



# **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**

## Modulo 2.3a

Density currents and mass transport

Docente: **Renata Lucchi**

## Modulo 2.3b

Bottom currents

Docente: **Michele Rebesco**

## ***Modulo 2.3a Density currents and mass transport***

***Docente: Renata G. Lucchi***

### ***OUTLINE***

- Nomenclature of processes and deposits
- Deposit classification
- Mass transport: creep, slide / slump, debris avalanches
- Gravity flows: laminar flow (debris flow)
- Turbulent flow (turbidity currents)

## Nomenclature

Depositional process → ***Deposit***

**down-slope processes:**

**driven by gravity forces**

- » Mass Transport → ***MTDs***
- » Turbidity currents → ***Turbidites***
- » Riverine outflows → ***Hyper (Hypo)- picnites***
- » Turbid meltwaters → ***Plumites***

**along-slope:**

**driven by density forces (thermo-haline origin)**

- » Contour currents → ***Contourites***



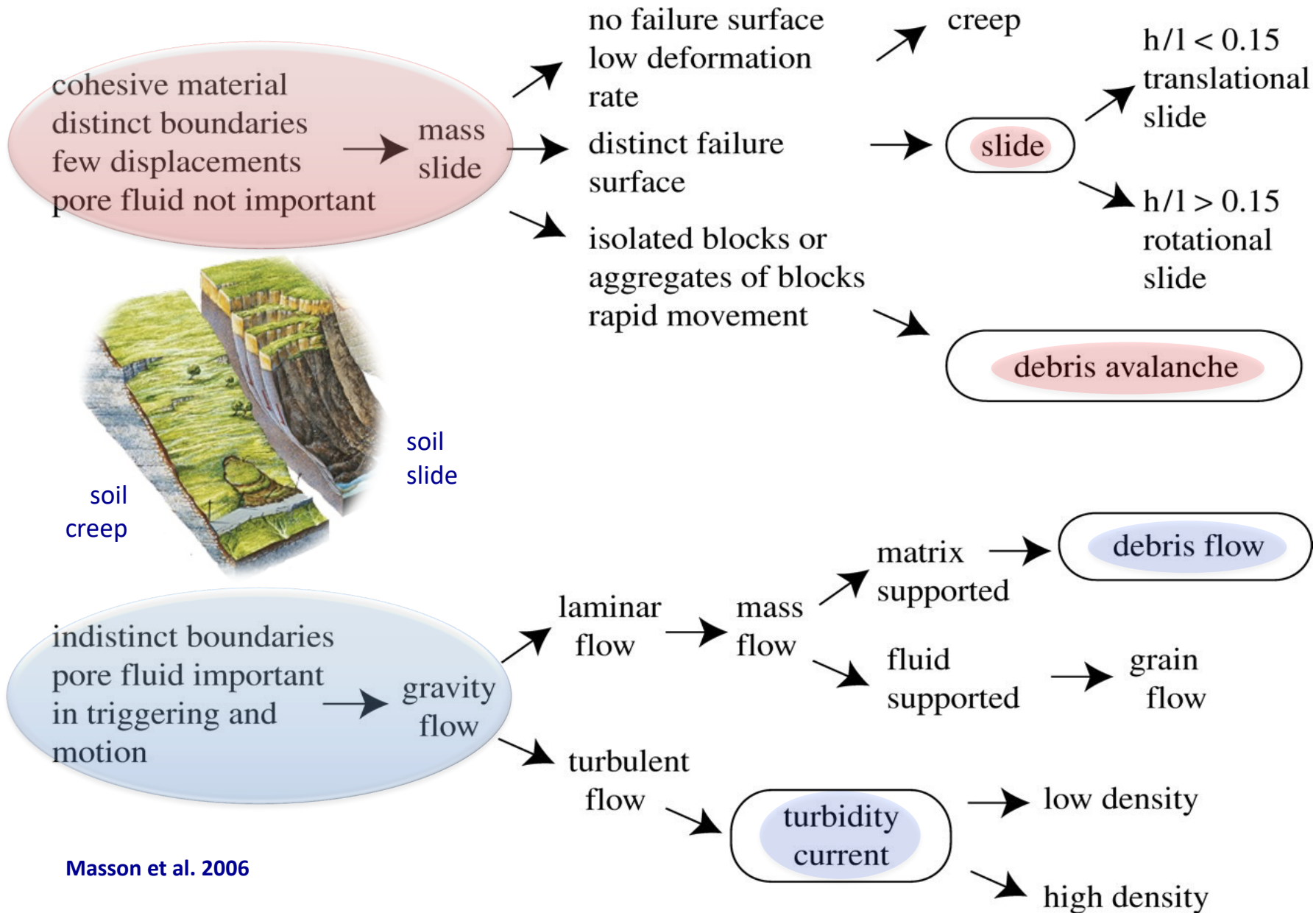
## Deposit's classification

- Reology (sediment deformation)
- Sediment mass mechanism of support (gravity, flow turbulence, grains interaction)
- Physical properties of the mass flow and deposit (sediment disturbance, shear strength, etc.)
- Morphological characteristics of the deposit

STOPPANI	1871	MIYABE	1935	VENZO & LARGAIOLLI	1968
A. PENCK	1874	LADD	1935	HUTCHINSON	1968
BALTZER	1875	HENNES	1936	SAVAGE	1968
MOLITOR	1894	SHARPE	1938	ZARUBA & MENCL	1969
PANTANELLI	1897	DI TELLA & BAY	1939	SKEMPTON & HUTCHINSON	1969
NEUMAYR	1898	MONTANARI	1940	VENZO & ULCIGRAI	1970
GUNTHER	1899	PRINCIPI	1945	DESIO	1971
DE MARCHI	1903	BENDEL	1948	BRUGNER & VALDINUCCI	1972
BRAUN	1907	MARESCA	1948	NEMCOCK et alii	1972
HOWE	1909	GORTANI	1948	VALLARIO & COPPOLA	1973
STINY	1910	IPPOLITO & COTECCHIA	1954	BLYTH & DE FREITAS	1974
ALMAGIA'	1910	SCHULTZ & CLEAVES	1955	NICOTERA	1975
ISSEL	1910	KRYNINE & JUDD	1957	VENZO	1976
TRABUCCO	1913	VARNES	1958	VARNES	1978
ROTIGLIANO	1916	DESIO	1959	CORNIELLO et alii	1980
W. PENCK	1924	PENTA	1959	HUTCHINSON	1988
TERZAGHI	1925	VENZO	1960	SASSA	1989
HEIM	1932	GOGUEL	1967	CRUDEN & VARNES	1996

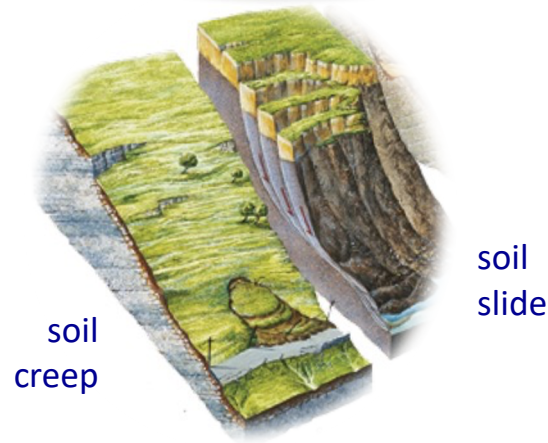
Martinsen, O. (1994). Mass movements. in: The geological deformation of sediments, (A. Maltman Ed.), Chapman and Hall, London, pp. 127-165.

- Mulder, T. and Cochonat, P. (1996). Classification of offshore mass movements. J. Sediment. Res., 66, 43-57.
- **Masson, D.G., Harbitz, C.B., Wynn, R.B, Pedersen, G., Lovholt, F.** (2006). Submarine Landslides: processes, triggers and hazard prediction. Phil. Trans. R. Soc. A, 364, pp 2009-2039.



cohesive material  
distinct boundaries  
few displacements  
pore fluid not important

→ mass slide



no failure surface  
low deformation  
rate

↗ creep

distinct failure  
surface

→ slide

$h/l < 0.15$   
translational  
slide

isolated blocks or  
aggregates of blocks  
rapid movement

$h/l > 0.15$   
rotational  
slide

→ debris avalanche

indistinct boundaries  
pore fluid important  
in triggering and  
motion

→ gravity flow

laminar flow → mass flow

matrix supported → debris flow

fluid supported → grain flow

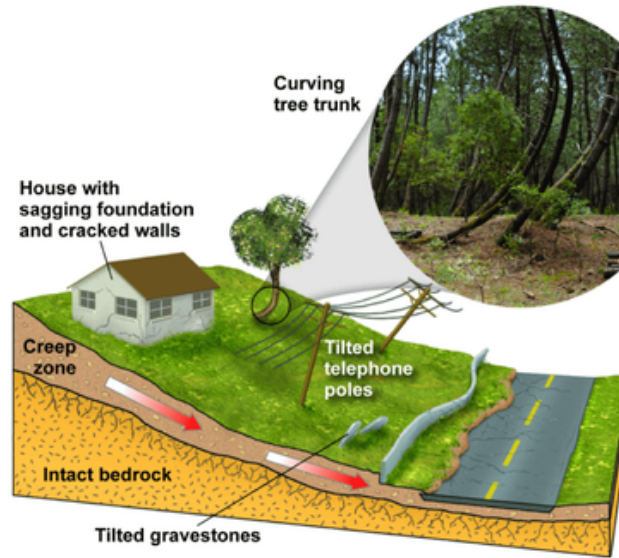
turbulent flow → turbidity current

→ low density

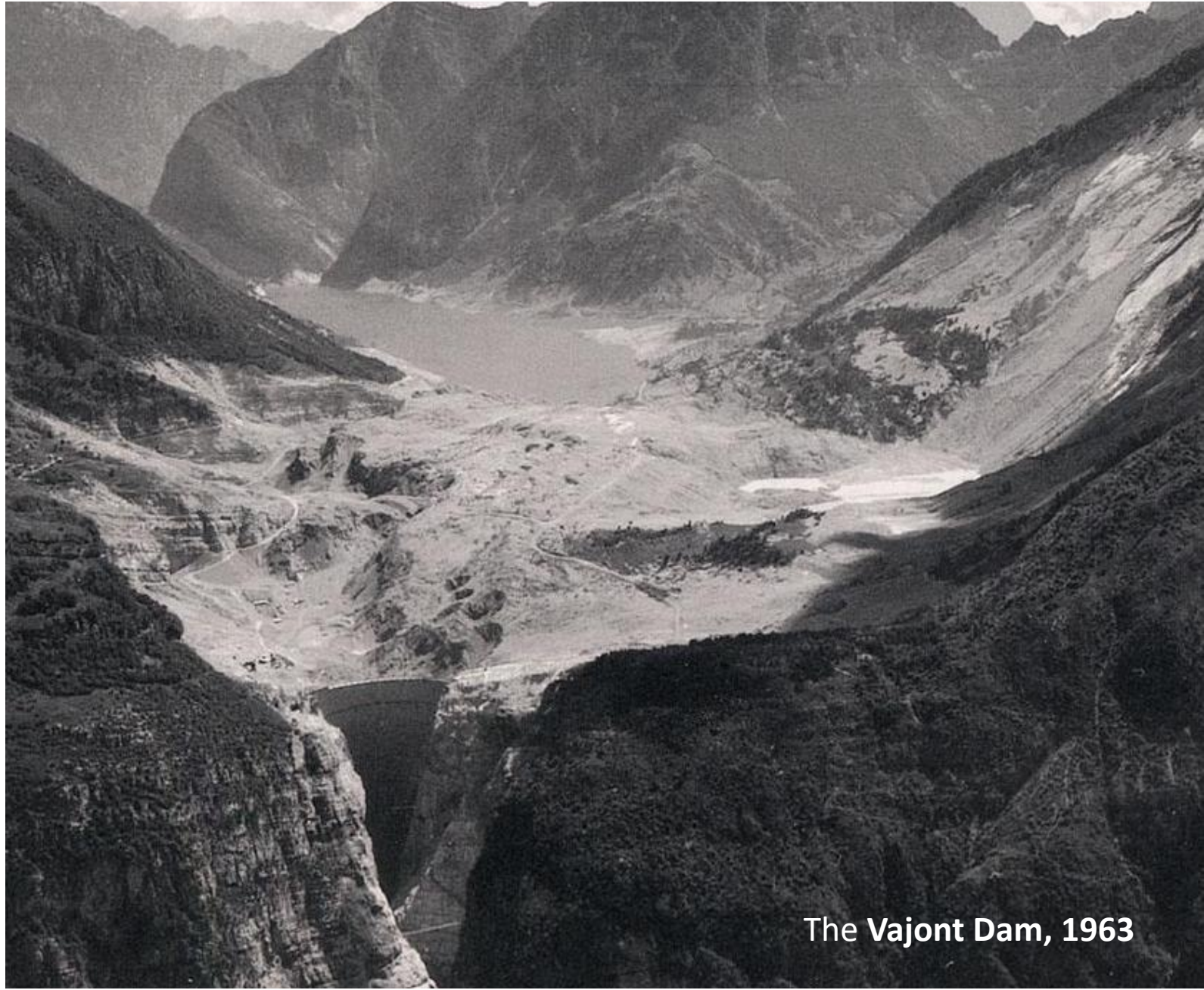
→ high density



## Creeping

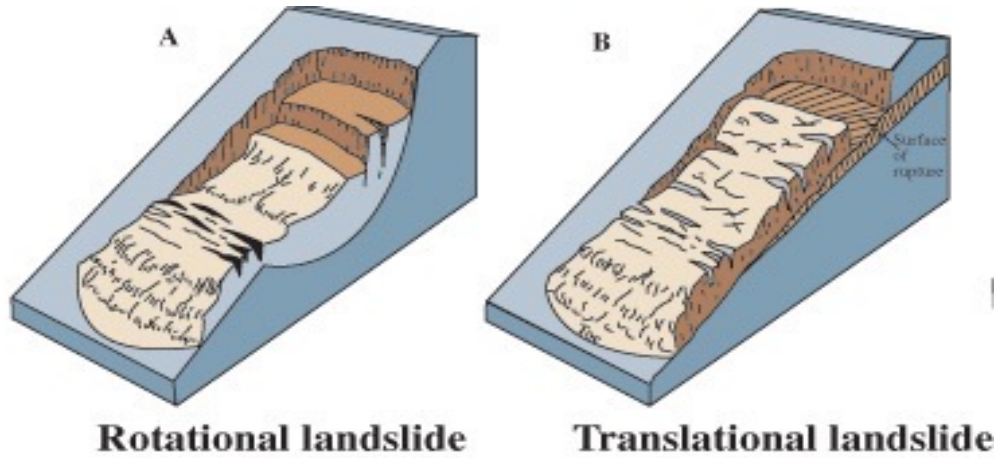




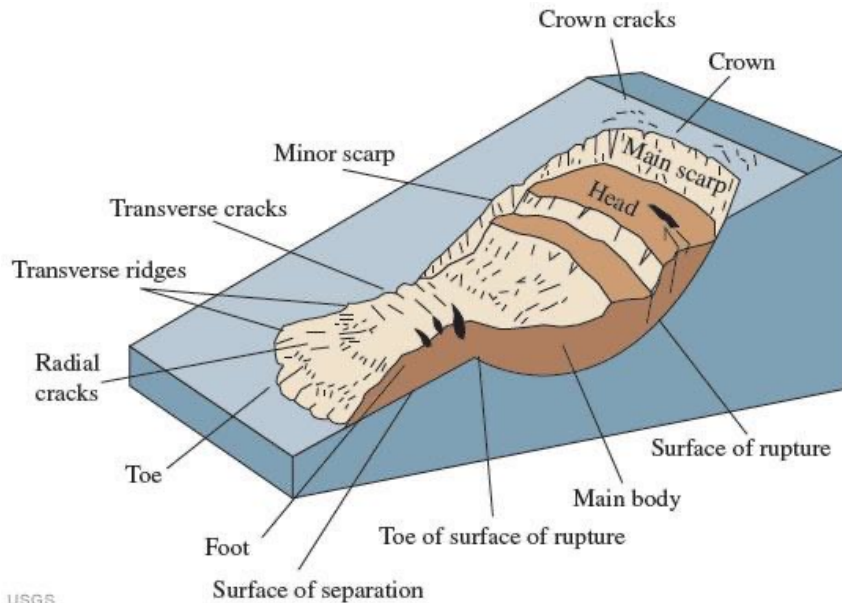


**The Vajont Dam, 1963**

# Slides/Slumps



La Conchita, California 1995 (from Fanti, UniFI)



Cruden, 1981

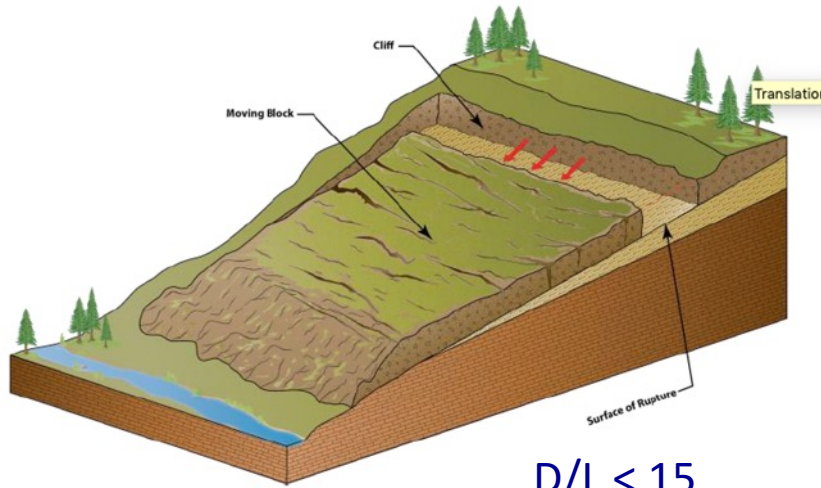


# Slides/Slump

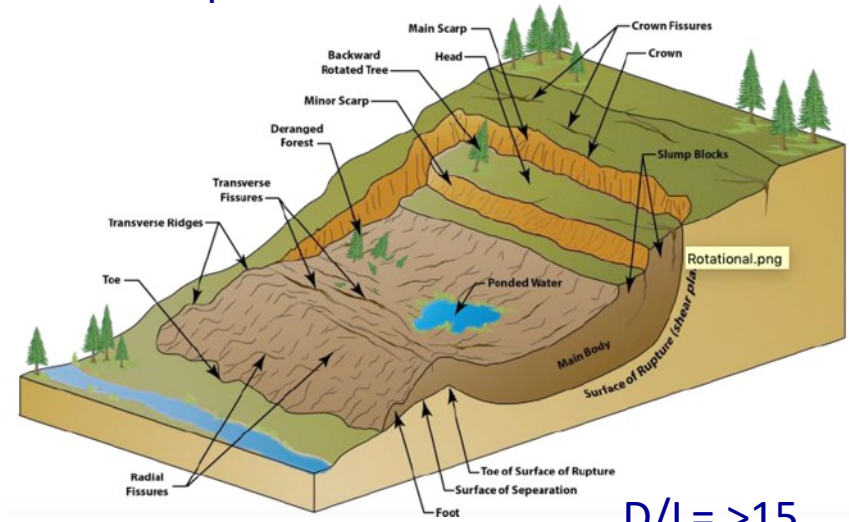
Numero di Skempton (1953)

D= spessore massimo frana

L= lunghezza lungo massima pendenza



$$D/L < 15$$



$$D/L = >15$$



Romania, foto M. Cremaschi



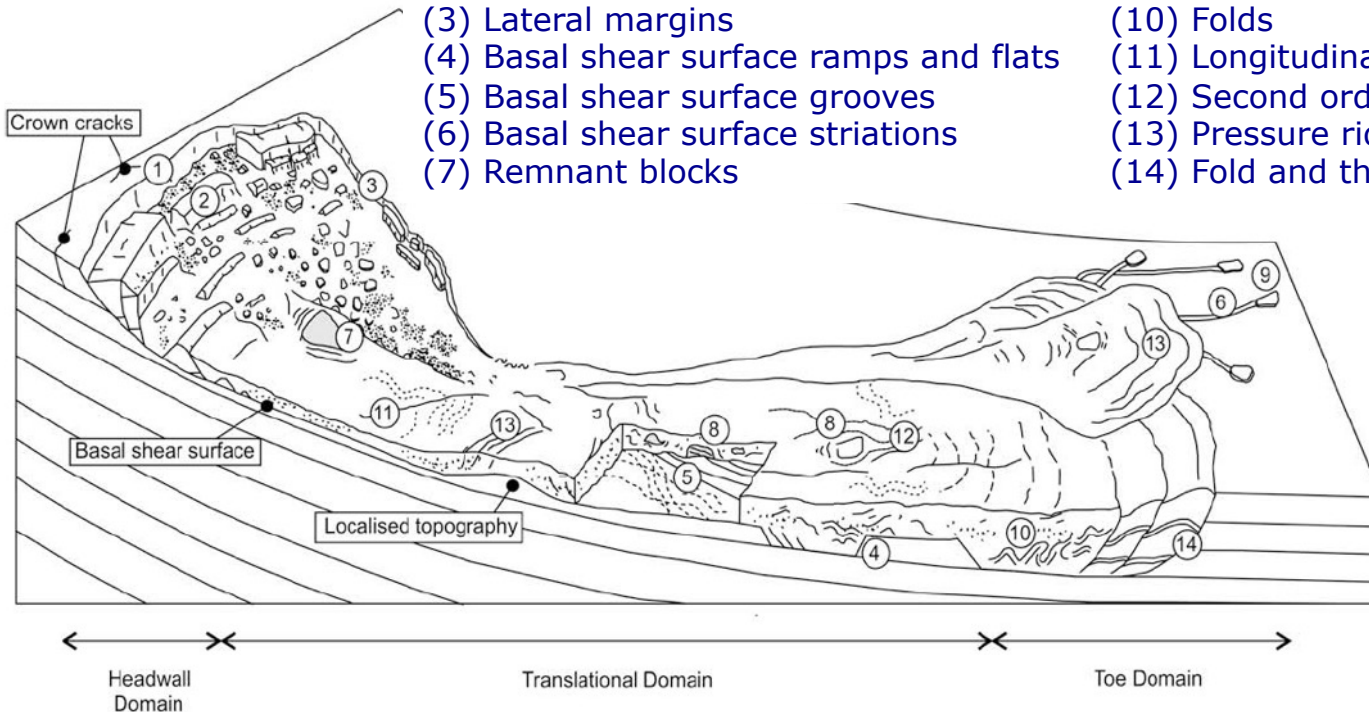
Pleistocene Submarine Landslides in the Boso Peninsula, Japan

# Complexity:

Once failure initiates, the event may **progress by means of a number of mass movement processes**. Although various subdivisions and classification schemes for these processes exist, each process represents part of a continuum, whereby one type may evolve into or trigger another.

Many submarine slope failures are likely to have involved a number of processes, possibly active at different stages of failure. Therefore, it is common that the depositional units resulting from submarine mass movements are defined as **'Mass-Transport Complexes (MTC)'**.

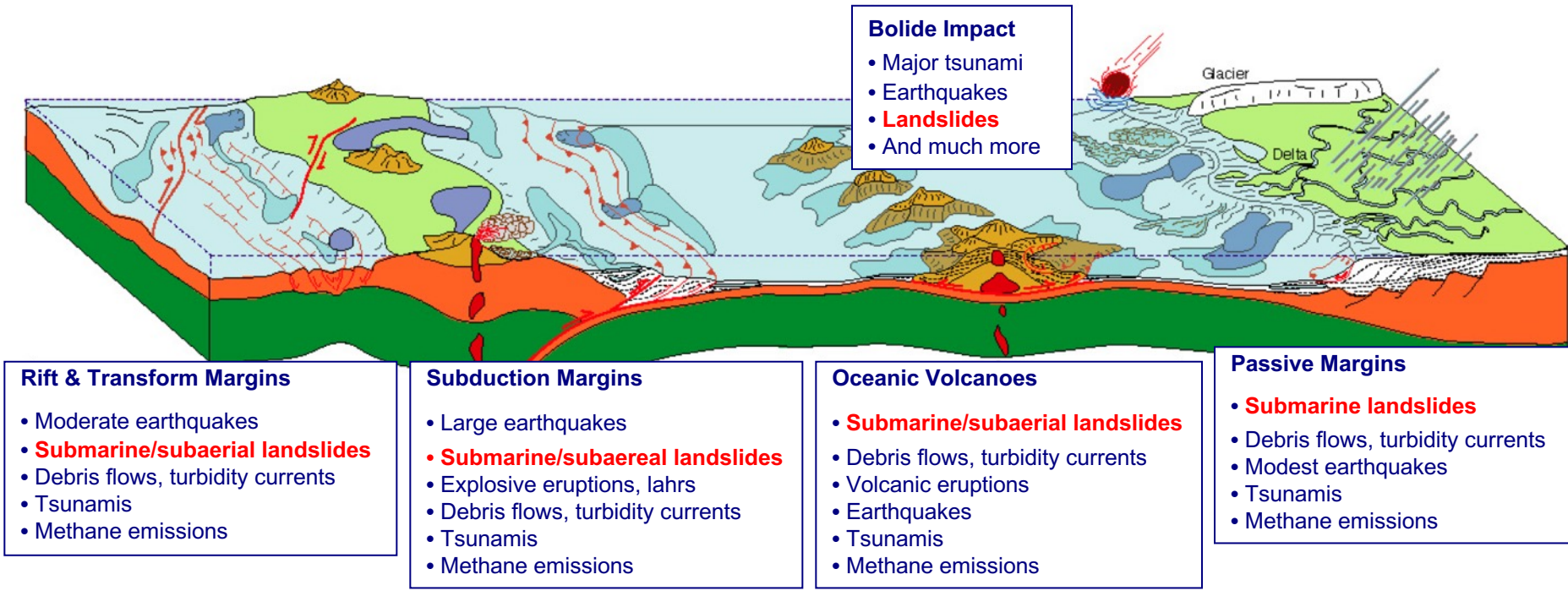
- |   |  |
|---|--|
| (1) Headwall scarp                      | (8) Translated blocks                            |
| (2) Extensional ridges and blocks       | (9) Out-runner blocks                            |
| (3) Lateral margins                     | (10) Folds                                       |
| (4) Basal shear surface ramps and flats | (11) Longitudinal shears/first order flow fabric |
| (5) Basal shear surface grooves         | (12) Second order flow fabric                    |
| (6) Basal shear surface striations      | (13) Pressure ridges                             |
| (7) Remnant blocks                      | (14) Fold and thrust systems                     |

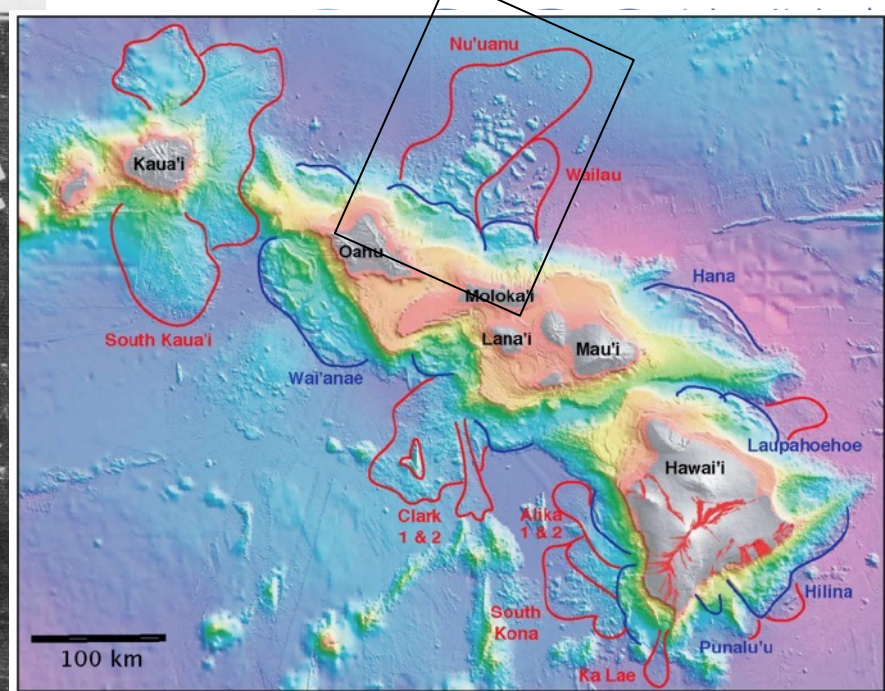




# Submarine slides/slumps

They are **ubiquitous** features of submarine slopes in all geological settings and at all water depths, particularly in areas where fine grained sediments predominate.





