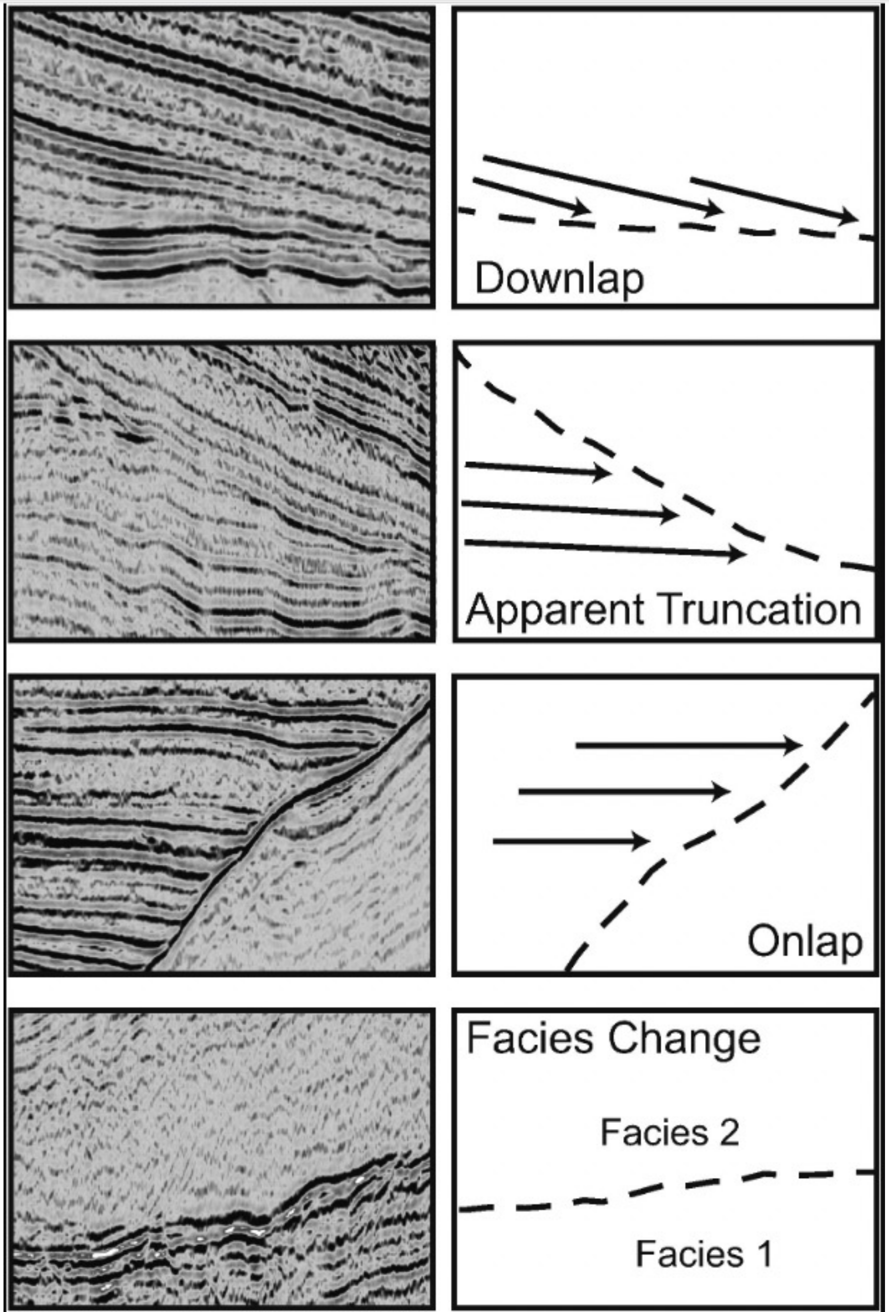
| | Seismic Facies Description | Seismic Facies Interpretation | Seismic Unit |
|---|---|---|---|
| seafloor | | | |
| G | High-amplitude parallel, continuous (onlapping onto underlying units) | Hemipelagic to pelagic sediments (including ice-rafted debris) | Unit 5 |
| Horizon H5 | | | |
| F | Moderate- to high-amplitude, concordant, semi-continuous (mounded geometries common) | Sediment wave-dominated muddy drift deposits (and minor moat levee features) | Unit 4 |
| E | Moderate- to low-amplitude and concordant (wavy geometries common) | | |
| Horizon H4 | | | |
| D | Very low-amplitude (transparent) | Muddy drift deposits | Unit 3 |
| Horizon H3 | | | |
| C | Moderate- to high-amplitude, semi-continuous to discontinuous | Interbedded pelagic sediments | Unit 2 |
| Horizon H2 | | | |
| B | Moderate- to high-amplitude, semi-continuous to continuous | Interbedded pelagic sediments (rare shallow-marine carbonate) | Unit 1 |
| Horizon H1 | | | |
| A | Moderate- to high-amplitude, discontinuous to chaotic (acoustic basement) | Volcanic basement (possibly rare shallow-marine carbonate) | |

# Exercises





Boyle et al (2017) Marine Geology 385, 185-203.



# Rebesco et al., 2021. Malta Escarpment. Marine Geology 441, 106596