Morgan et al., 2009. Scientific Drilling

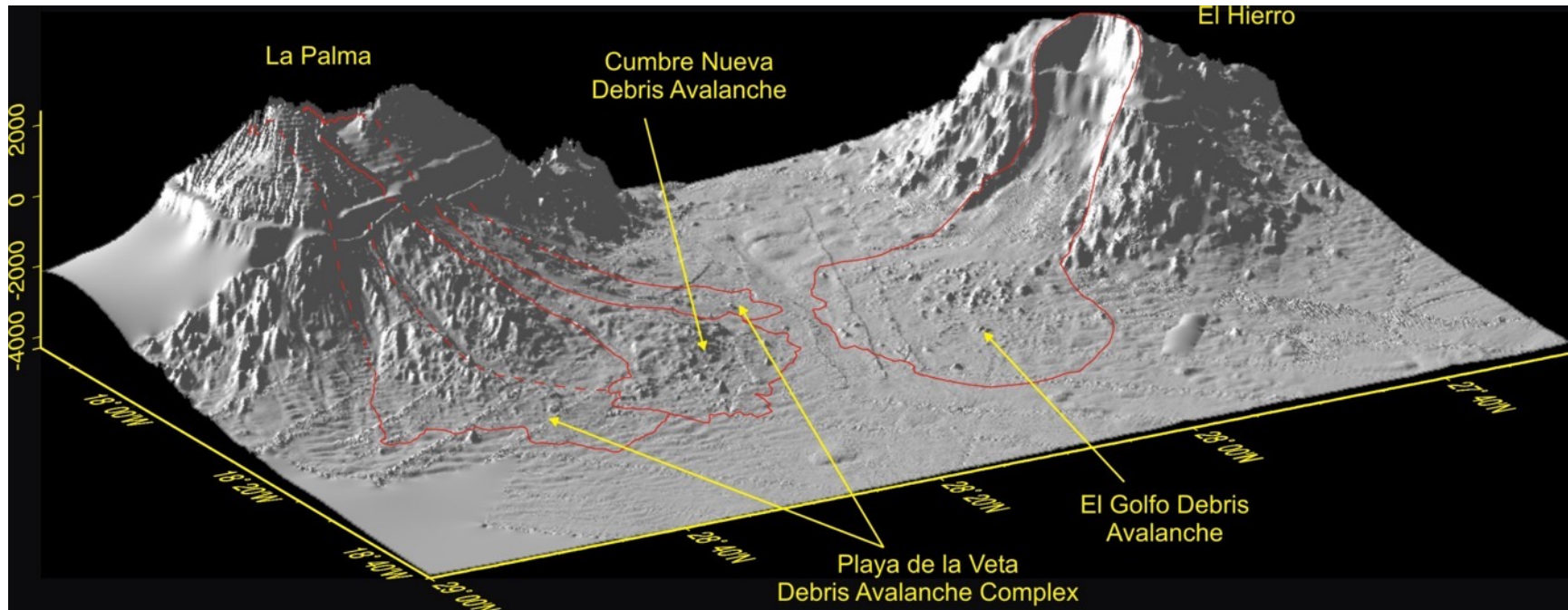
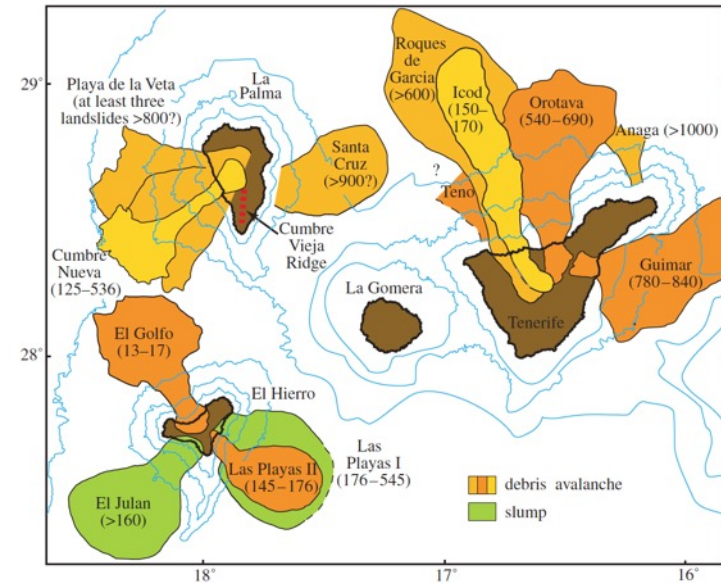
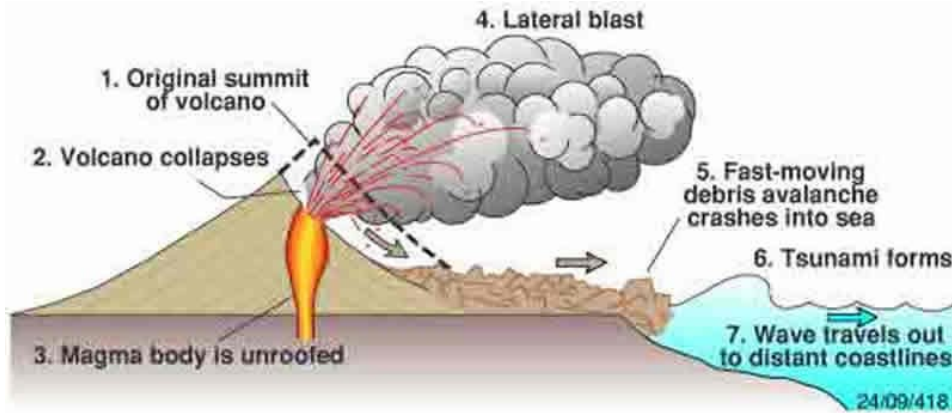
**Submarine  
debris avalanches**

**Volcanic Island Margins  
Hawaii**

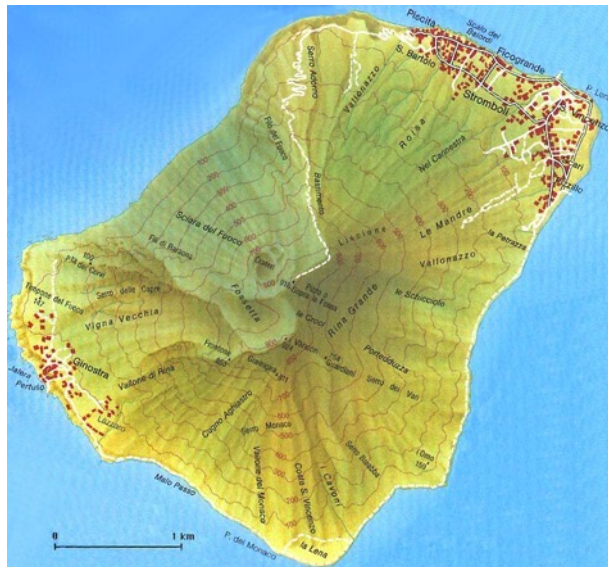
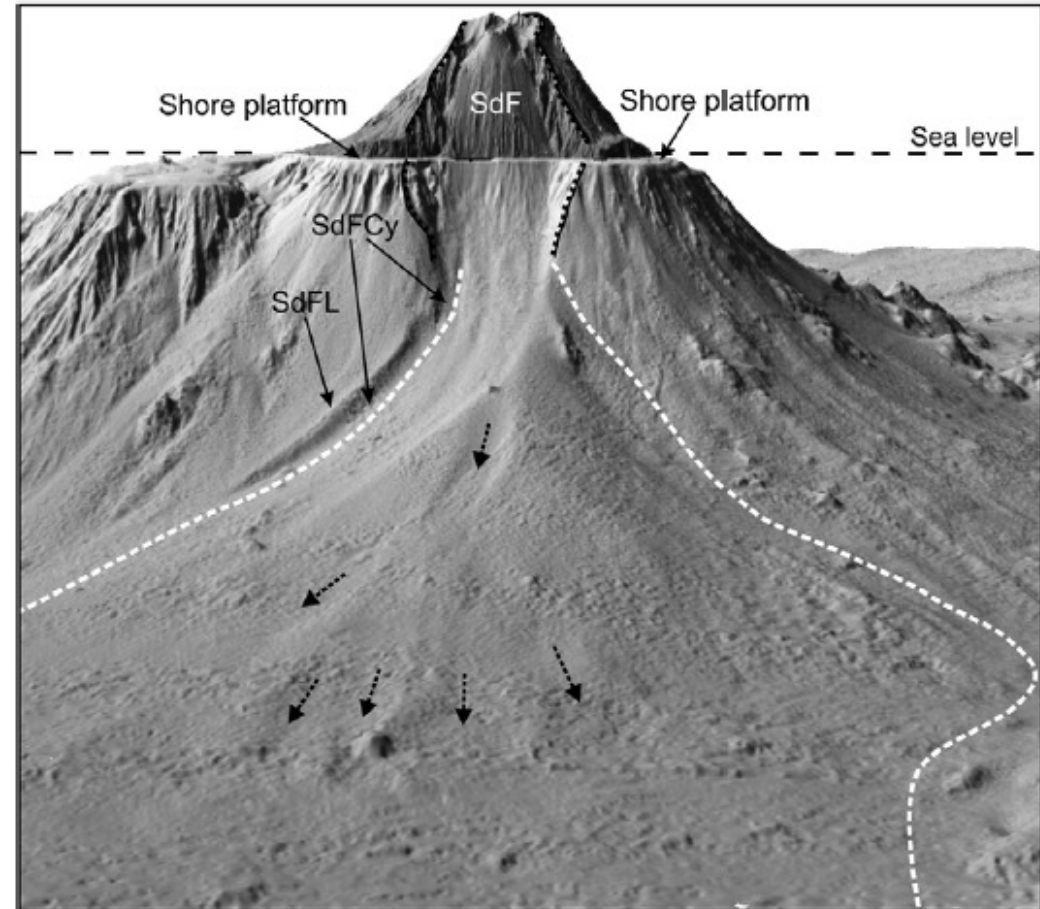
Moore et al., 1994. JGR



# Volcanic Island Margins Canarie



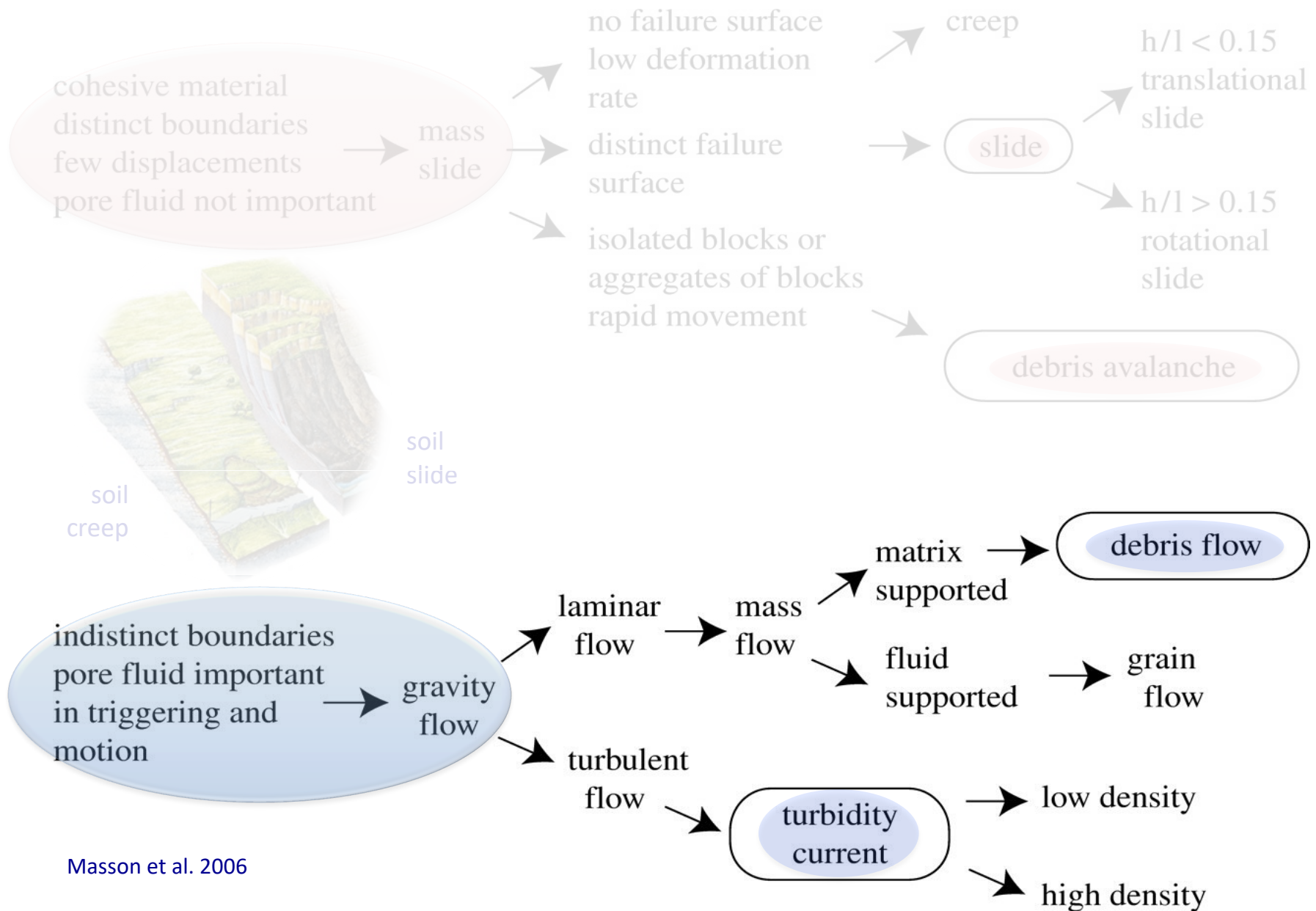
## Volcanic Island Margins Stromboli, Lipari Islands, Italy



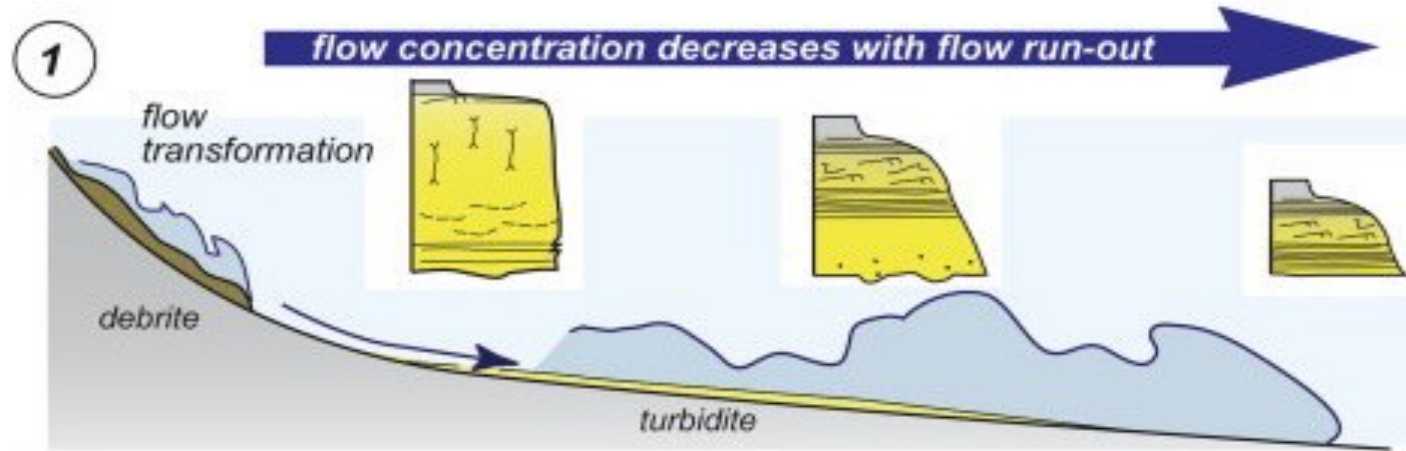
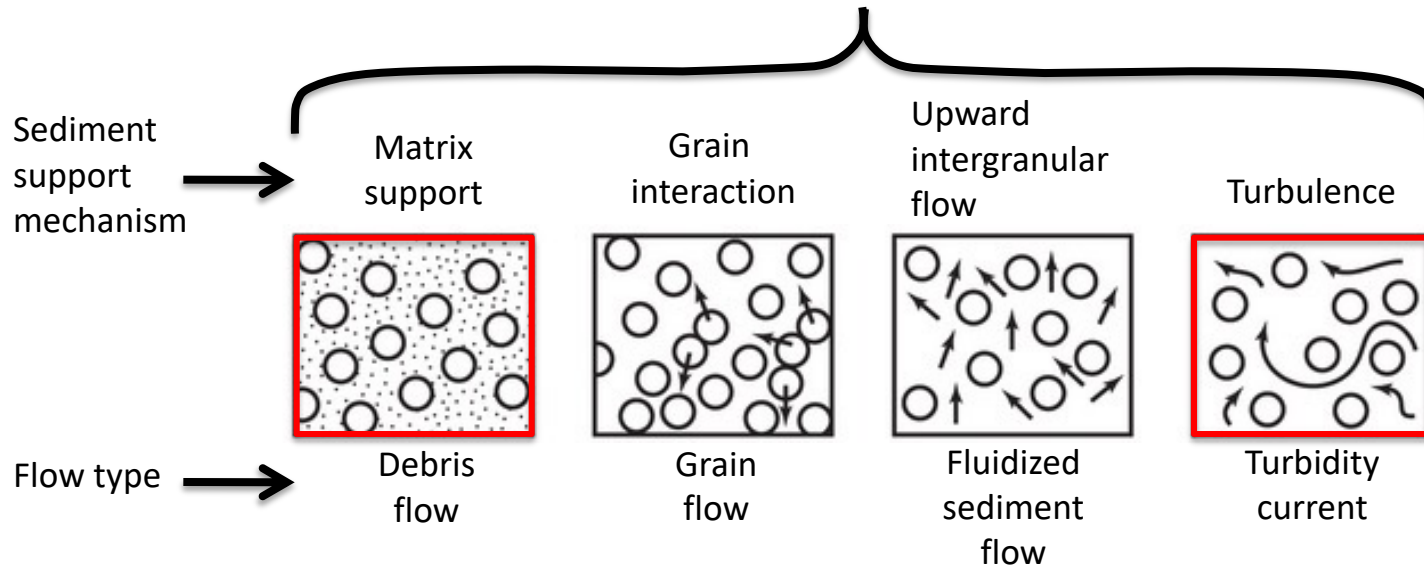
**Stromboli Sciara di Fuoco  
100.000 y**

Romagnoli et al., 2009. Marine Geology





# Gravity flows



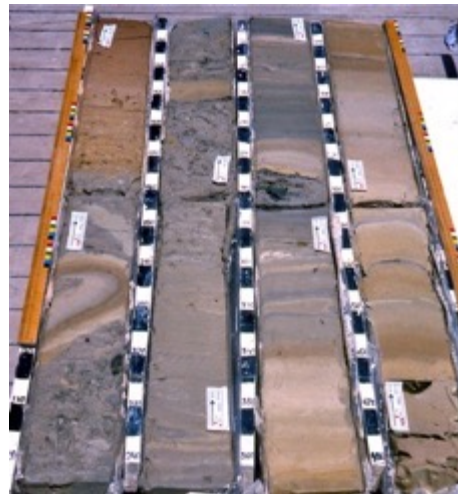
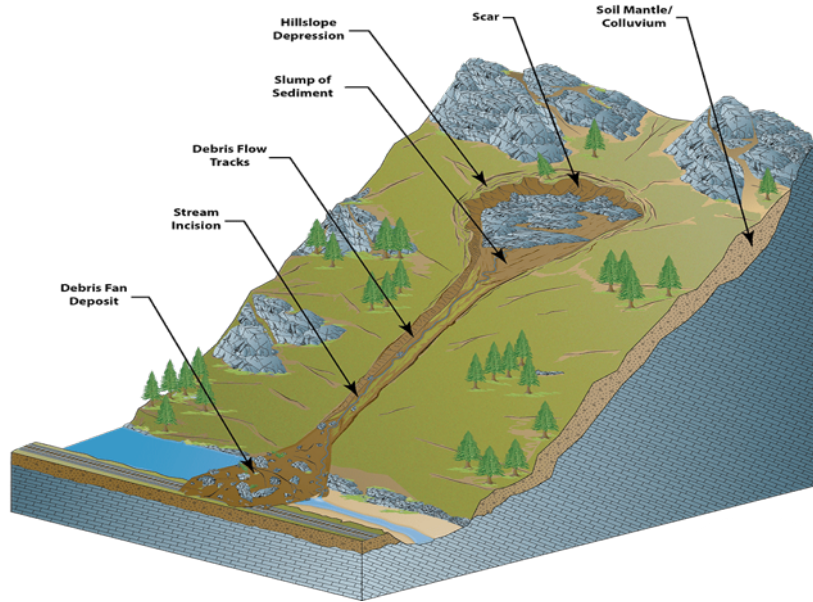


# Debris flows

Laminar flux supported by the water-rich muddy matrix

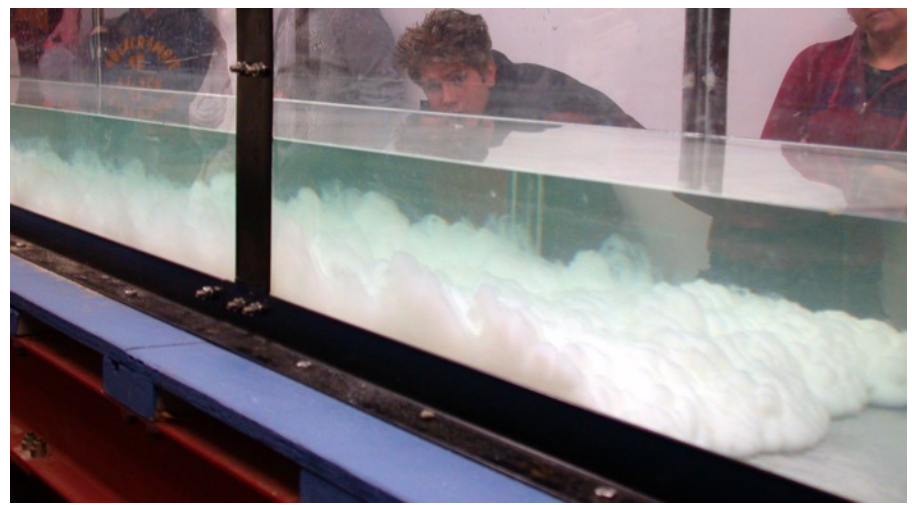
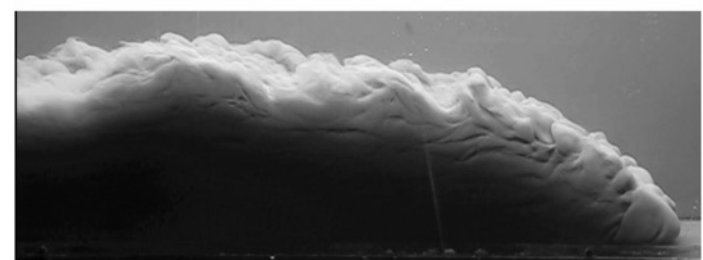
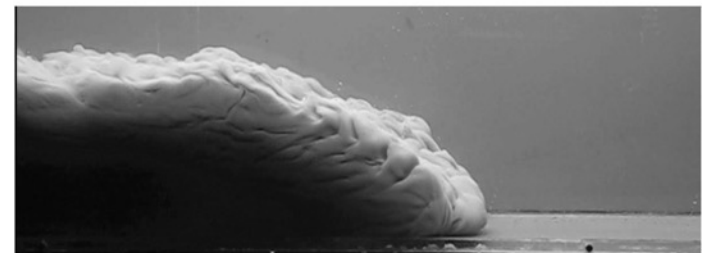
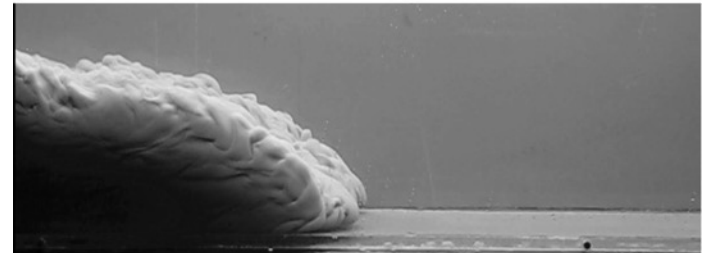
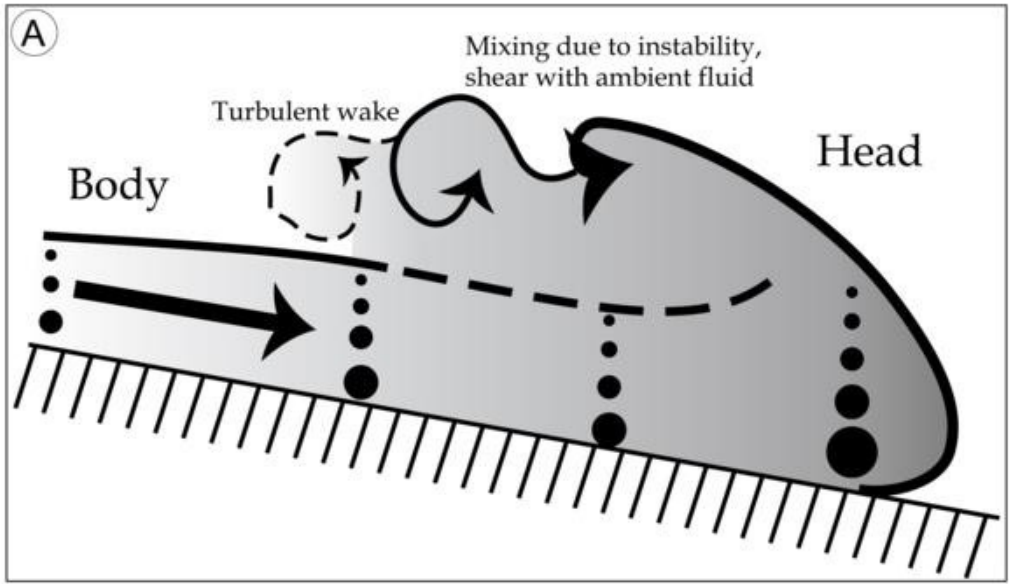
**Debris flow:** mud/sand <1; pebbles >5%

**Mud flow:** mud/sand >1; pebbles <5%



# Turbidity flows

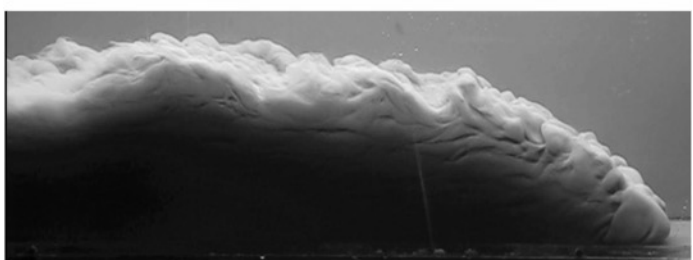
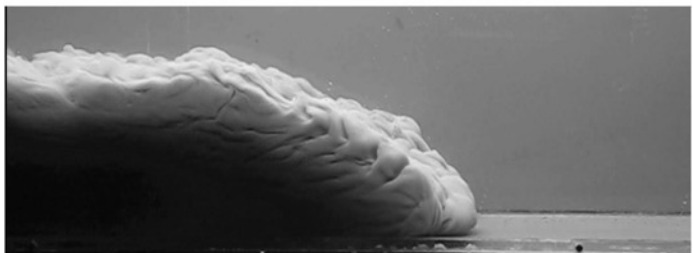
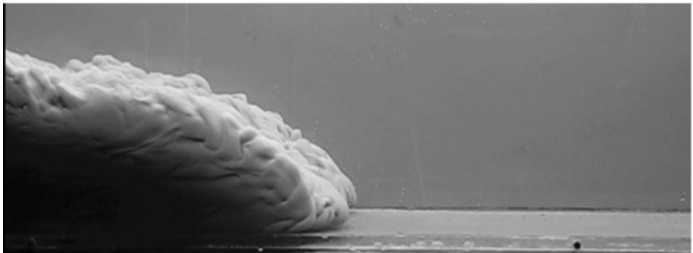
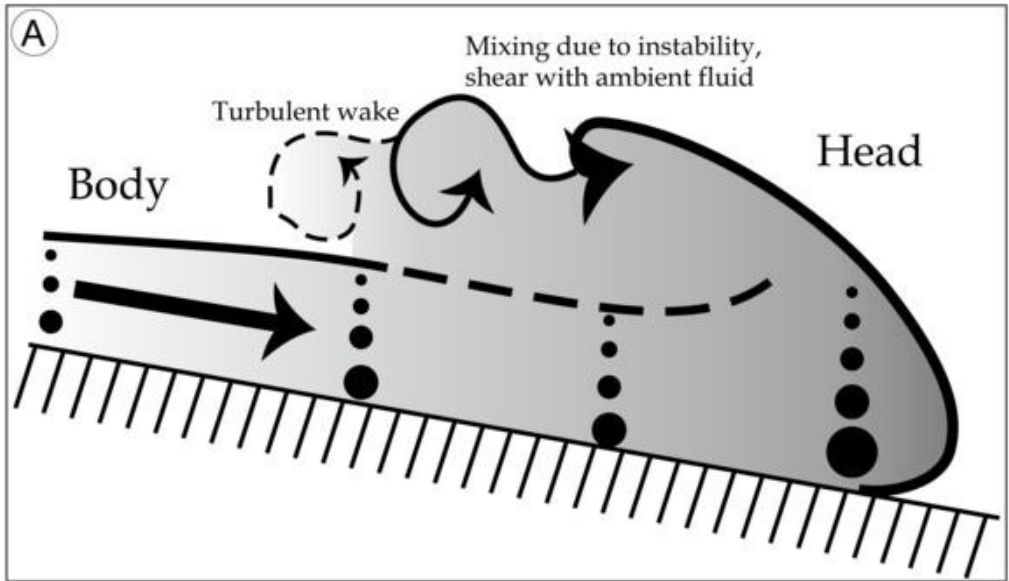
Density currents in which the granular support is maintained by the vertical component of the turbulent flux





# Turbidity flows

Density currents in which the granular support is maintained by the vertical component of the turbulent flux



**TYPE OF EVENT**

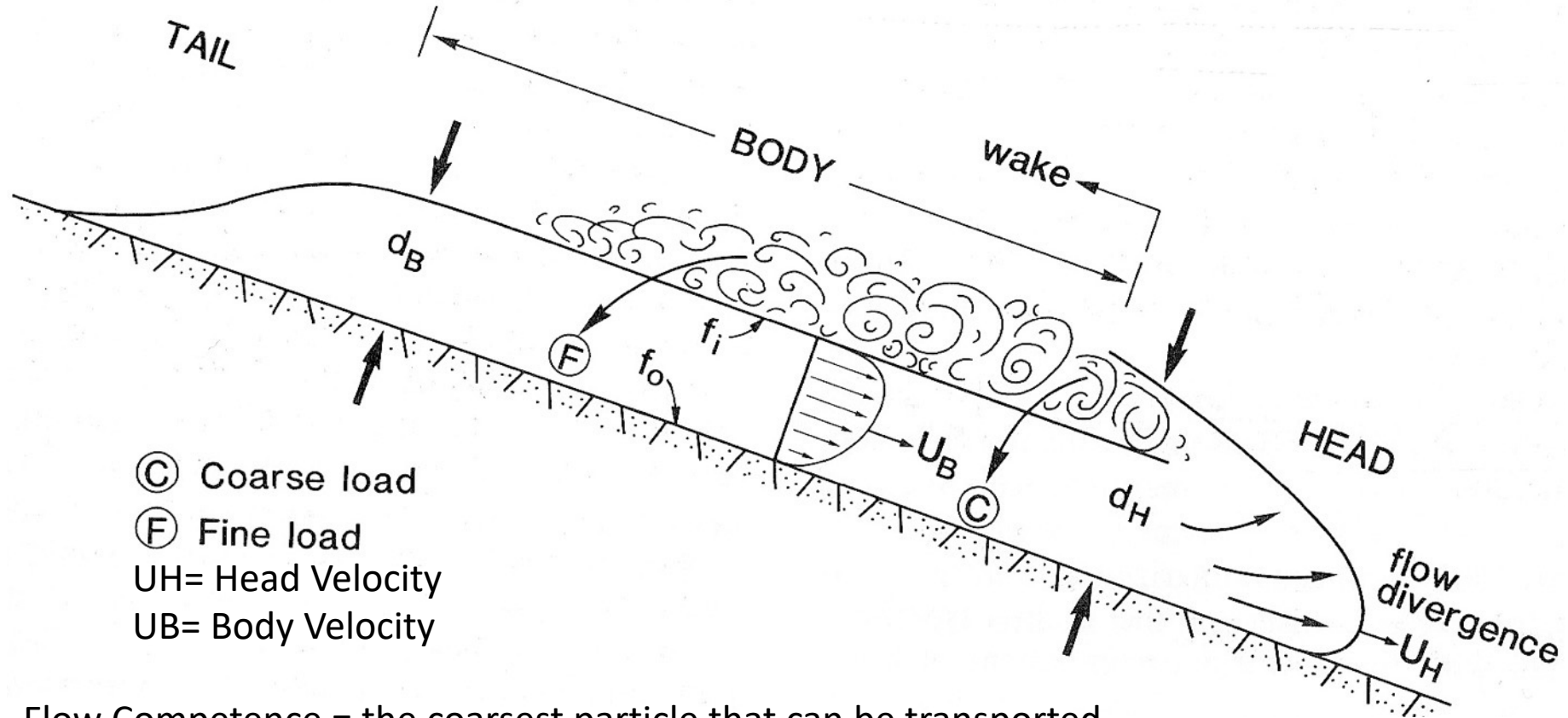
Long steady flow (e.g. river fed)  
Short surge-type (e.g. river floods, slope instability)

**FLOW DENSITY**

High density (higher velocity)  $>1.1 \text{ g/cm}^3$   
Low density (lower velocity)  $<1.1 \text{ g/cm}^3$

**FLOW TRANSFER**

Confined (canyon, channel, levee, deep-sea fan )  
Unconfined



Flow Competence = the coarsest particle that can be transported

Flow divergence

→ fluid ambient entrainment

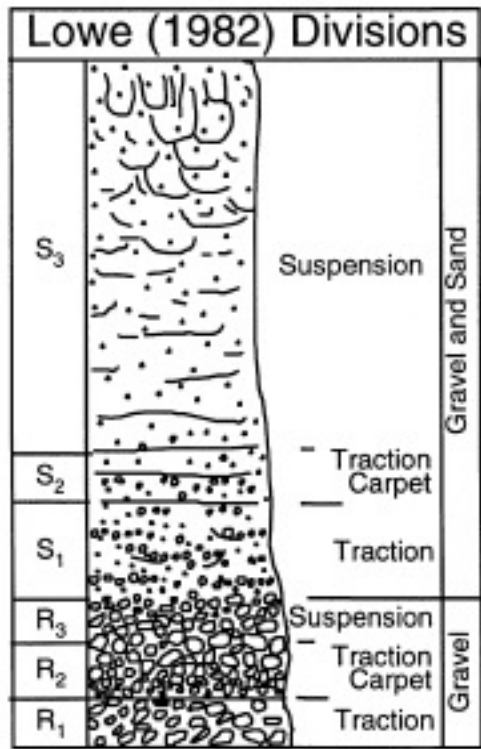
→ flow dilution

→ reduced speed

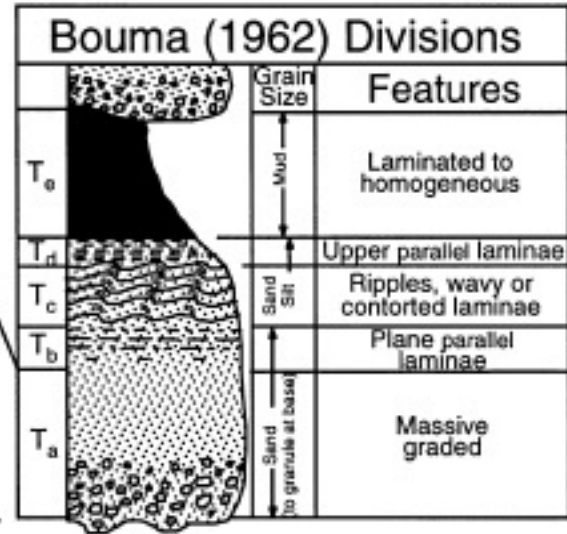
→ reduced competence

**Turbidite facies**

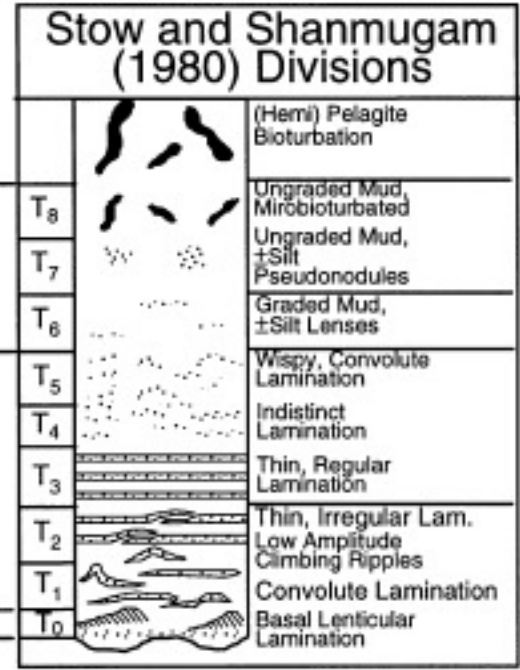
**Coarse-Grained Turbidites**



**Classic Turbidites**



**Fine-Grained Turbidites**



← Low-Density Turbidity Currents →

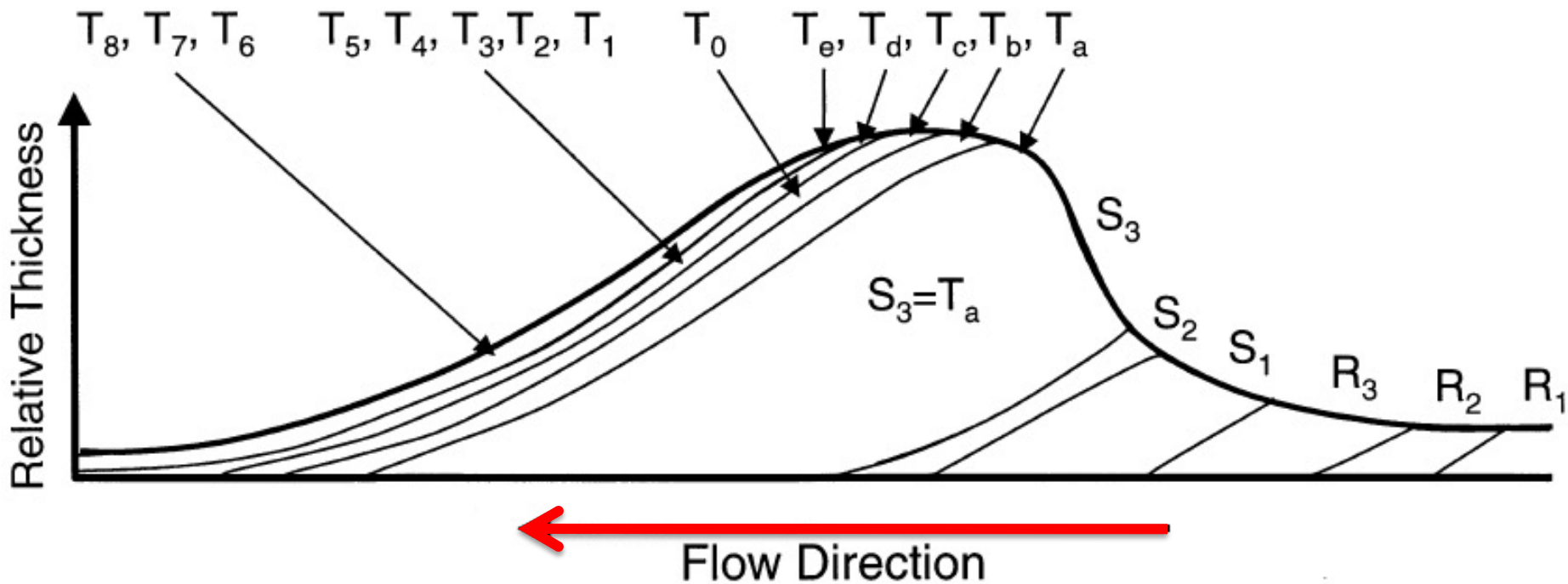
← High-Density Turbidity Currents →

**LOW DENSITY turbidity flows**

Stow and Shanmugam (1980)

Bouma (1962)

Low (1982)



- Shanmugam, G., 2000. 50 years of the turbidite paradigm (1950s-1990s): deep-water processes and facies models – a critical perspective. *Marine and Petroleum Geology* 17, 285-342.
- Kevin Pickering, Richard Hiscott, 2014. *Deep Marine Systems: Processes, Deposits, Environments, Tectonic and Sedimentation*. Wiley-Blackwell, ISBN: 978-1-4051-2578-9, 776p.



# Turbidite facies

## Fine-Grained Turbidites

### Coarse-Grained Turbidites

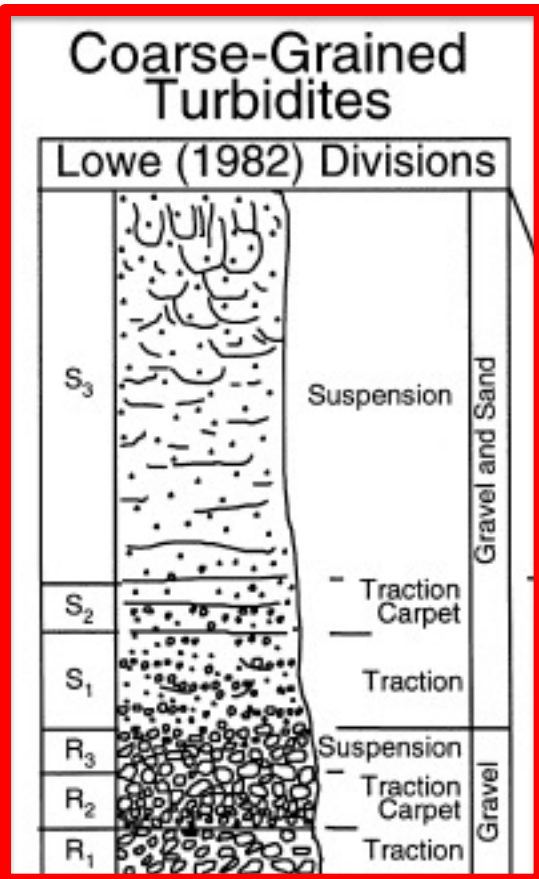
### Classic Turbidites

### Stow and Shanmugam (1980) Divisions

#### Loew (1982) Divisions

Bouma (1962) Divisions		Grain Size	Features
T <sub>a</sub>		Mud	Laminated to homogeneous
T <sub>b</sub>		Sand/Silt	Upper parallel laminae
T <sub>c</sub>		Sand/Silt	Ripples, wavy or contorted laminae
T <sub>d</sub>		Sand/Silt	Plane parallel laminae
T <sub>e</sub>		Sand to granule at base	Massive graded

Stow and Shanmugam (1980) Divisions		Features
T <sub>8</sub>		(Hemi) Pelagite Bioturbation
T <sub>7</sub>		Ungraded Mud, Microbioturbated
T <sub>6</sub>		Ungraded Mud, ± Silt Pseudonodules
T <sub>5</sub>		Graded Mud, ± Silt Lenses
T <sub>4</sub>		Wispy, Convolute Lamination
T <sub>3</sub>		Indistinct Lamination
T <sub>2</sub>		Thin, Regular Lamination
T <sub>1</sub>		Thin, Irregular Lam. Low Amplitude Climbing Ripples
T <sub>0</sub>		Convolute Lamination Basal Lenticular Lamination

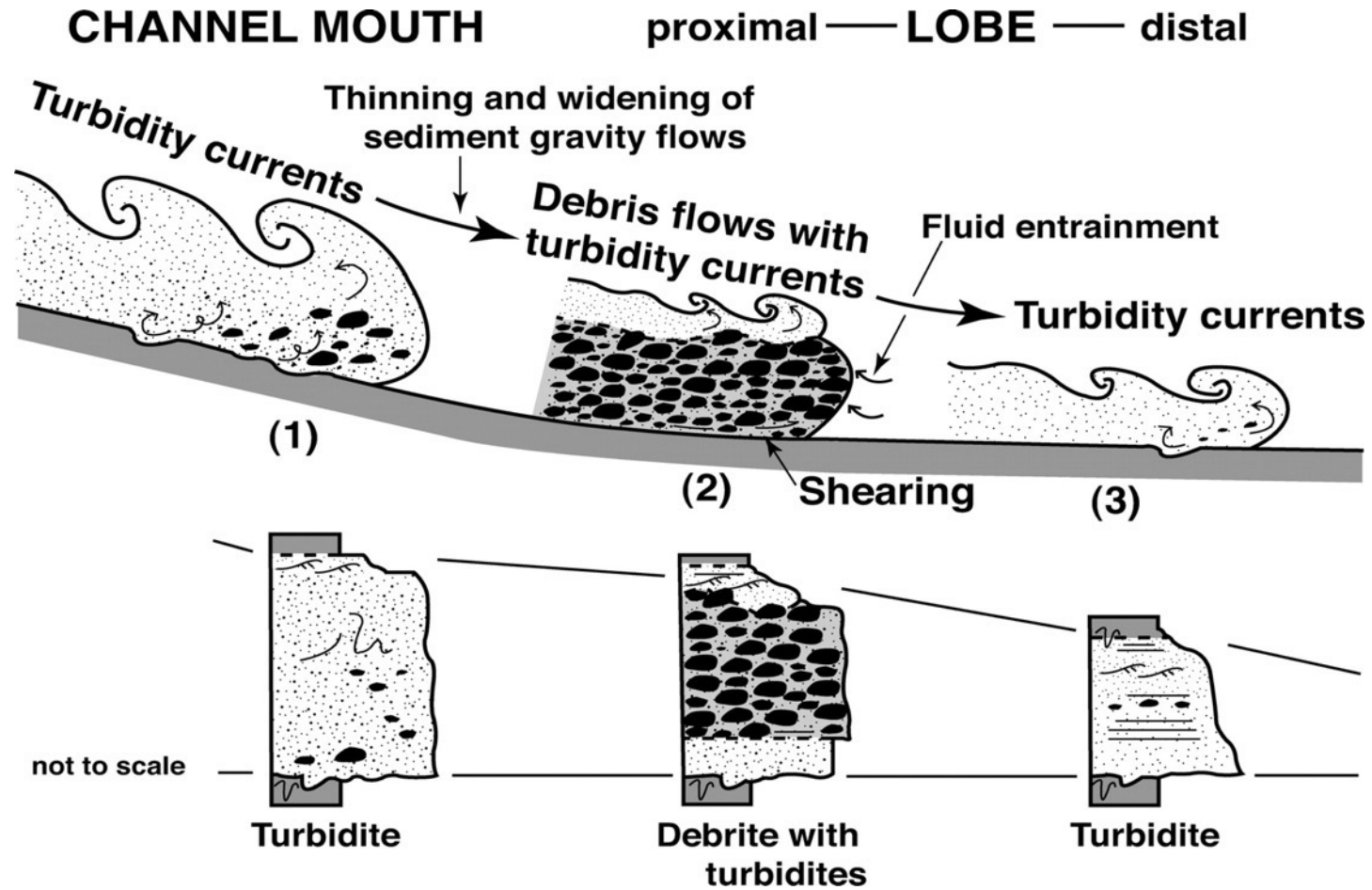


← Low-Density Turbidity Currents →

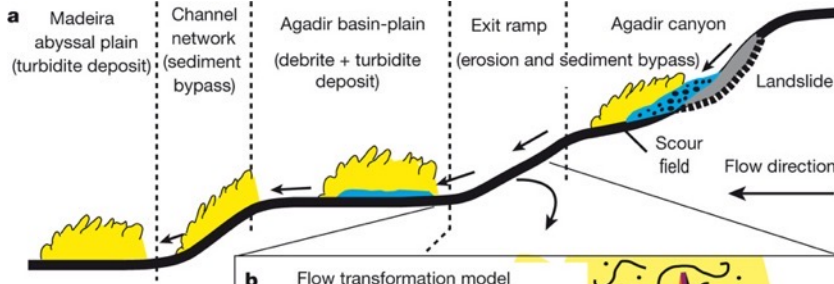
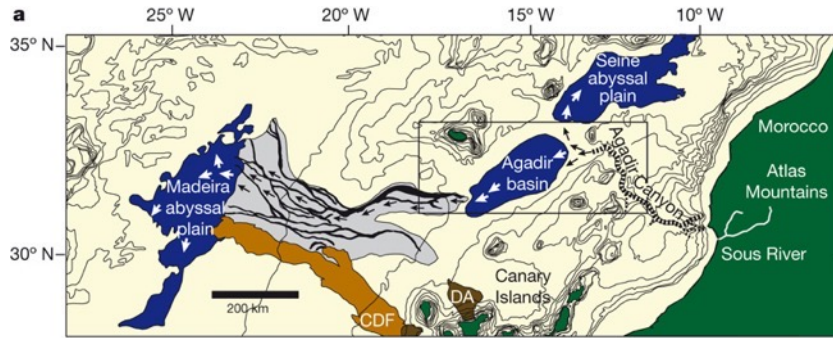
← High-Density Turbidity Currents →

# HIGH DENSITY turbidity flows

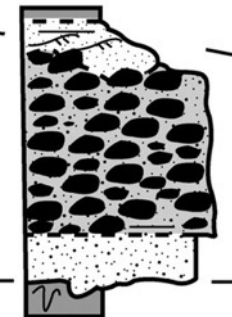
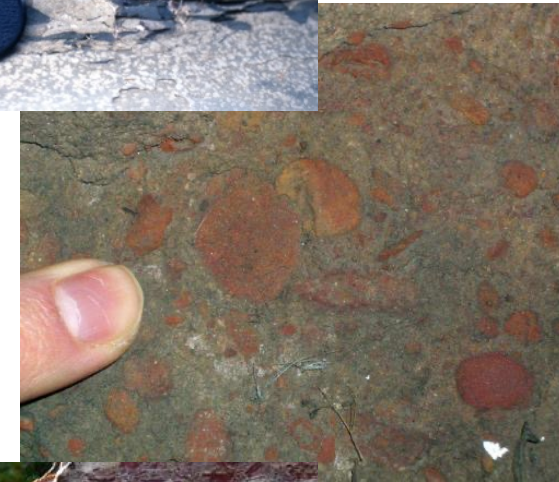
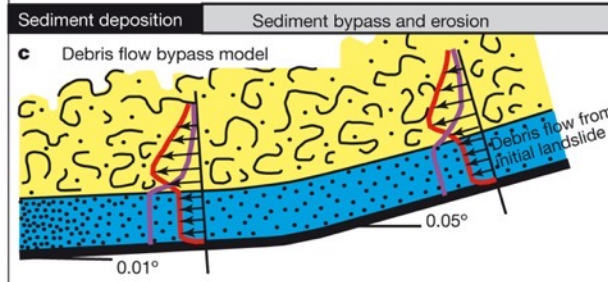
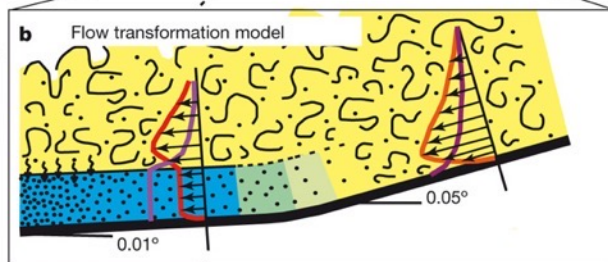
## The *linked debrite*





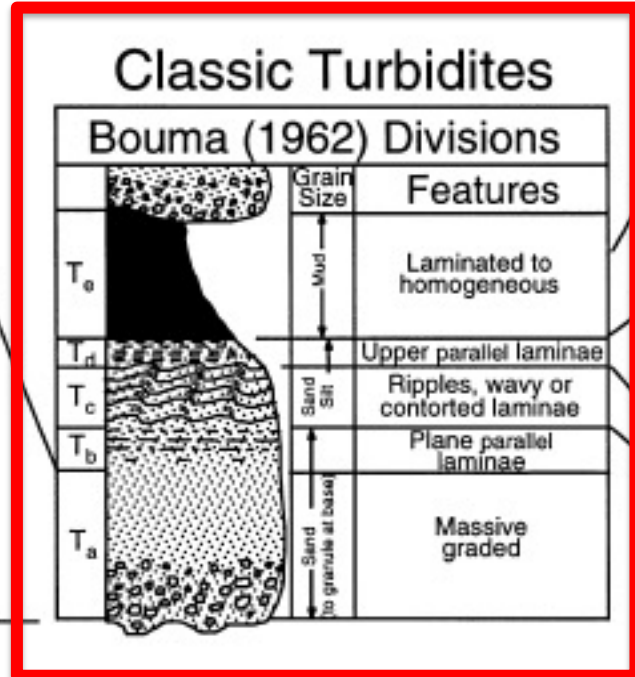
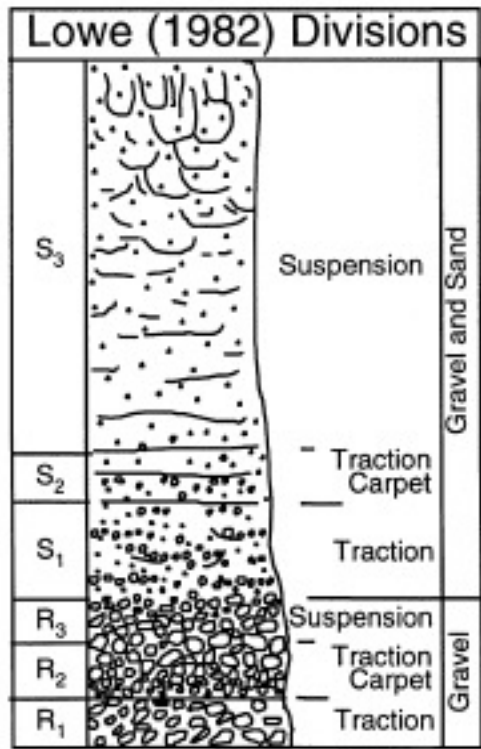


- Turbidity current (sediment supported mainly by turbulence)
- Debris flow (sediment supported mainly by mechanisms other than turbulence, although flow can be weakly turbulent)
- Density profile
- Velocity profile

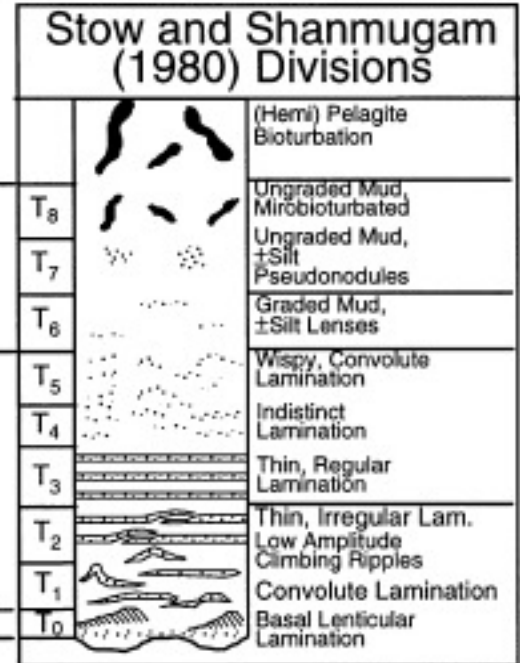


# Turbidite facies

## Coarse-Grained Turbidites



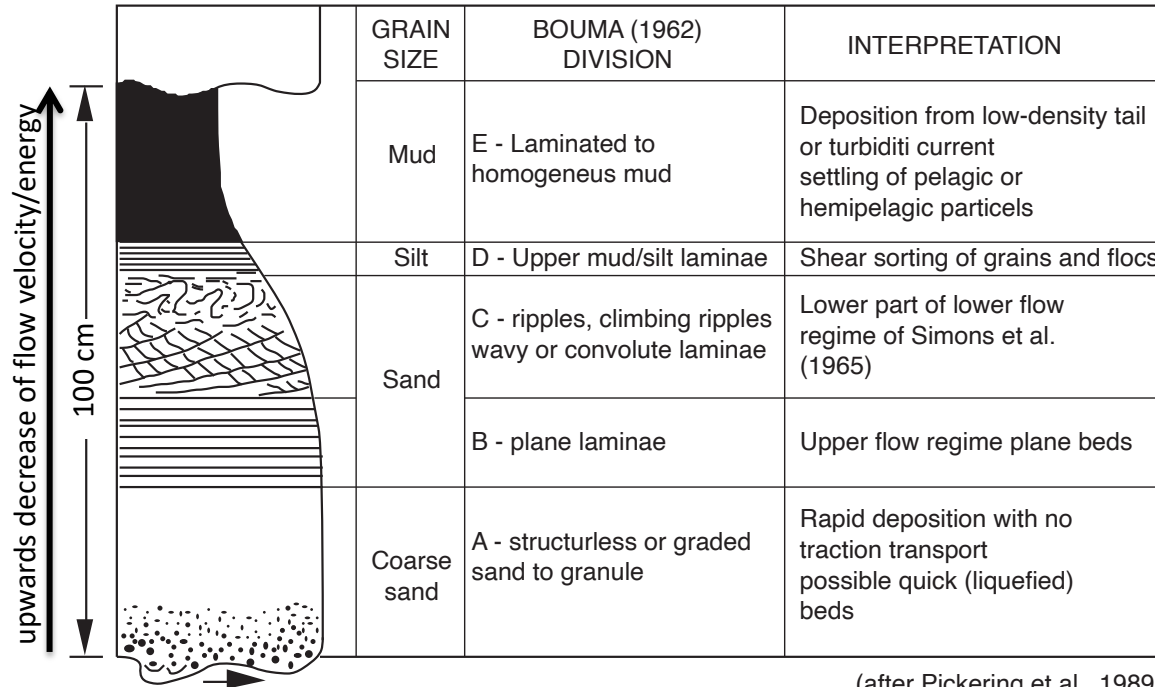
## Fine-Grained Turbidites



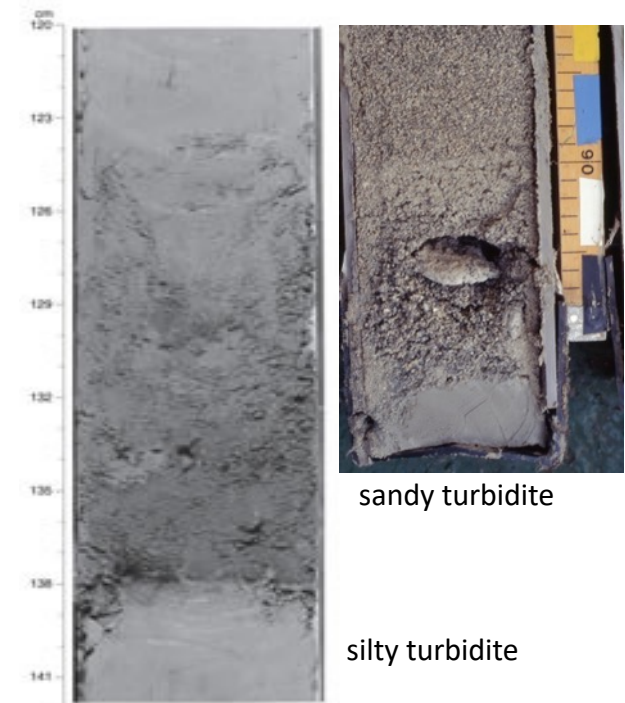
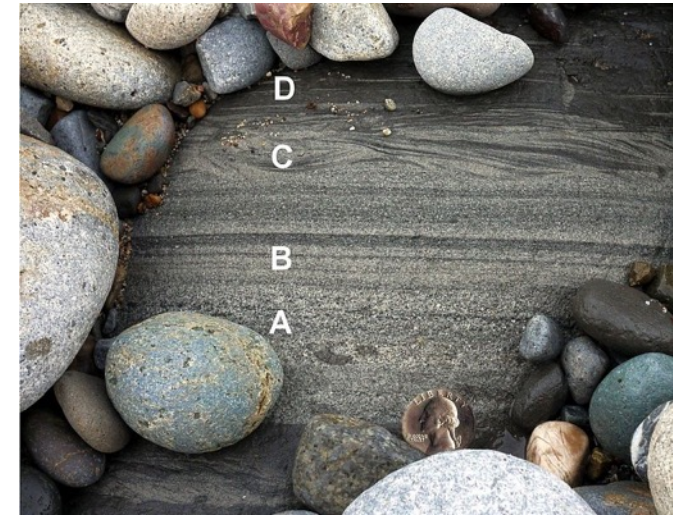
← Low-Density Turbidity Currents →

← High-Density Turbidity Currents →

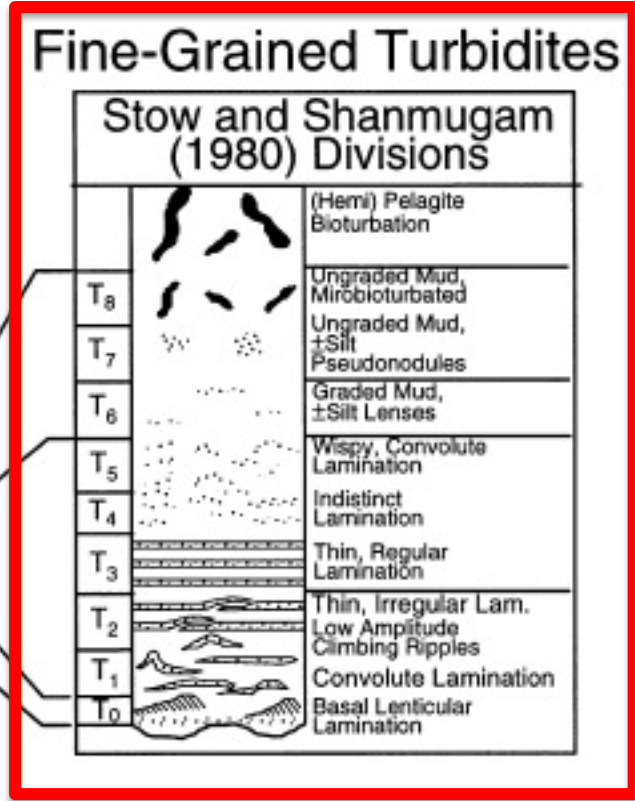
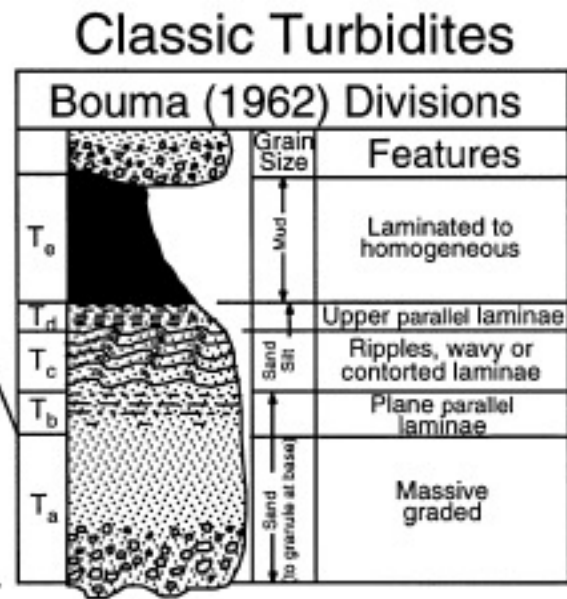
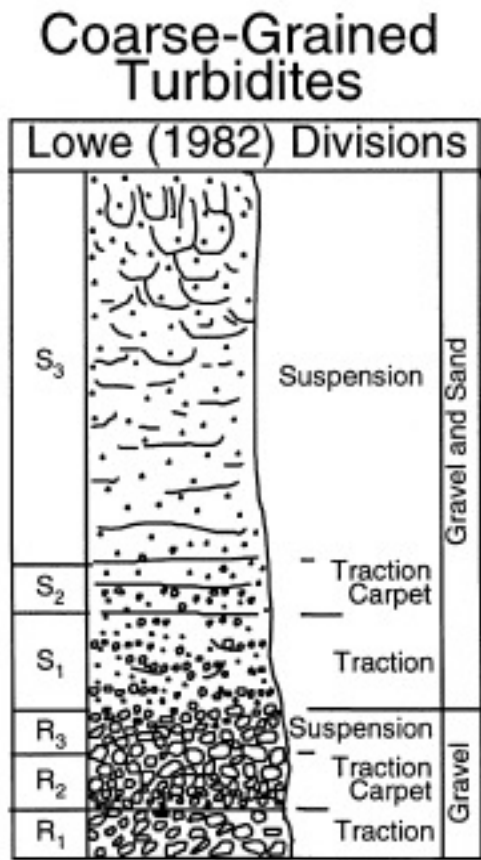




(after Pickering et al., 1989)

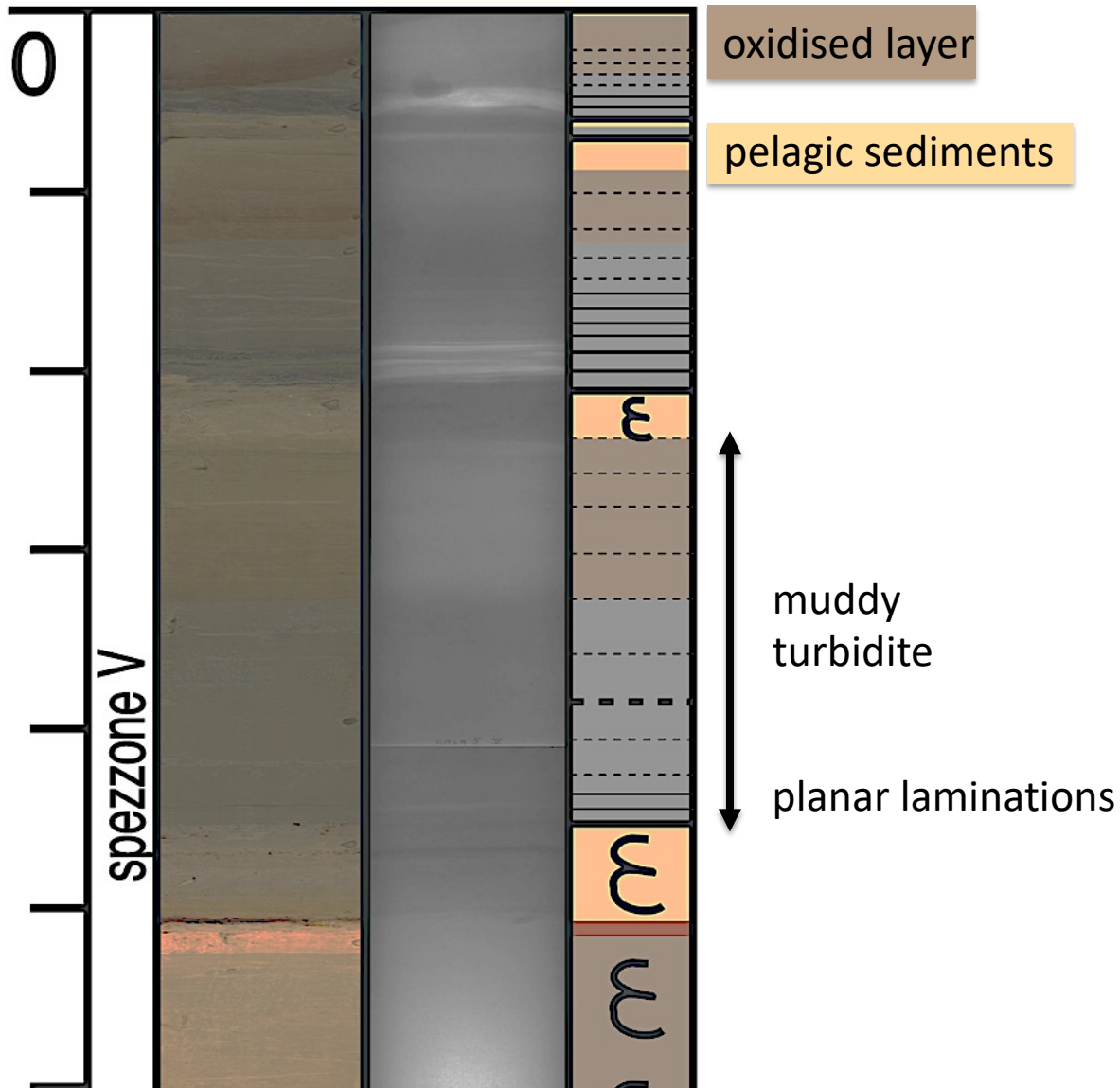


# Turbidite facies



← High-Density Turbidity Currents →

← Low-Density Turbidity Currents →

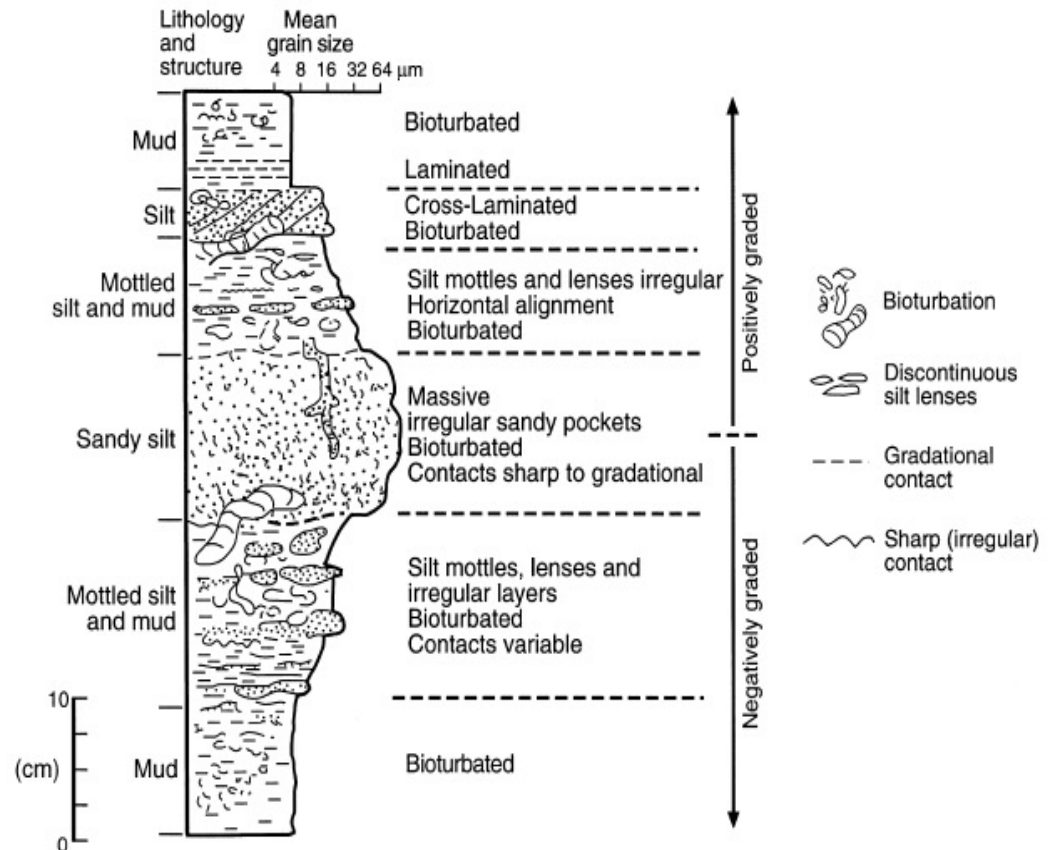
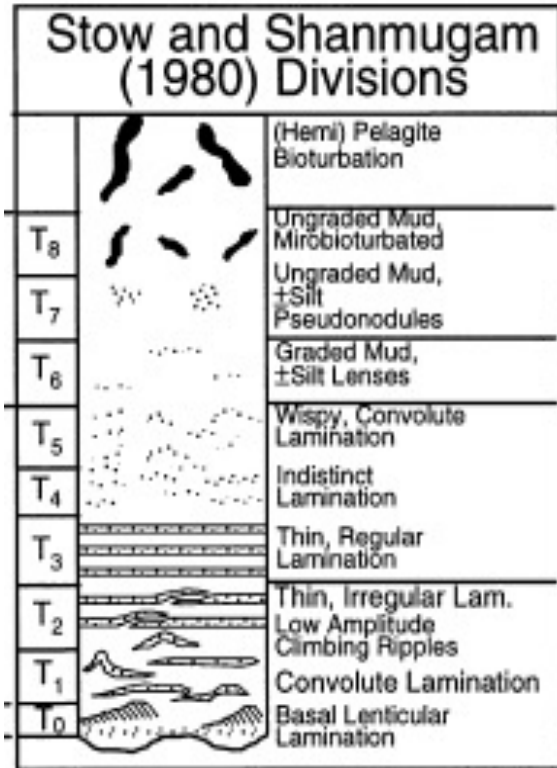




**Fine-grained turbidites**

*versus*

**Contourites**



## Modulo 2.3b Bottom Currents. Docente: Michele Rebesco

### Outline:

- Introduction
- Importance
- Thermohaline circulation
- Coriolis effect
- Sediment entrainment

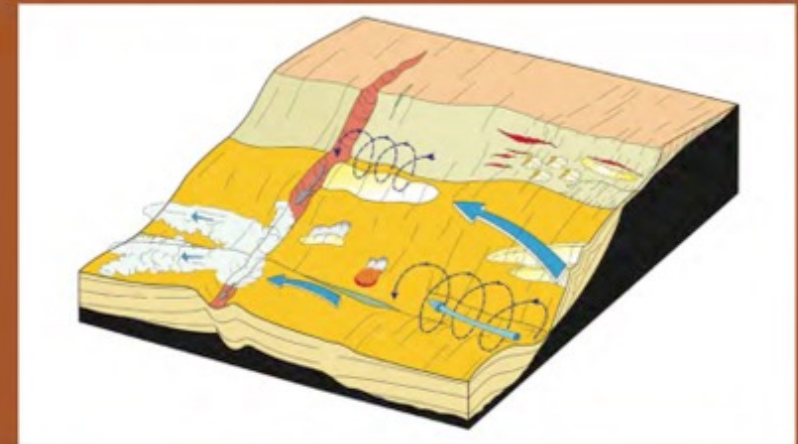
Bottom  
currents  
=  
Along-slope  
currents  
=  
Contour  
currents  
>  
Contourites



DEVELOPMENTS IN SEDIMENTOLOGY 60

# CONTOURITES

EDITED BY  
M. REBESCO & A. CAMERLENGHI



SERIES EDITOR: A. J. VAN LOON

*Michele Rebesco, F. Javier Hernández-  
Molina, David Van Rooij, Anna Wåhlin*

**Contourites and associated sediments  
controlled by deep-water circulation processes:  
state-of-the-art and future considerations**



A review for the 50<sup>th</sup> Anniversary Issue of *Marine Geology*  
Volume 352, 2014

42 pages, 27 figures, 522 references



Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Royal Holloway University of London



Renard Centre of Marine Geology, Ghent University

University of Gothenburg



This contribution is a product of the IGCP-619 and INQUA-1204 projects



# Glossary

## for alongslope sedimentary processes

Bottom current:

any 'persistent' water current near the sea-floor, generally with a net alongslope flow

Contourites:

sediments deposited or significantly affected by bottom currents.

Most widely accepted feature being the bioturbation. Discussion about the traction structures, which are present on the seafloor, apparently not preserved

Sediment drift:

sediment body (sheeted or mounded) produced by bottom currents.

Generally fine-grained, with large dimensions in many cases, typically separated from the slope by a moat



# The research on contourites is maturing.

However, many uncertainties remain, such as lack of indisputable diagnostic criteria for identifying contourites.

This field is now advancing similarly to how turbidite research progressed in the 60s.

Indeed, there is still a glaring disparity in knowledge between the former and the latter: a recent (end of June 2020) online search for the term contourites yielded about 666 results on Scopus and 49,100 on Google, whereas the same search for turbidites gave about 9,936 and 590,000 results, respectively—about 15 times more in each case.

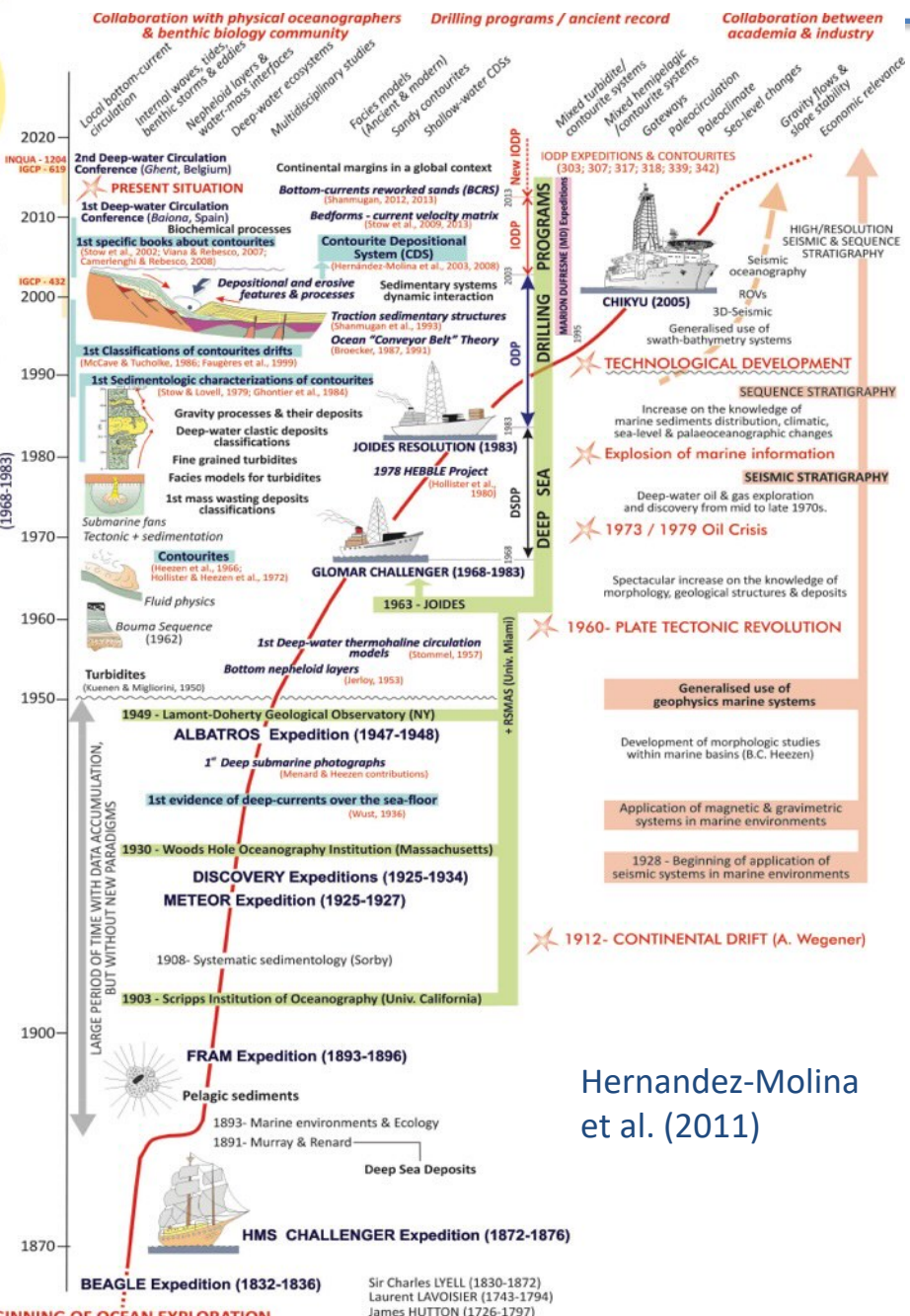
Scopus

Document search

Search



**OCEANOGRAPHY IN THE XX & XXI CENTURIES**  
**"CONTOURITE REVOLUTION"** (1966-present day)  
**"TURBIDITE REVOLUTION"** (1950-1968)  
**"BOOM"** OF MARINE INFORMATION (1968-1983)  
**FIRST HALF OF XX CENTURY**  
**ONSET OF MARINE SCIENCES**  
**SCIENTIFIC KNOWLEDGE OF XIX CENTURY**  
**THE BEGINNING OF OCEAN EXPLORATION**



## Evolution of knowledge

Since a seminal papers in early sixties, the contourite paradigm has progressed gradually.

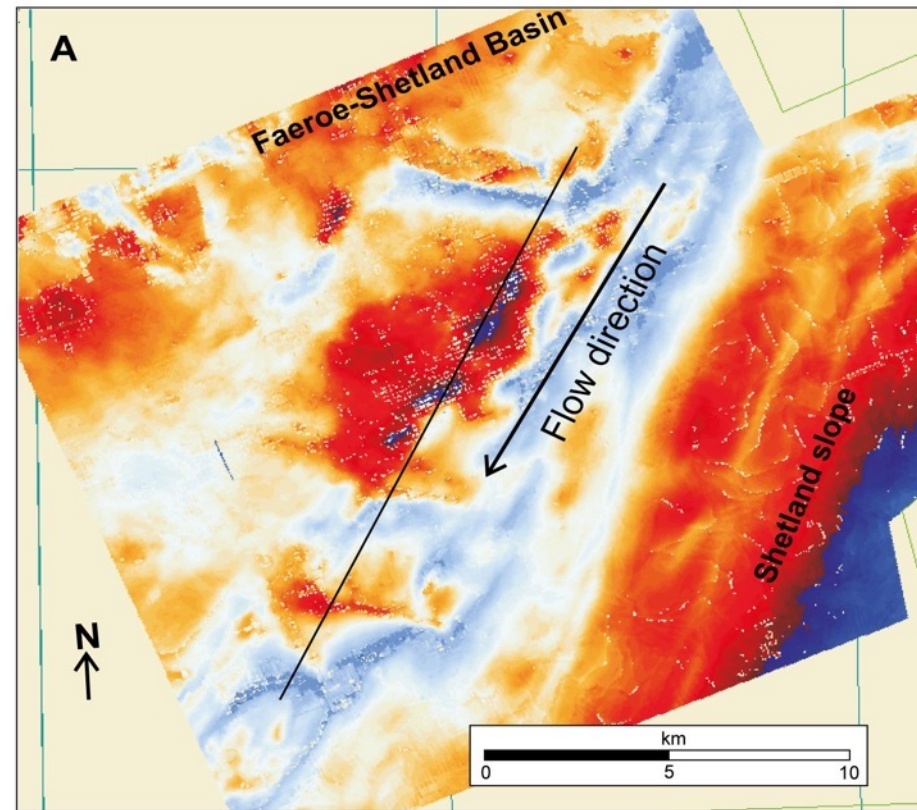
Though for many years associated research was the realm of a few specialists, contourites and bottom currents are of paramount importance in several areas of basic and applied research.

Hernandez-Molina et al. (2011)

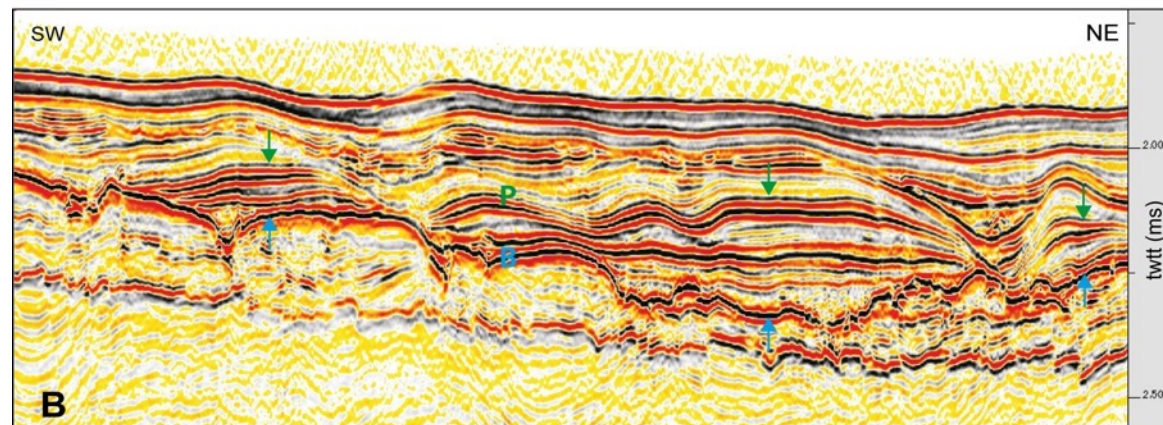


## Significance for palaeoceanography (geophysics)

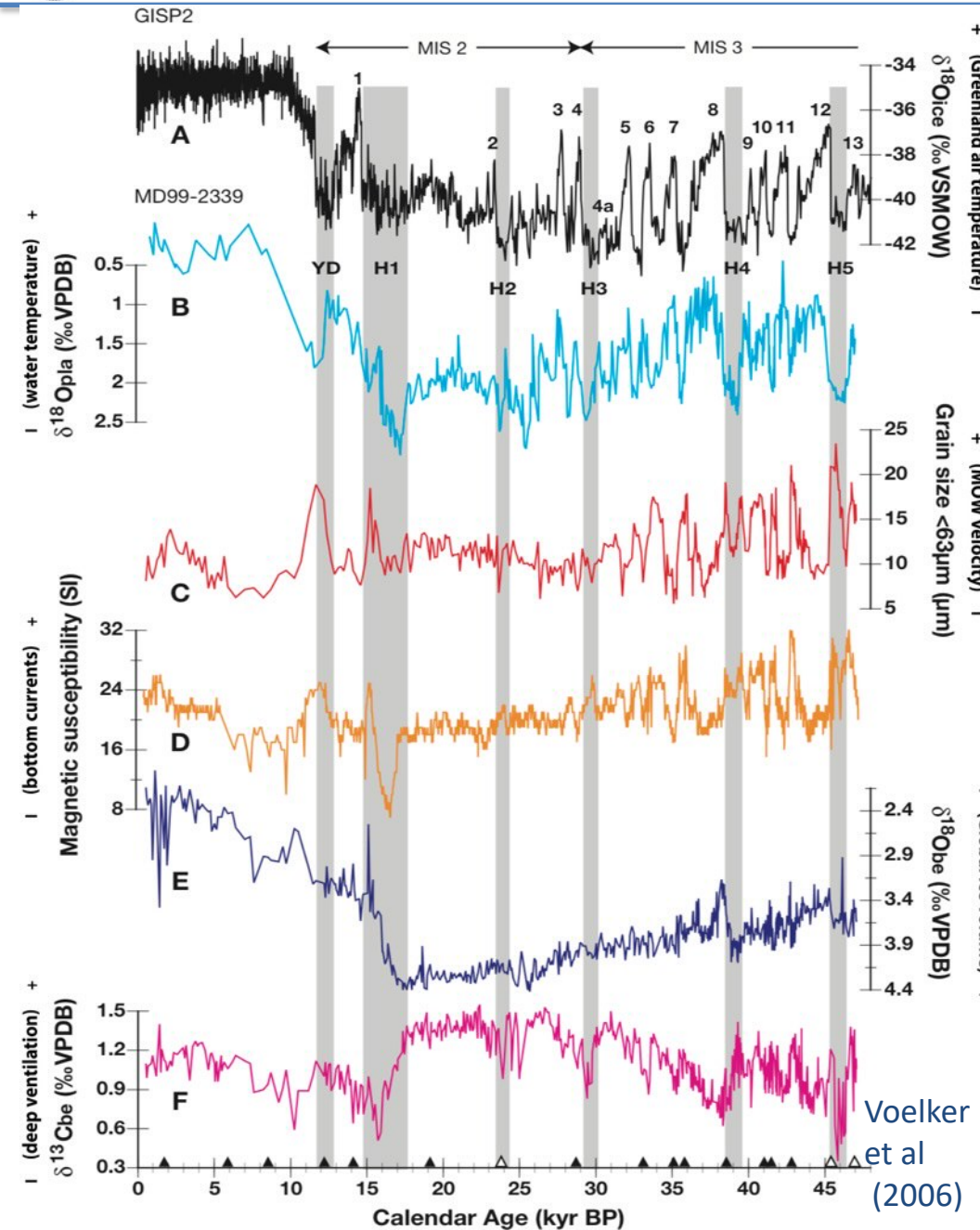
From contourite deposits, the history of ocean circulation and climate can be extracted using discrete sampling analyses (with geochemical, faunal, sedimentological techniques), continuous geophysical-chemical logging and seismic imaging. The latter allows to visualize drift geometry, internal reflections configuration and seismic facies, hence providing **palaeoceanographic information** about palaeo-current pathways and changes in current energy and direction on timescales from tens of thousands to millions of years.



Knutz (2008)







Voelker et al (2006)

## Significance for paleoceanography (geology)

Contourite research addresses a broad range of time scales including the human one (tens of years), like rapid ocean-climate variability in the North Atlantic. The reconstruction of leads and lags between various parameters of ocean-climate changes at multi-decadal time scales is allowed by the records from rapidly accumulating muddy contourite deposits. This information, whose **resolution approaches that from ice-core archives**, is crucial for a better understanding of global teleconnections, feedback thresholds and forcing mechanisms that determine the past and present climate system.



## Significance for geohazard (slope stability)

The distribution, composition and physical properties of contourites are vital for the occurrence of **submarine slope instabilities**.

Contouritic sediments are prone to failure because of five main factors:

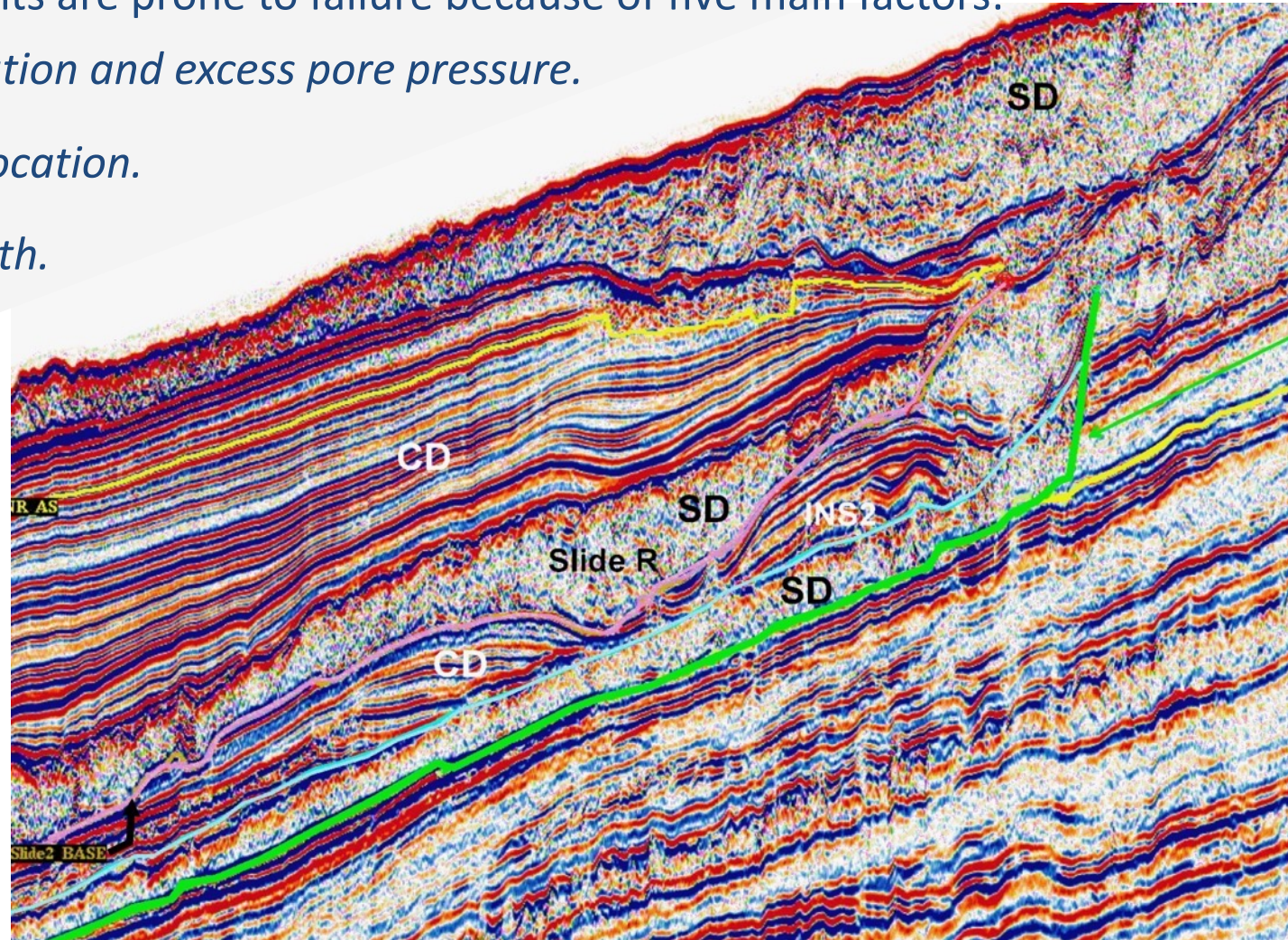
(a) *under-consolidation and excess pore pressure.*

(b) *geometry and location.*

(c) *low shear strength.*

(d) *gas charging.*

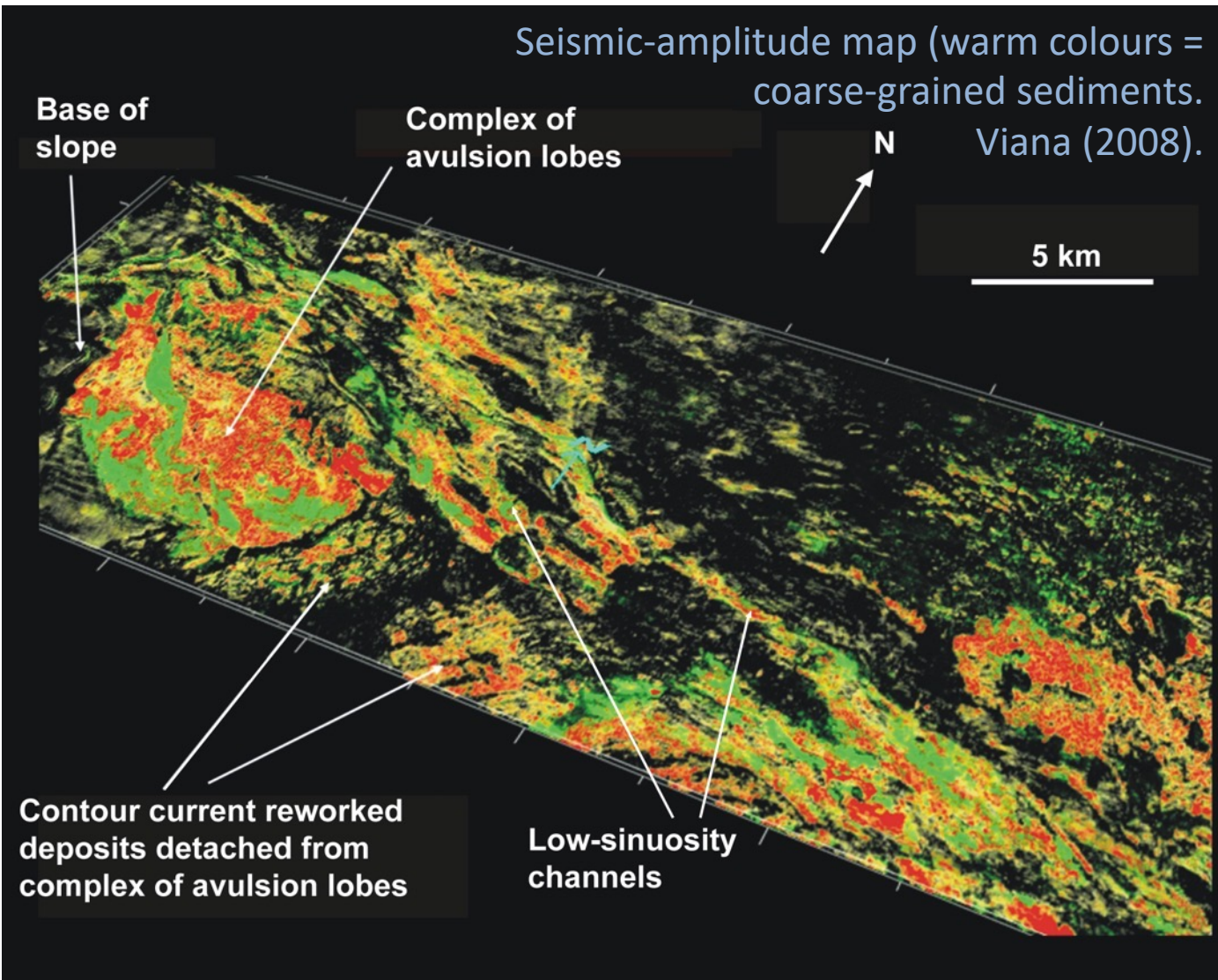
(e) *loading.*





## Significance for hydrocarbon exploration

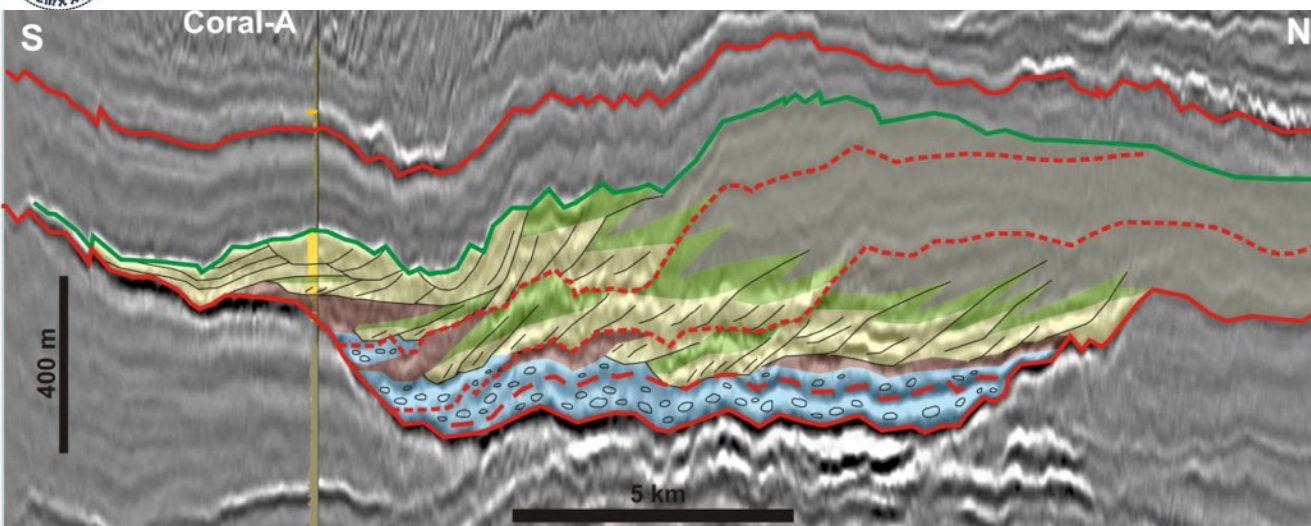
The action of contour currents has an impact on the petroleum systems in many aspects, including reservoir geometry and quality, and the distribution of sealing rocks.



Changes of the seafloor topography by erosion or deposition induced by bottom currents can result in a re-adjustment of the sediment accommodation space and the creation of sub-basins, which act as sediment traps or gateways for sediment transfer.

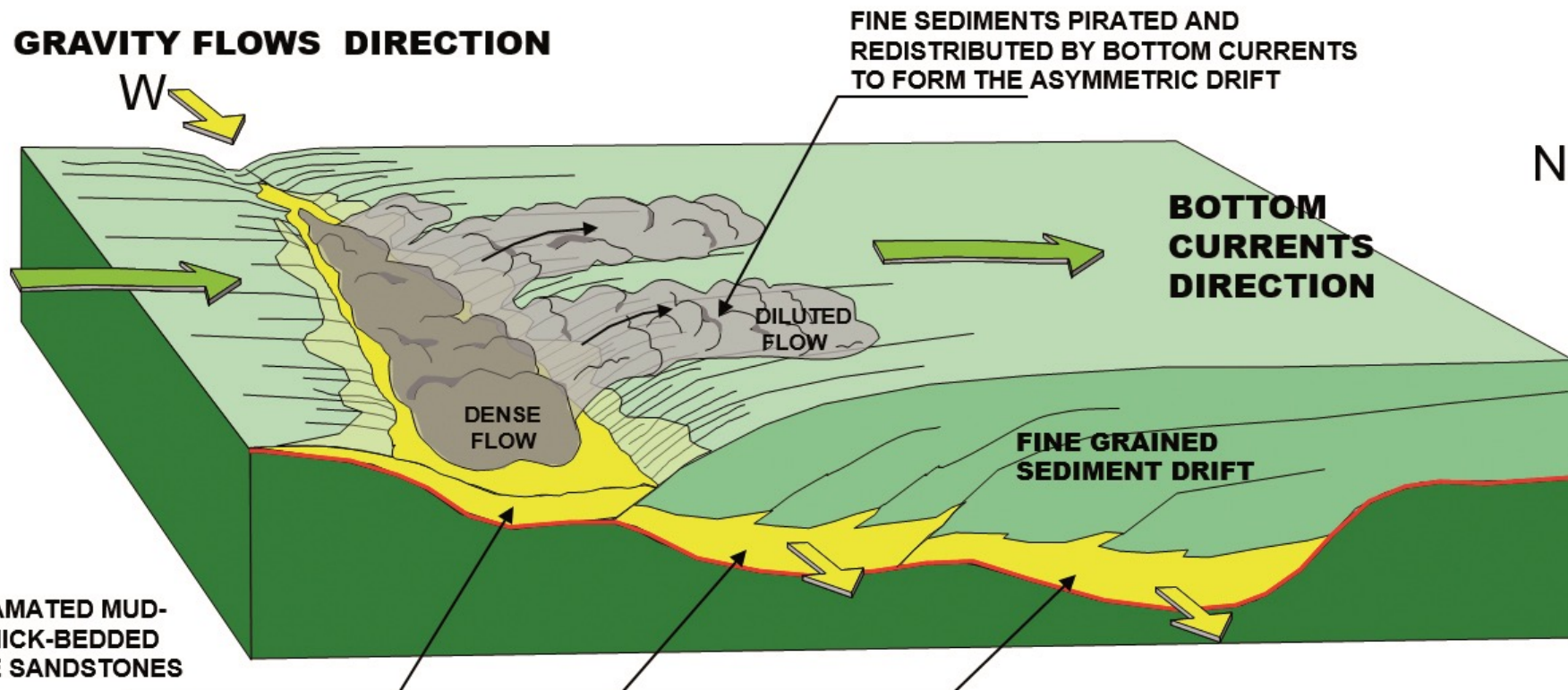
Coarse-grained contourites deposited by robust flows may represent hydrocarbon reservoirs, whereas fine-grained contourites accumulated by weak bottom currents may provide sealing (and source) rocks.





- Hemipelagitic Shale Complexes
- Sandy Channel-Lobe Complexes
- Mud/Fine-grained dominated Drift-mound
- Channel complex lag deposits
- Mud-prone mass transport deposits and slumps

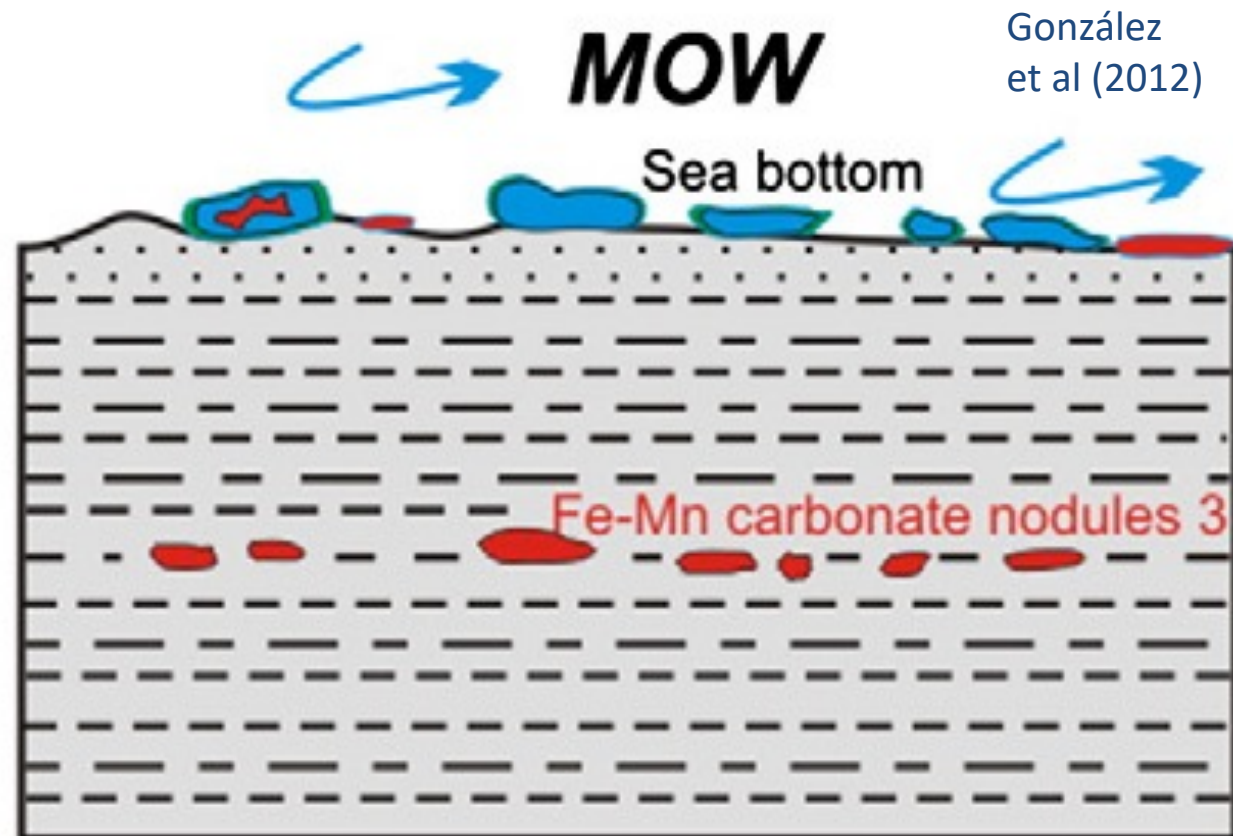
**Mozambique: >80TCF**  
(Trillion Cubic Feet) [2.265 km<sup>3</sup>]  
of natural gas  
(Fonnesu et al., 2019)



The nodule may grow below the redox boundary within the sediments, forming an original concretion composed essentially of Fe–Mn carbonates. The erosive action of the Mediterranean Outflow Water (MOW) during the glacial periods produces the exhumation of Fe–Mn carbonate nodules that are replaced by Fe–Mn oxides through the action of the oxidising sea-bottom water. In eroding areas, the oldest nodules will be concentrated as an erosional lag on the seafloor, while the newest ones will form at depth.

## Significance for polymetallic nodules

Contourite research reveals as a tool with an interesting potential for ferromanganese nodule exploration (Juan et al., 2018)



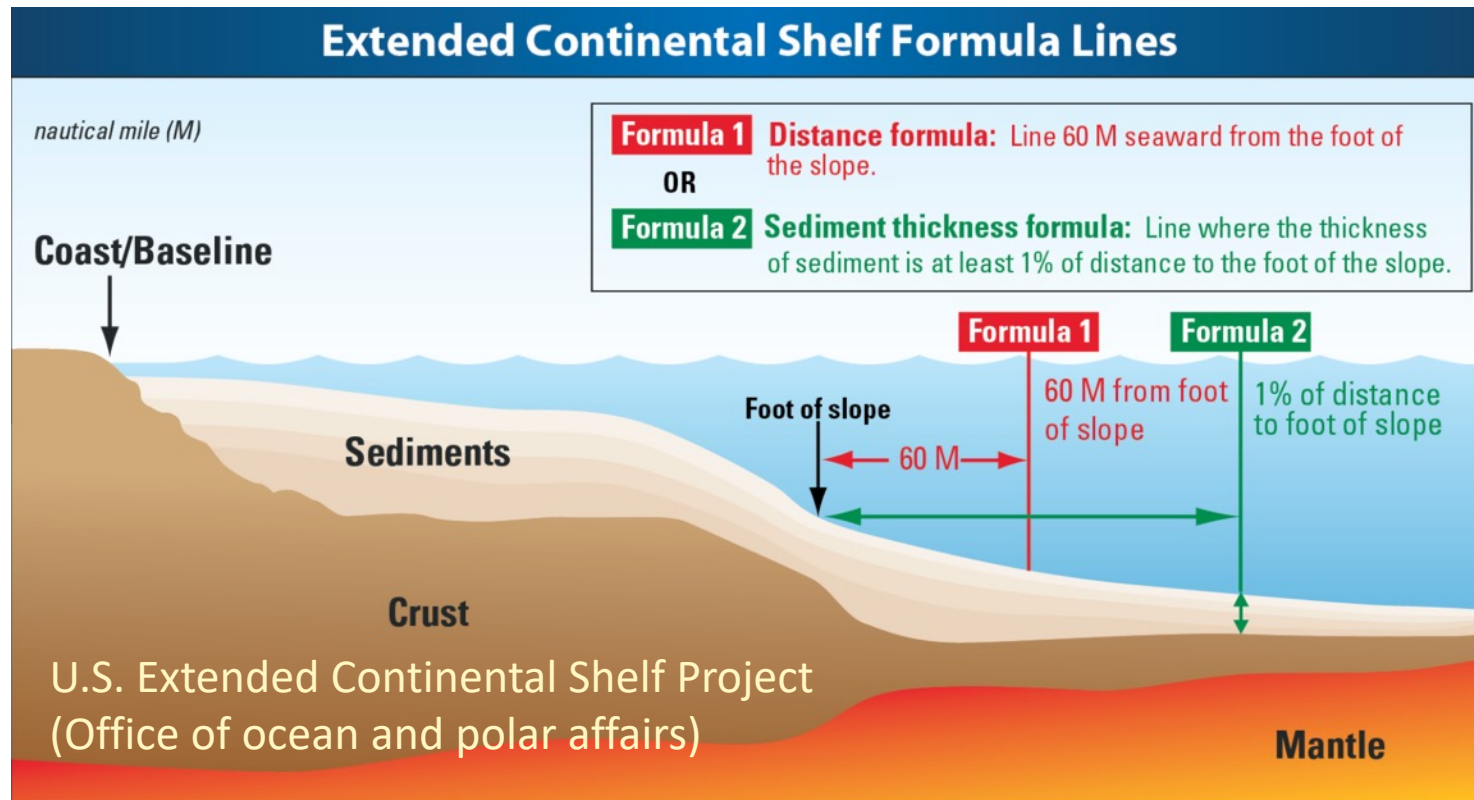


## Significance for the definition of the “extended continental shelf”

The “**extended continental shelf**” is the portion of the continental shelf beyond 200 nautical miles under the Law of the Sea Convention. It is an important maritime zone that holds many resources and vital habitats for marine life: knowledge of its exact extent is necessary for national security and good management. Large sediment bodies deposited by contour-following currents are developed all along the margin. These drifts tend to form bathymetric steps in profile, where they onlap the margin.

Stacked drifts create several steps.

Understanding the geomorphological consequences of deep sea sedimentation processes is important to extended continental shelf mapping (Mosher et al., 2016)

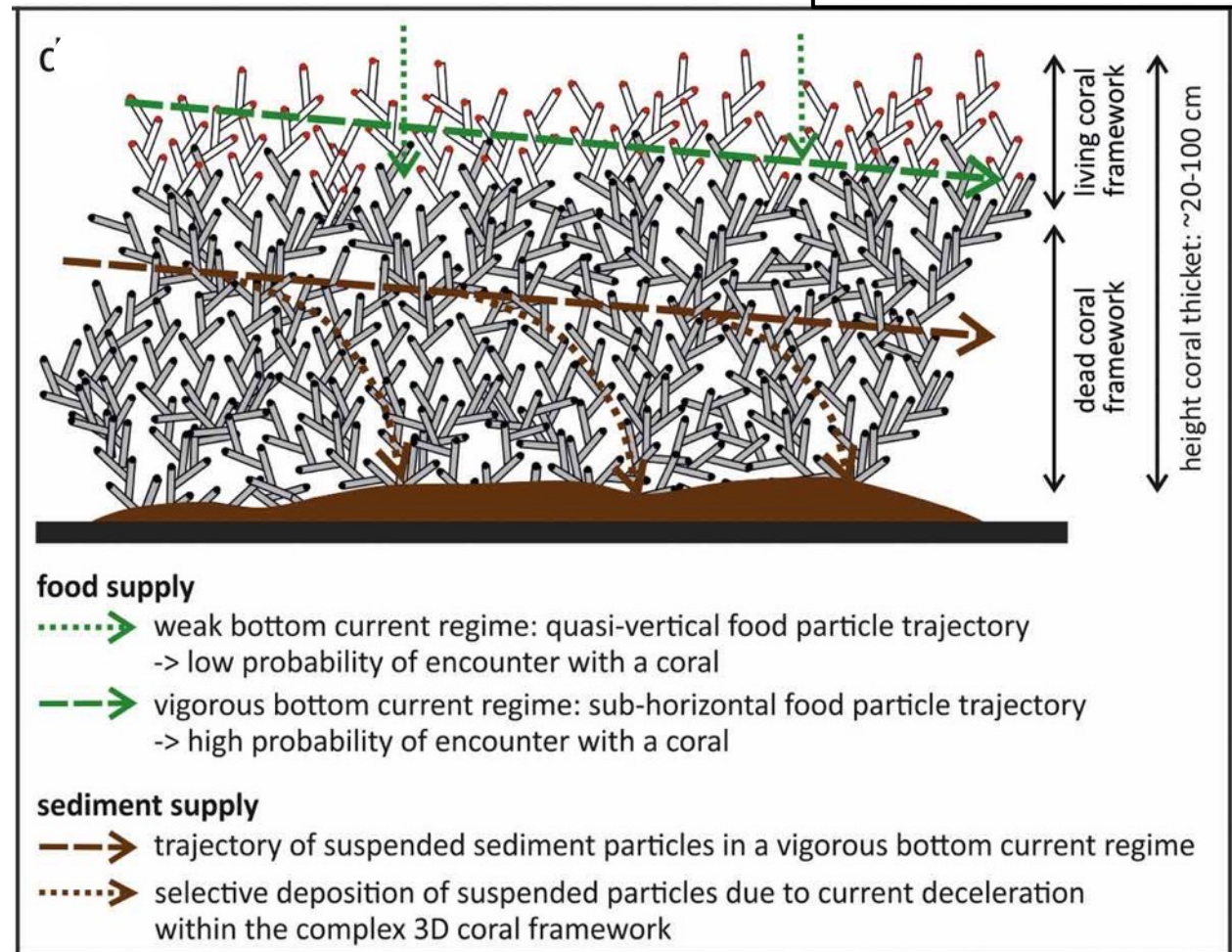




Bottom currents are one important factor controlling deep-water ecosystems. The likelihood for a coral to catch **food particles** sinking through the water column is appreciably enhanced when their trajectory is sub-horizontal in response to the action of a sideways bottom current flow. Currents also help promoting **hardground** substrates eventually suitable for coral colonization, limit excess silting, and help coral **dissemination** over long distances (Rebesco & Taviani, 2016)

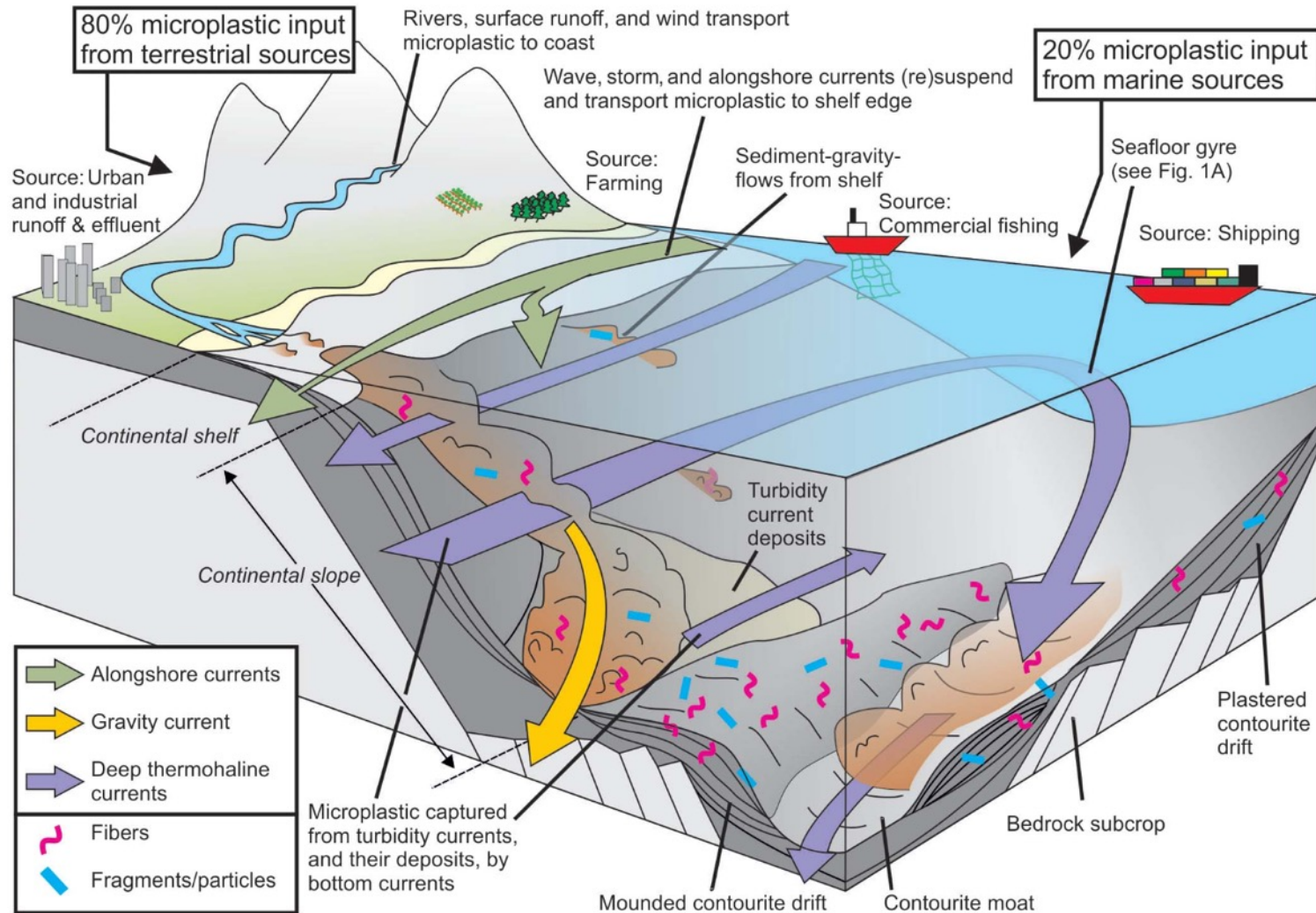
## Significance for the ecological health of deepwater ecosystems

Hebbeln et al. (2016)

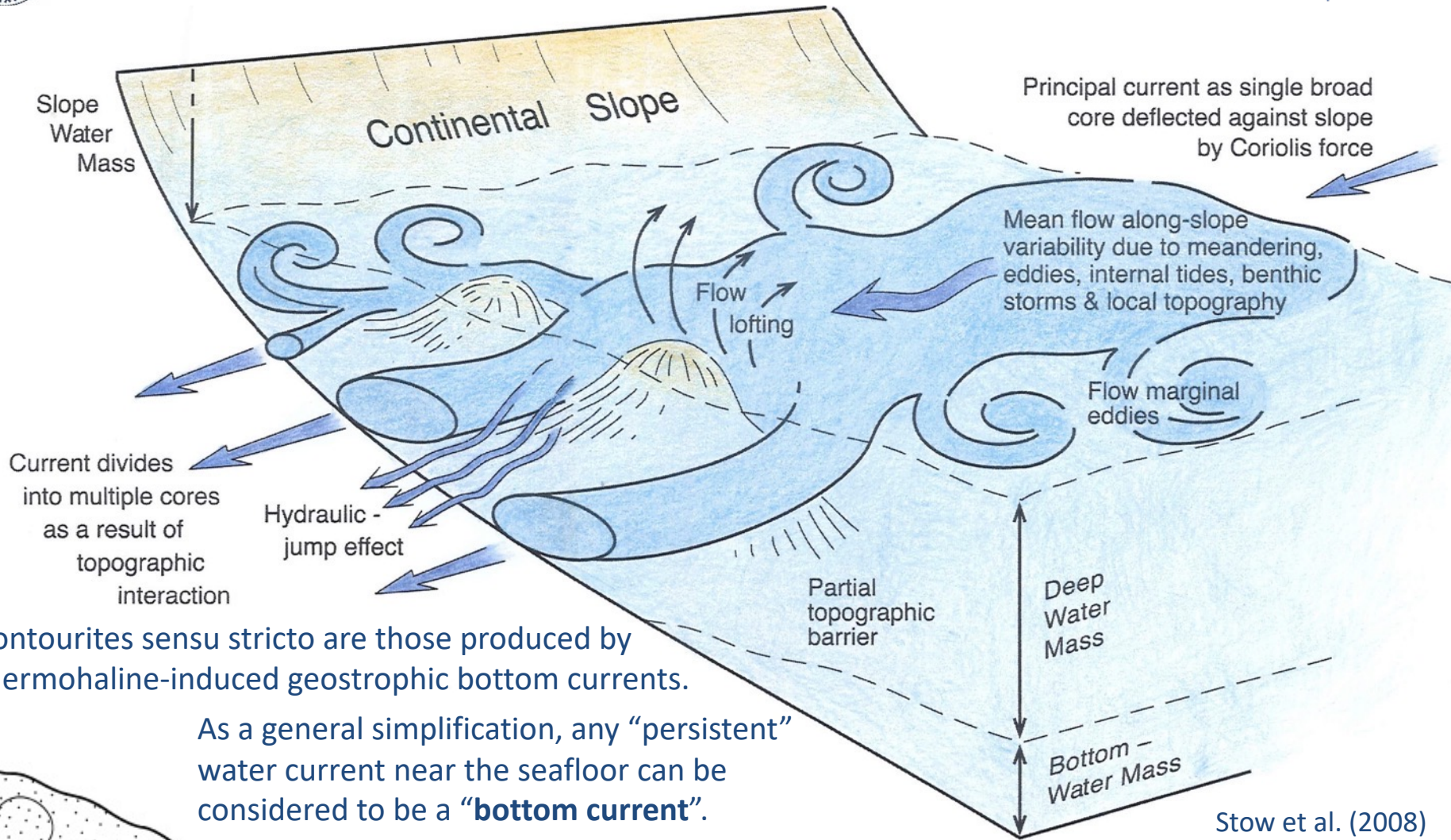


## Significance for accumulation of microplastics and contaminants

Thermohaline-driven currents, which build extensive seafloor sediment accumulations, can control the distribution of microplastics and create hotspots with the highest concentrations reported for any seafloor setting (Kane et al., 2020)



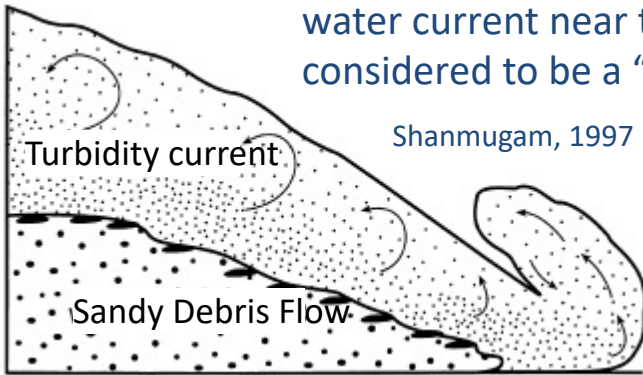




Stow et al. (2008)

Contourites sensu stricto are those produced by thermohaline-induced geostrophic bottom currents.

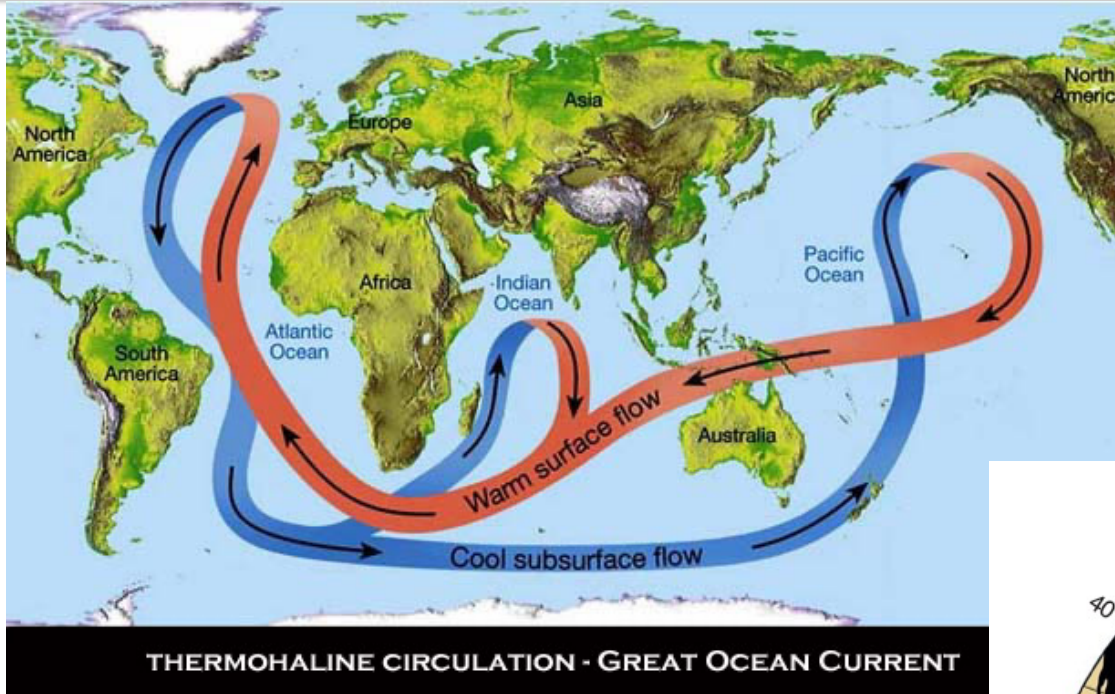
As a general simplification, any “persistent” water current near the seafloor can be considered to be a “**bottom current**”.



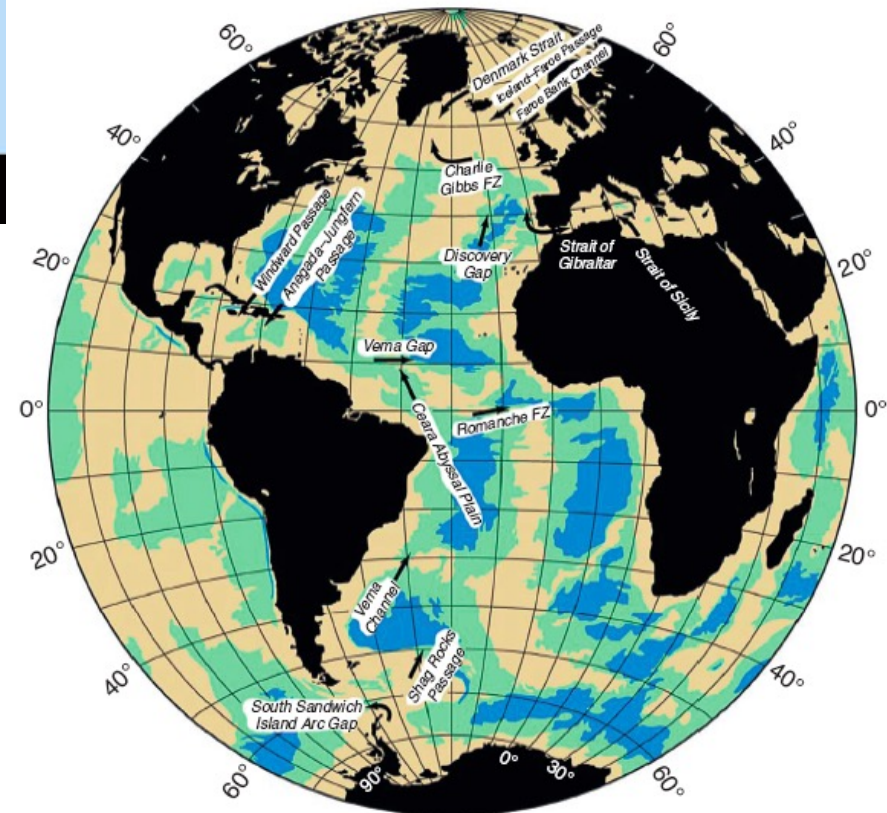
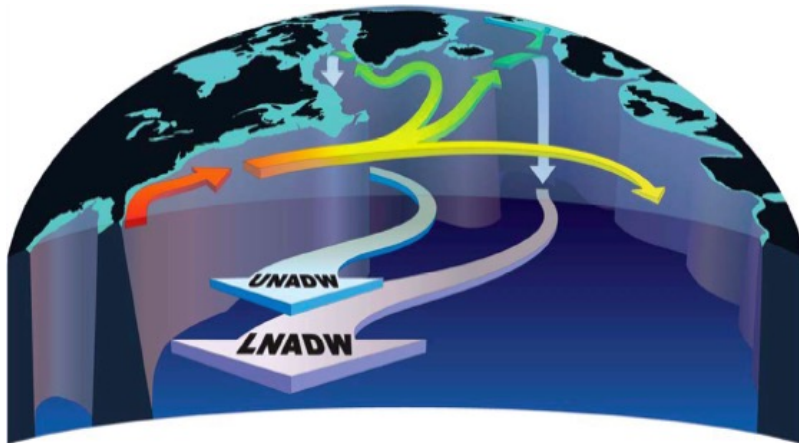
Shanmugam, 1997

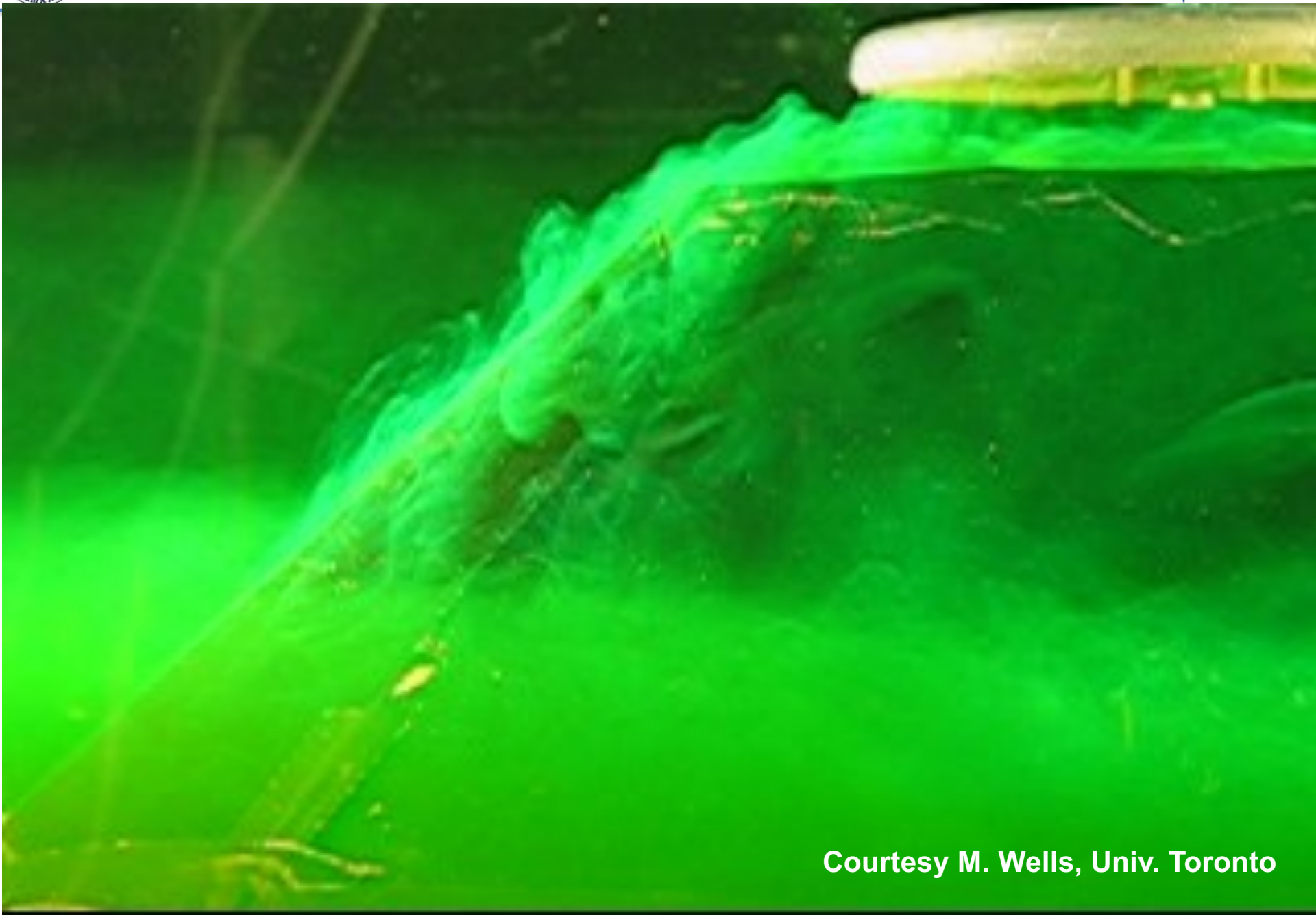
In addition, a number of associated processes are: benthic storms; overflows; interfaces between water masses; vertical eddies; horizontal vortices; tides and internal tides; internal waves and solitons; tsunami related traction current and rogue or cyclonic waves.





# Thermoaline circulation

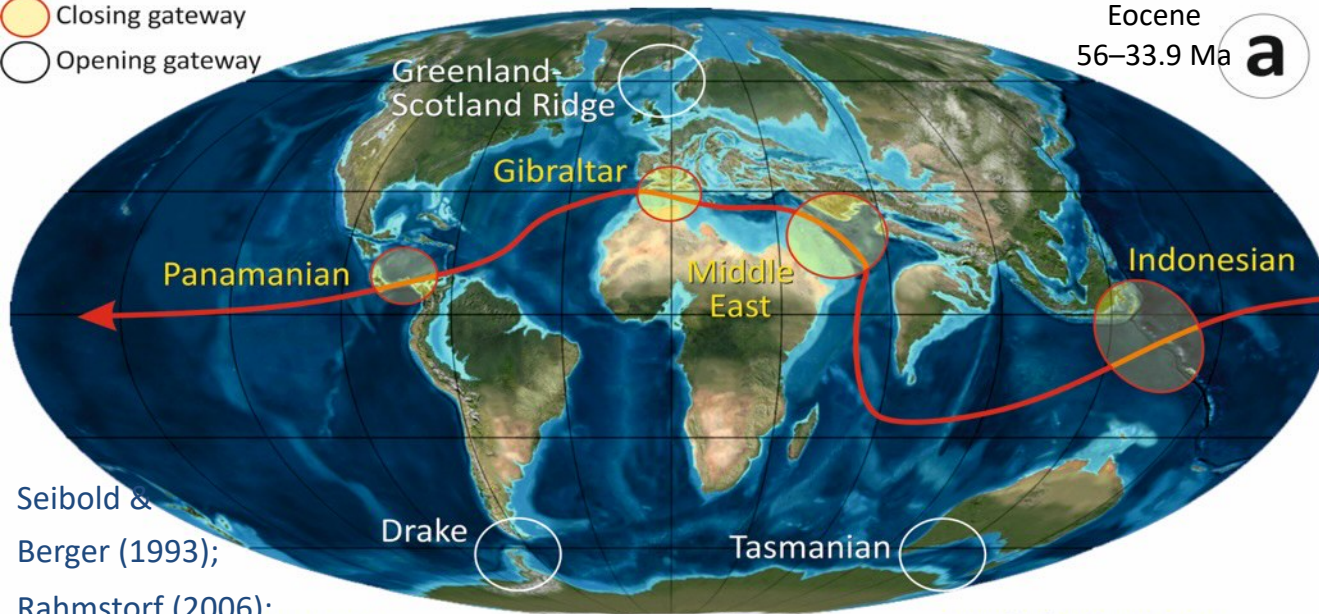






- Closing gateway
- Opening gateway

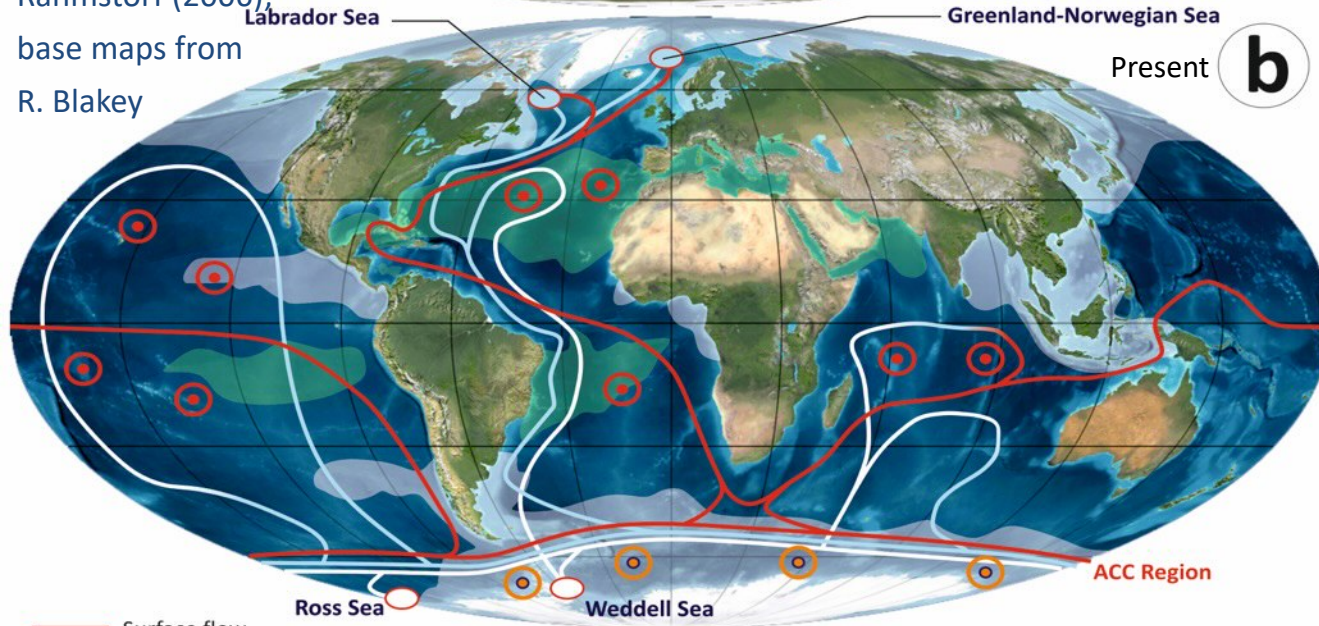
Eocene  
56–33.9 Ma **a**



Seibold & Berger (1993);  
Rahmstorf (2006);  
base maps from  
R. Blakey

The deep waters of the oceans are primarily formed in marginal seas or shallow shelf regions where cooling and/or ice formation makes the water cold and dense, or strong evaporation makes the water highly saline. The relatively dense water thus formed flows out into the ocean via narrow or shallow straits or over the continental margin, steered to the right (in the Northern Hemisphere) by Earth's rotation. When it is no longer constricted by the topography it reshapes into a wider structure, and adjusts under the forces of gravity, Earth's rotation, and bottom friction.

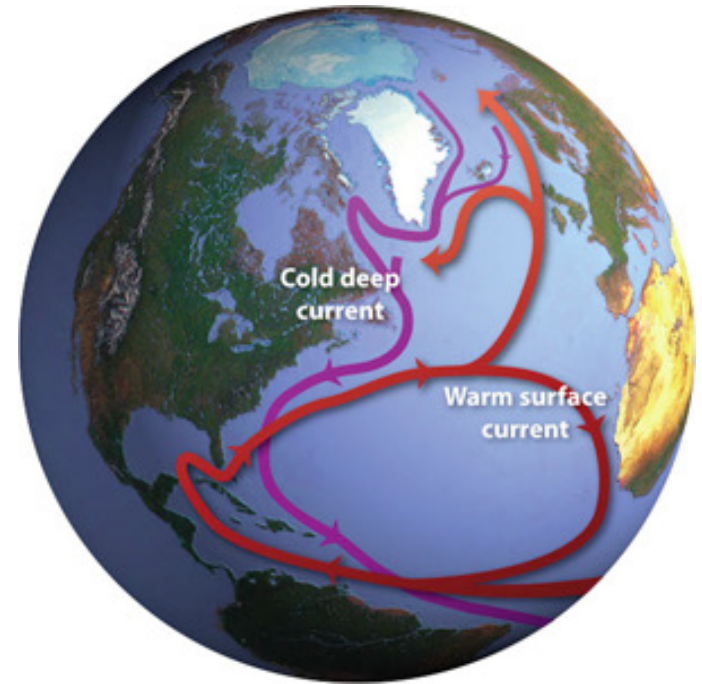
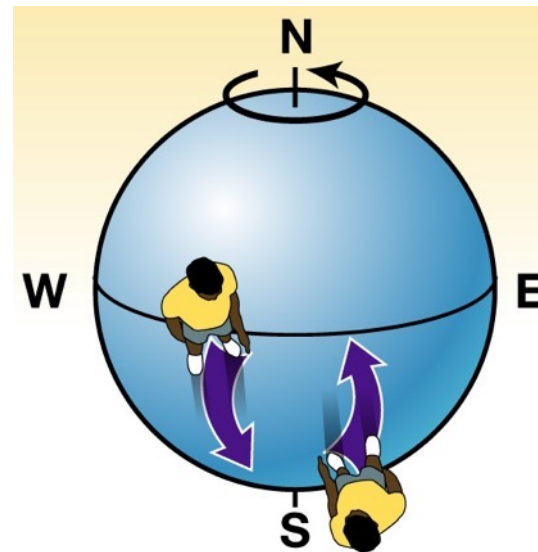
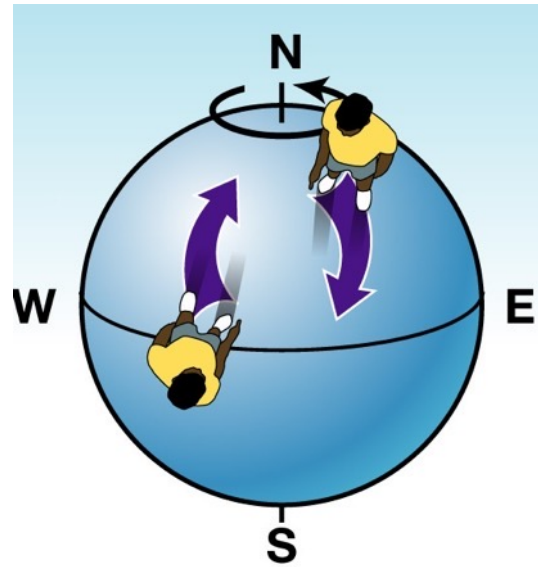
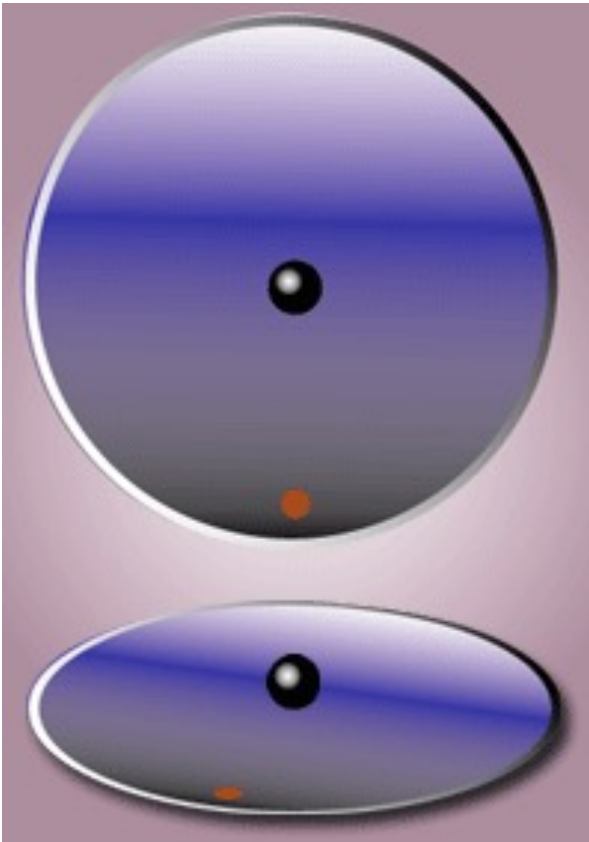
Present **b**



- Surface flow
- Deep flow
- Bottom flow
- Deep Water Formation (NH)
- Deep Water Formation (SH)
- Wind-driven upwelling
- Mixing-driven upwelling
- Salinity > 36 ‰
- Salinity < 34 ‰

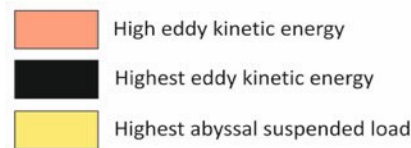
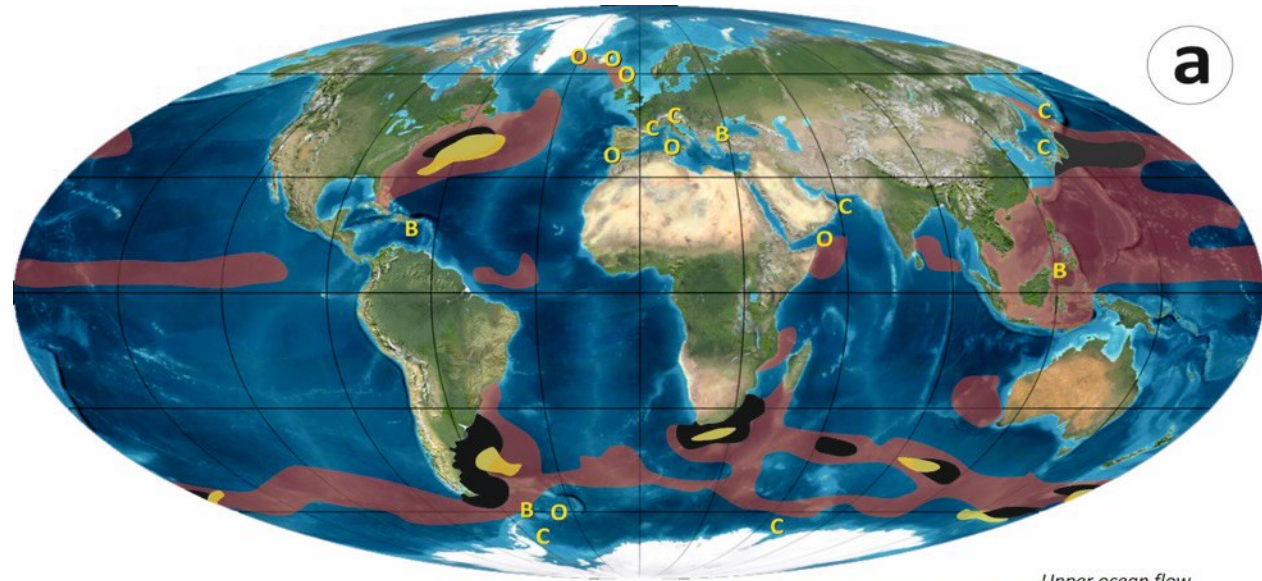


# Coriolis effect

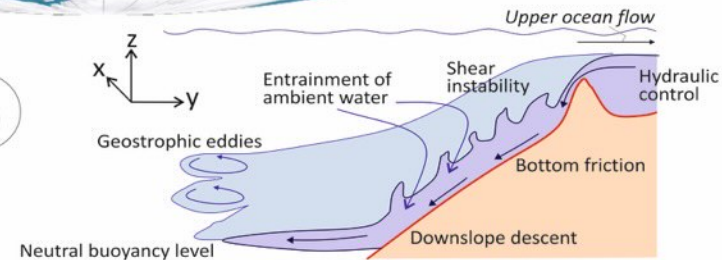


In physics, the Coriolis effect is a deflection of moving objects when they are viewed in a rotating reference frame

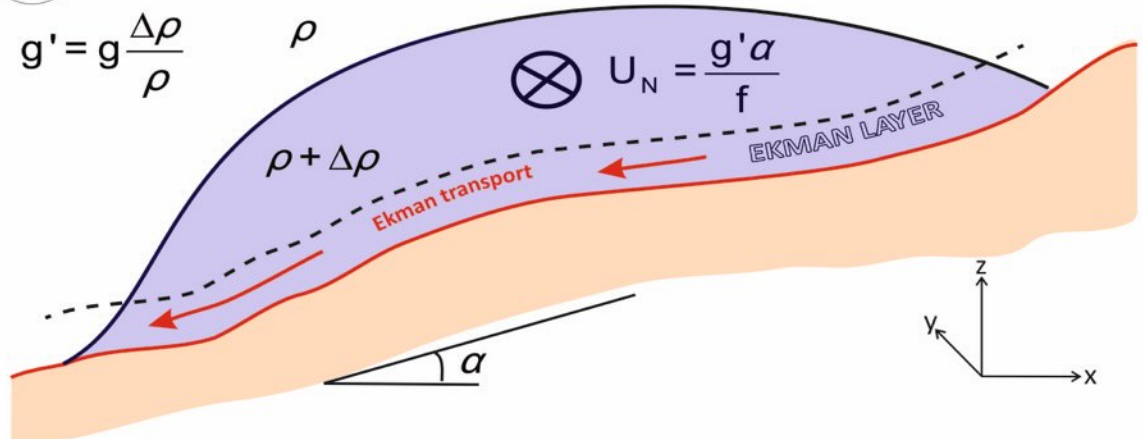
a) Map showing the relationship between kinetic energy and suspended load (Legg et al., 2009, base map from R. Blakey). O: Overflow; B: Open-ocean overflow; C: Cascading. b) Physical processes acting in overflows. c) Sketch of a dense overflow showing the coordinate System and some of the notations used (ambient density:  $\rho$ ; plume density:  $\rho + \Delta\rho$ ; reduced gravity:  $g'$ ; bottomslope:  $\alpha$ ; Coriolis parameter:  $f$ ; and Nof velocity:  $U_N$ ). Also shown are the Ekman layer and the benthic Ekman transport.



**b**

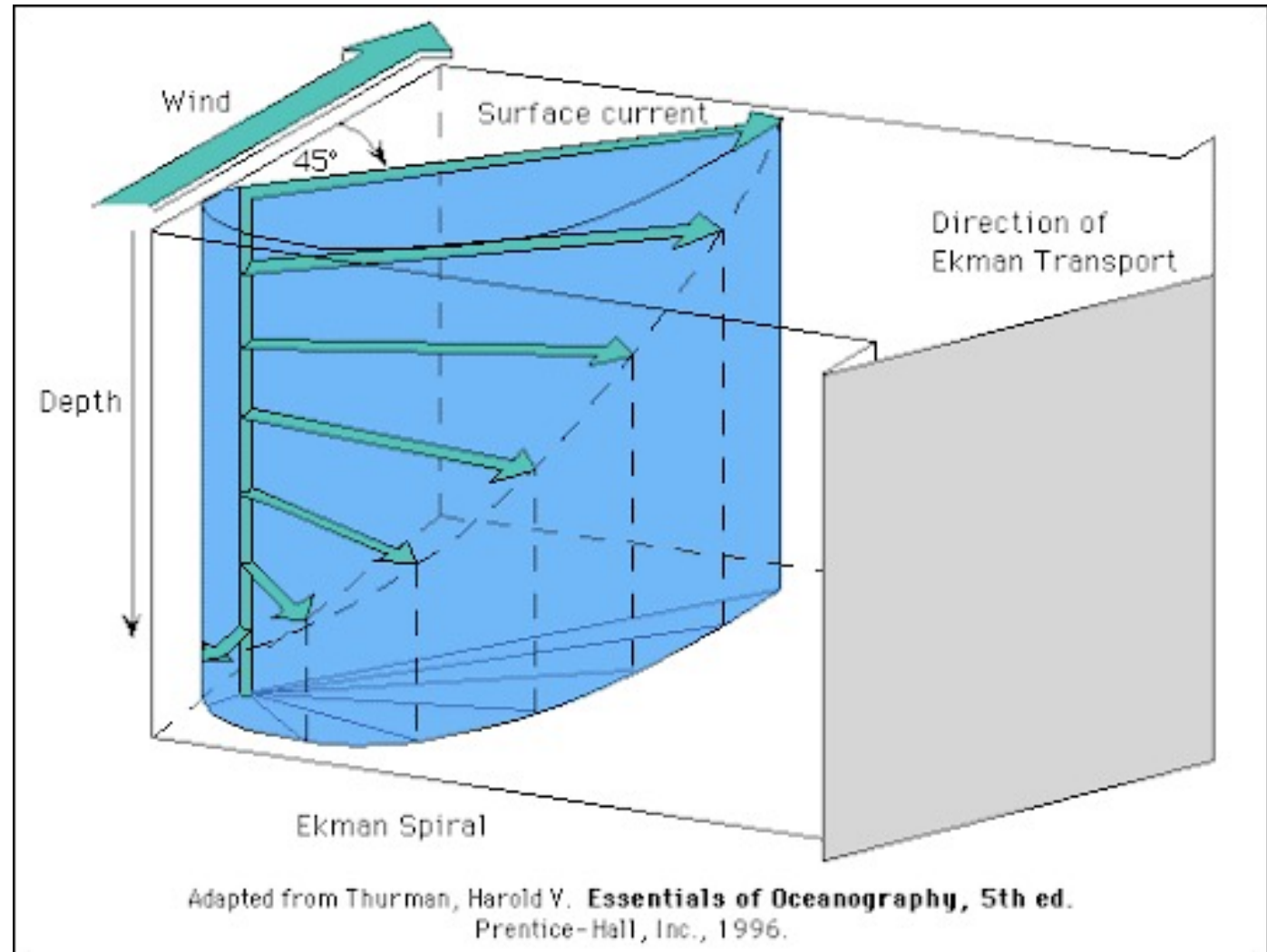


**c**

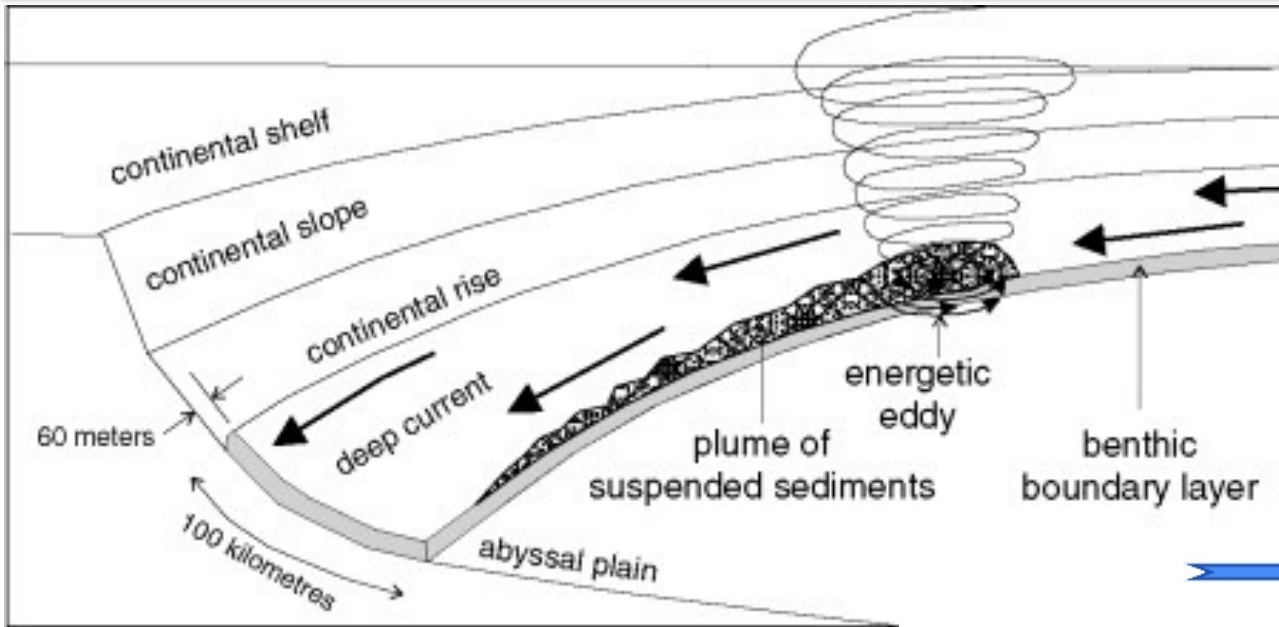


# Ekman layer

The Ekman layer is the layer in a fluid where the flow is the result of a balance between pressure gradient, Coriolis and turbulent drag forces. In the picture above, the wind blowing North creates a surface stress and a resulting Ekman spiral is found below it in the column of water.

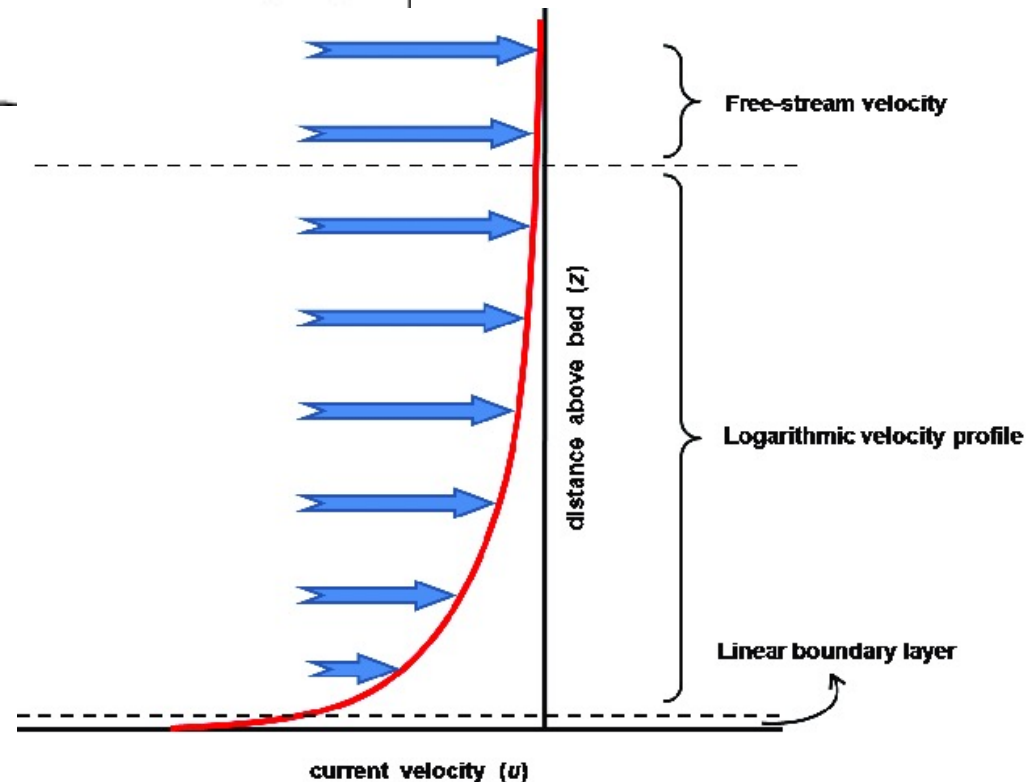






# Benthic boundary layer

The benthic boundary layer (BBL) is the layer of water directly above the sediment at the bottom of a body of water. It is generated by the friction of the water moving over the surface of the substrate.

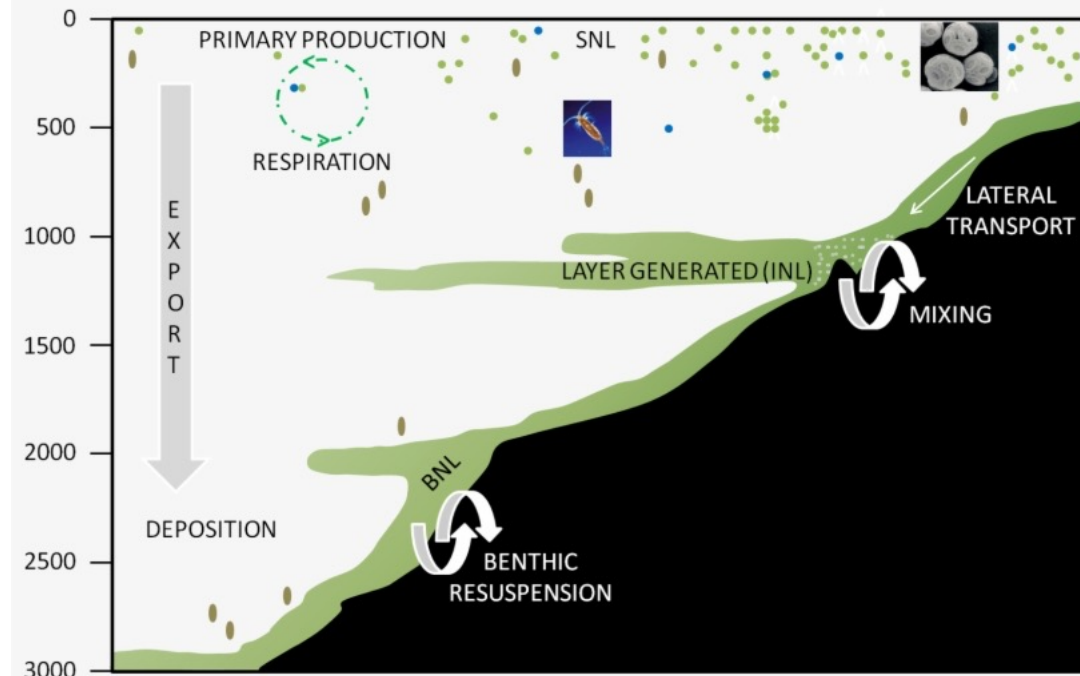


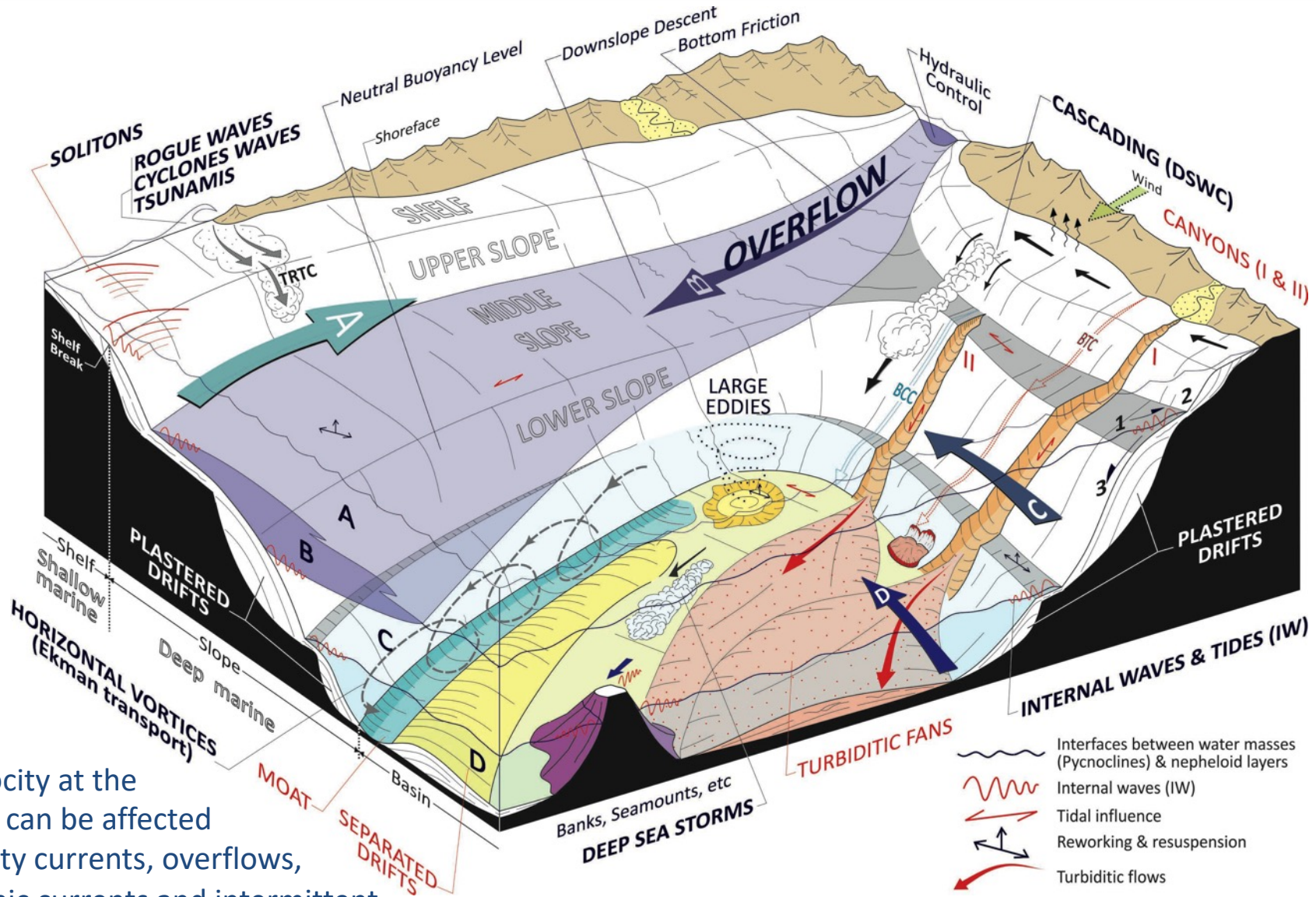
# Nepheloid layers

Nepheloid layers (NLs) are zones of increased turbidity relative to waters above and/or below in the oceans. NL thickness is mainly in the range 50–1000 m. The turbidity is conferred by particulate matter and most commonly detected by light scattering or attenuation (hence 'nepheloid' meaning cloudy). Most material in NLs is produced by resuspension of bottom sediments, often on continental margins, and also from ridges and seamounts, due to bottom shear stress from thermohaline currents and internal waves and tides.

Resuspended material is diffused upward in bottom mixed layers which periodically separate and spread away from their source. As they spread they lose particles through aggregation and sinking of larger particles. This confers a generally decreasing turbidity upward from the ocean bottom because higher layers have usually separated farther away.

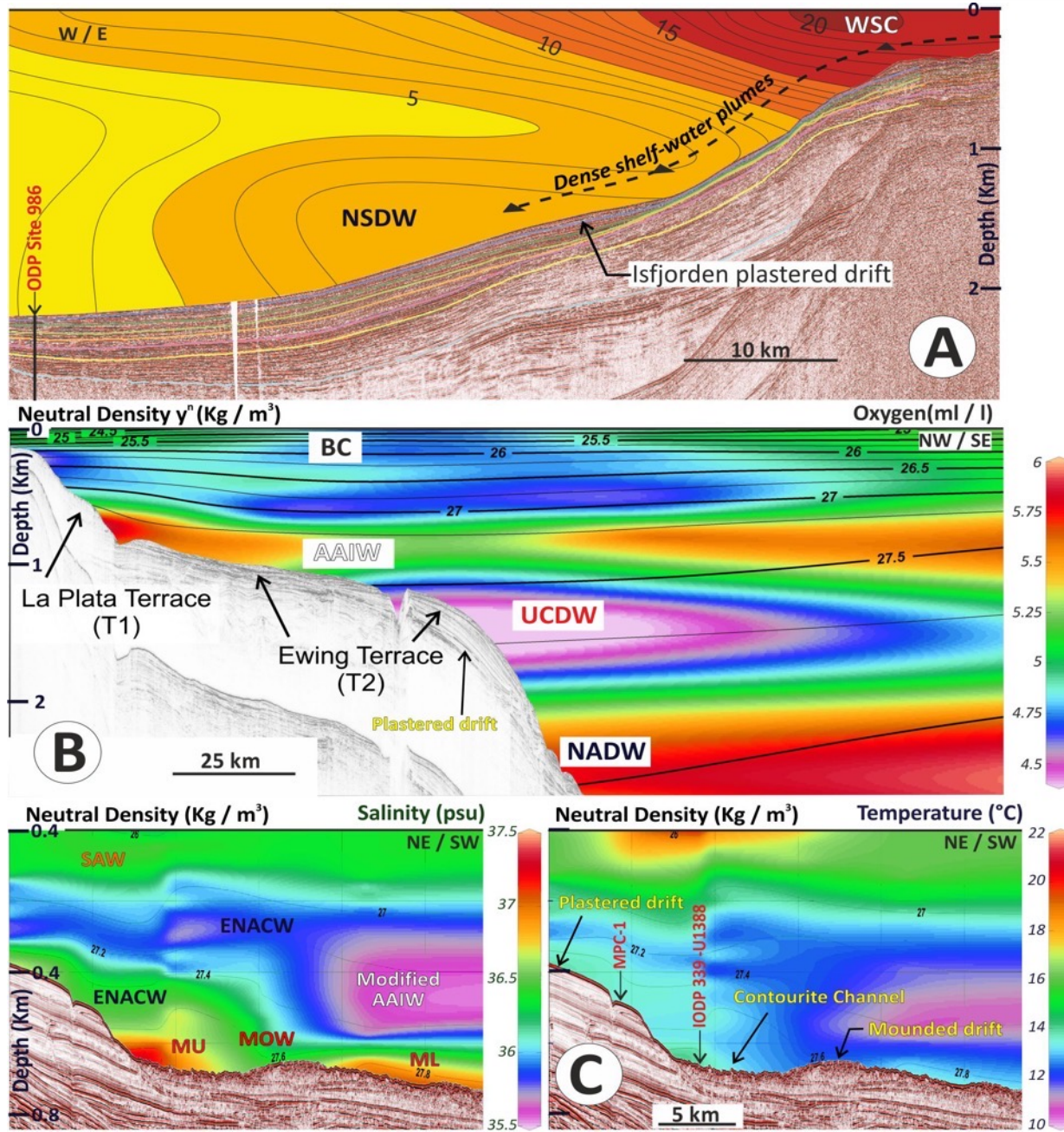
McCave, in Encyclopedia  
of Ocean Sciences, 2009





The velocity at the seafloor can be affected by density currents, overflows, barotropic currents and intermittent processes (cascading, giant eddies, deep sea storms, vortices, internal waves, internal tides, tsunamis, cyclone waves, and rogue waves)



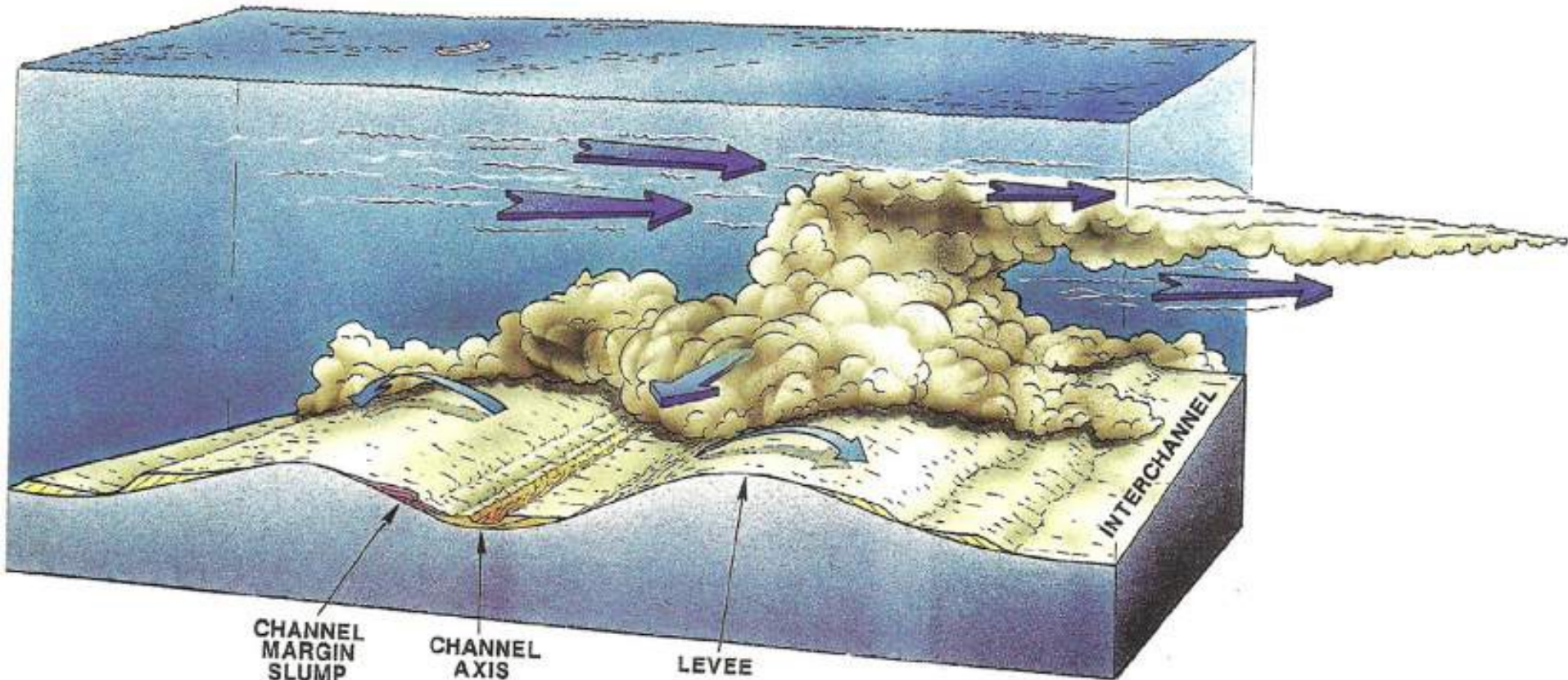


Examples of combining physical oceanographic data with geologic/geophysical data, showing the relationship amongst the long-term current regime, the seafloor morphology and the sub-bottom sediment geometry. A) Western Spitsbergen margin (Rebesco et al., 2013); B) Argentine margin, North of the Mar del Plata Canyon (Preu et al., 2013); and C) Gulf of Cádiz, from the exit of the Strait of Gibraltar (Hernández-Molina et al., 2014).

The black numbers and lines in (A) refer to current velocity (cm/s), but in (B) and (C) they refer to isopycnals and neutral density ( $\text{kg/m}^3$ ).



# Sediment entrainment



CHANNEL  
MARGIN  
SLUMP

CHANNEL  
AXIS

LEVEE

INTERCHANNEL

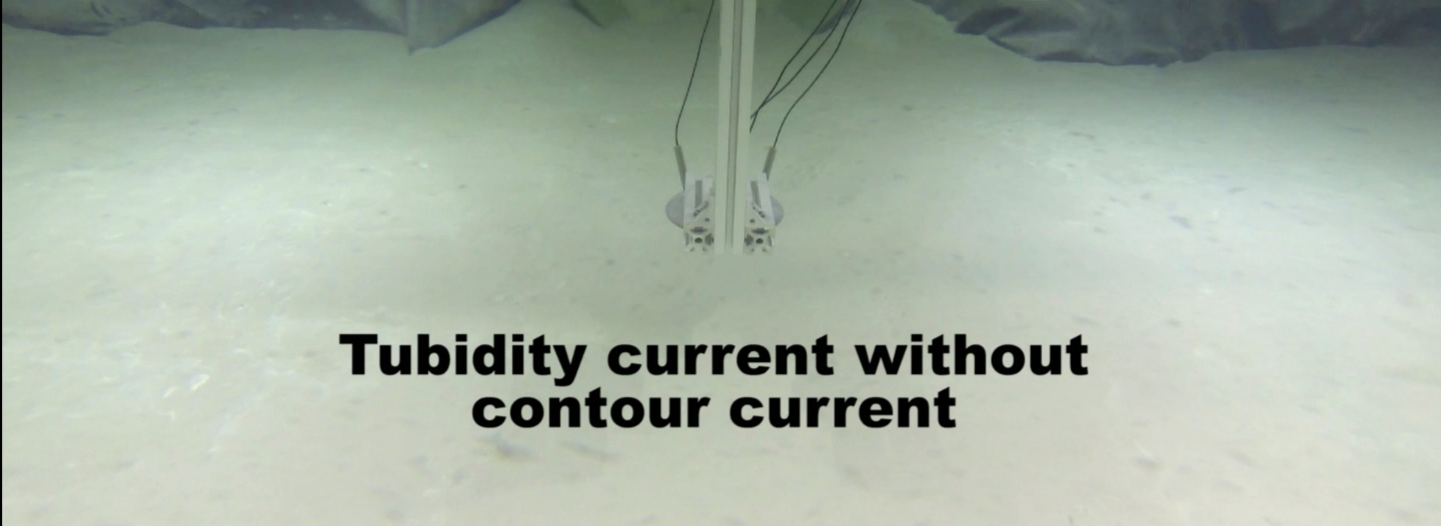
(Shanmugam et al., 1993a)



AXIAL TURBIDITY CURRENTS

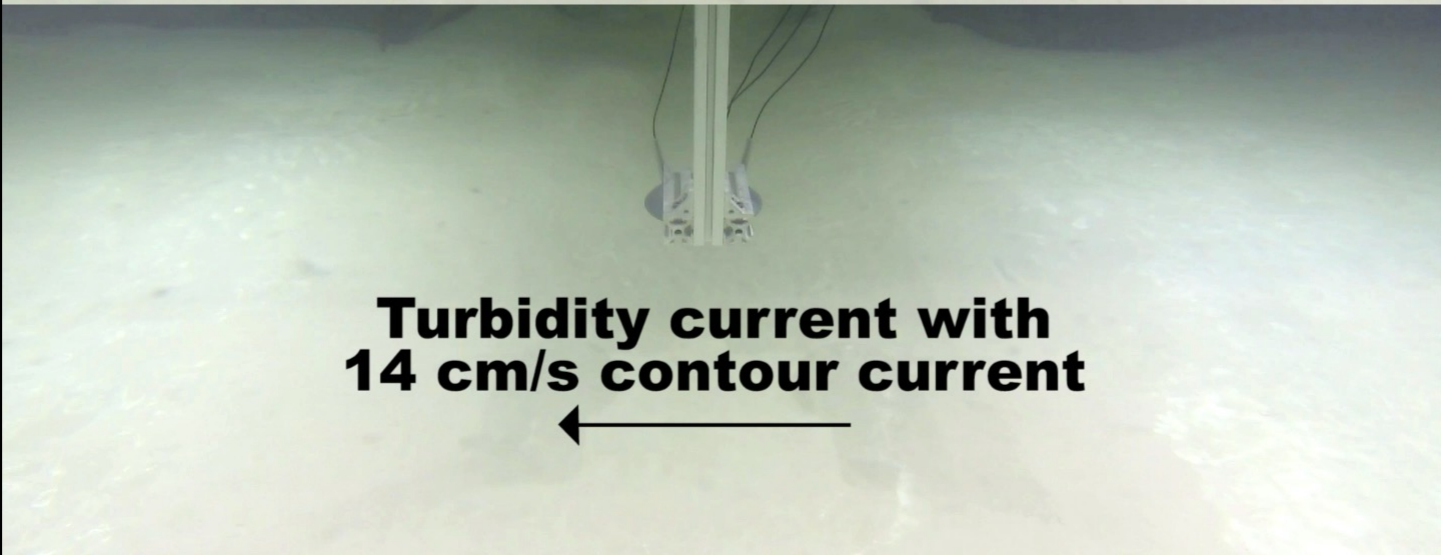
OVERBANK "TURBIDITY" CURRENTS

CONTOUR CURRENTS (BOTTOM CURRENTS)



**Turbidity current without  
contour current**

This image shows a turbidity current in a tank. A central vertical rod with a sensor at the bottom is visible. The water is clear, and the turbidity current is a faint, diffuse plume of sediment moving horizontally across the bottom of the tank.



**Turbidity current with  
14 cm/s contour current**

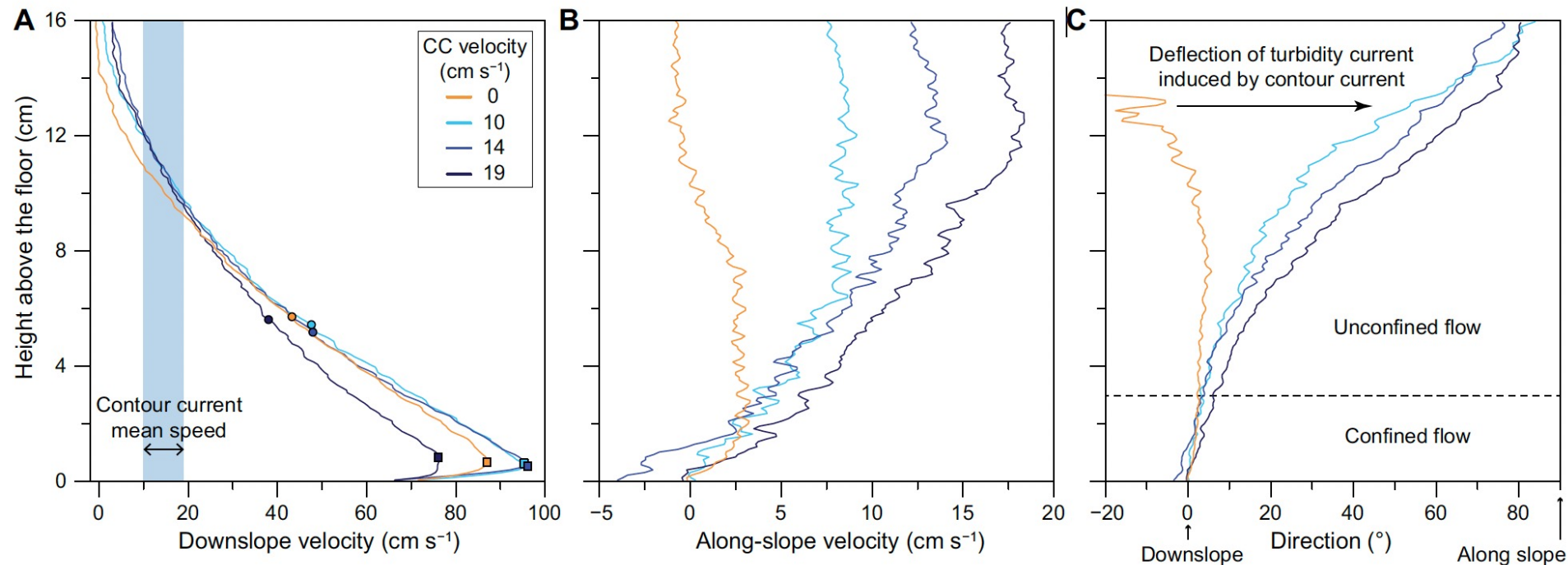
This image shows a turbidity current in a tank, similar to the one above. A central vertical rod with a sensor at the bottom is visible. The water is clear, and the turbidity current is a faint, diffuse plume of sediment moving horizontally across the bottom of the tank. A black arrow points to the left, indicating the direction of the contour current.

video of a turbidity current during two experiments: a turbidity current flowing in standing water without a contour current (A); and a turbidity current interacting with a contour current of  $14 \text{ cm s}^{-1}$  (B). The UDOP 4000 velocimeter, used to measure velocity profiles during experiments, can be observed in the center of the images



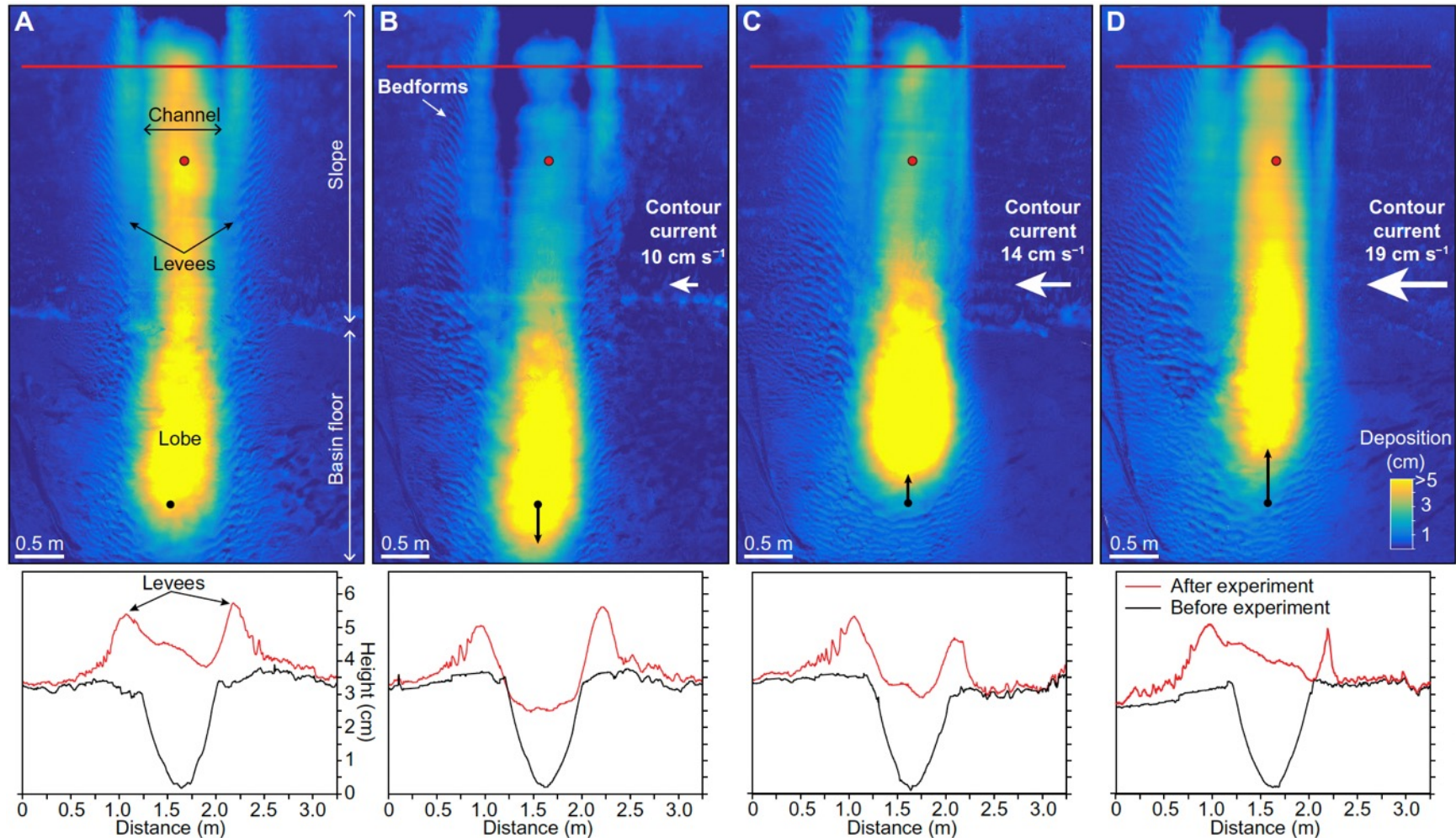
# Velocity profiles and deflection

(A) Time-averaged downslope velocity profile for all experiments. Squares represent maximum velocity of turbidity currents, and circles represent flow thickness, which is here defined as the height at which the velocity is half the velocity maximum. Vertical light-blue band indicates the range of mean contour current speed used in the experiments (10–19 cm s<sup>-1</sup>). (B) Time-averaged, along-slope velocity profile for all experiments. (C) Time-averaged direction of turbidity current for each experiment. CC—contour current.



## Deposition maps and cross sections during experiments of turbidity currents.

Red lines represent location of cross sections. Red dot represents the point of current velocity measurements. Black dots and black arrows represent how the frontal part of the deposit with sediment deposition  $>5$  cm was displaced compared to the experiment in standing water. In the cross sections, black and red lines indicate the profile before and after the experiment, respectively.





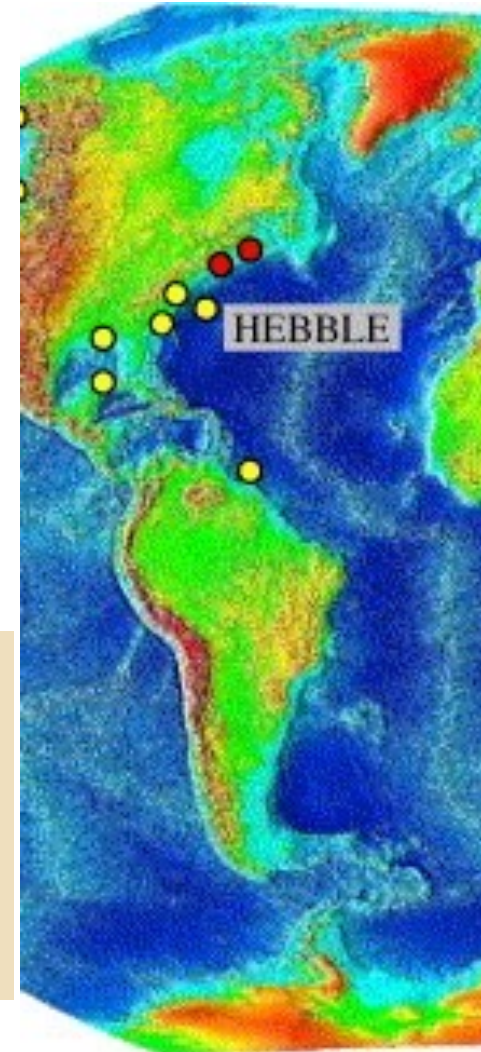


# Benthic Storms

Hollister and Nowell (1991)  
HEBBLE epilogue. Marine  
Geology, 99 445-460

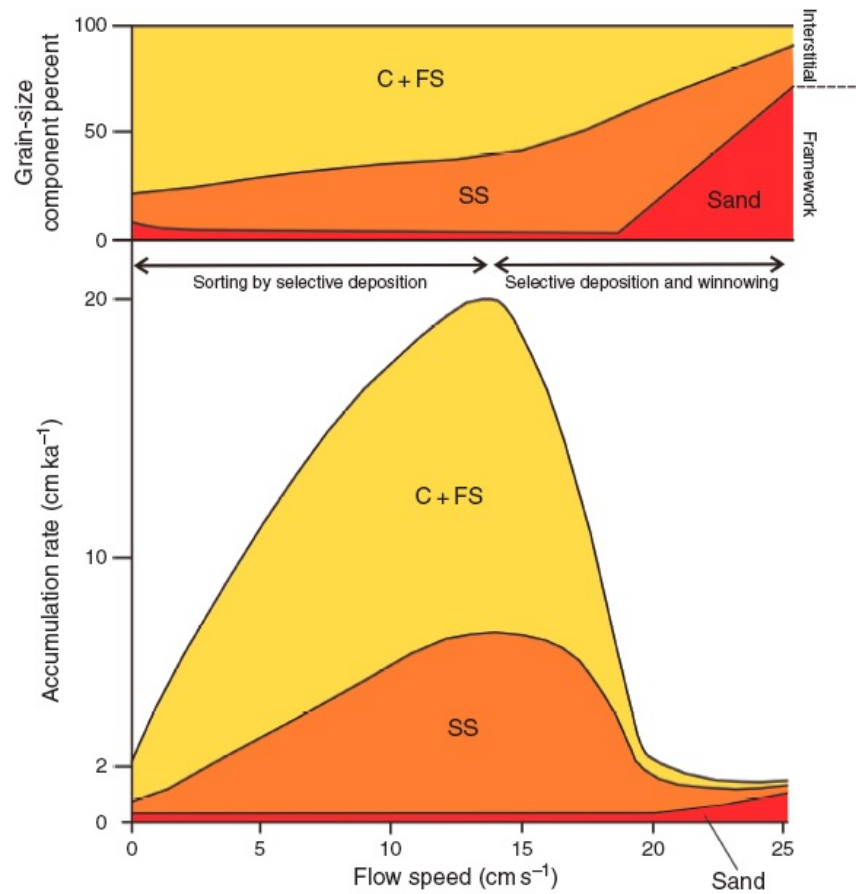
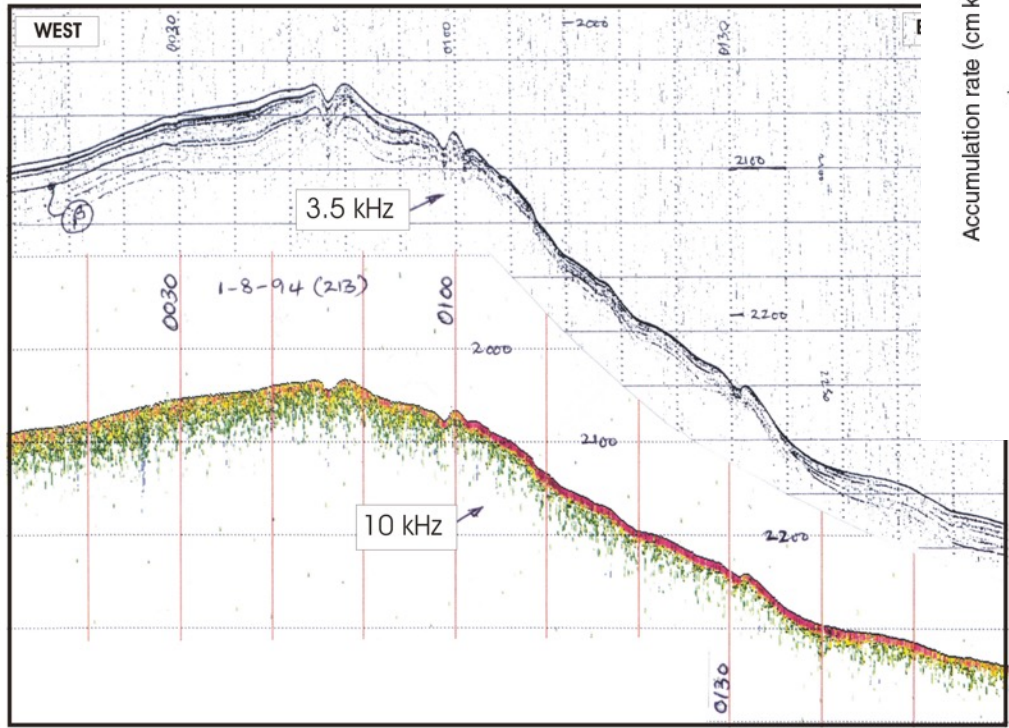
## Benthic storm characteristics in the HEBBLE area

Duration	2–20 days (most last about 3–5 days)
Frequency	8–10 storms per year
Maximum velocities measured 10–50m above bottom	15–40 cm/s
Maximum concentrations 1–5m above bottom	3500–10 000m g/l
Direction of highest energy events	Westerly, parallel to contours
Estimated sediment flux rates during storms	20–200 cm <sup>3</sup> /m <sup>2</sup> per day





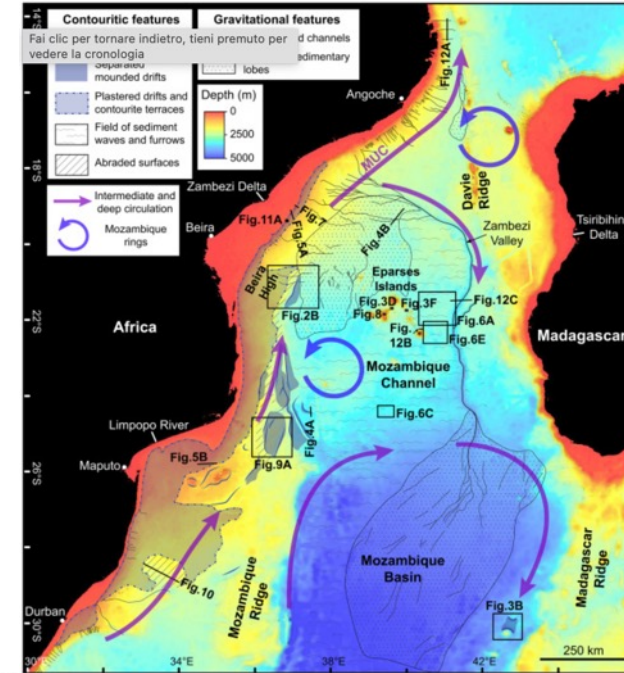
Sediment properties vary over mud waves because flow near the bed is strongly controlled by local topography. Mud waves can be either like dunes migrating in the direction of flow, or, more commonly, like anti-dunes responding to in-phase lee-wave disturbances in the stratified water column. In the latter case, the flow slows down on the upstream face, yielding a maximum deposition rate and speeds up over the downstream face, resulting in slower deposition or even erosion and coarser silt.



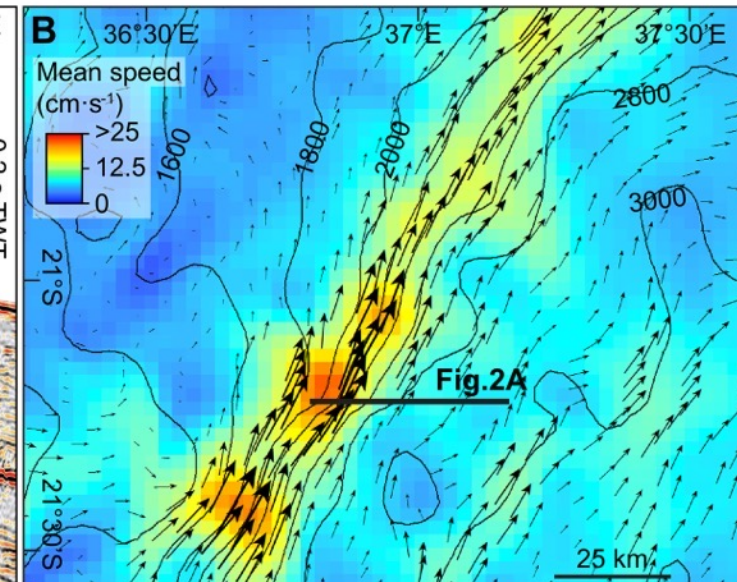
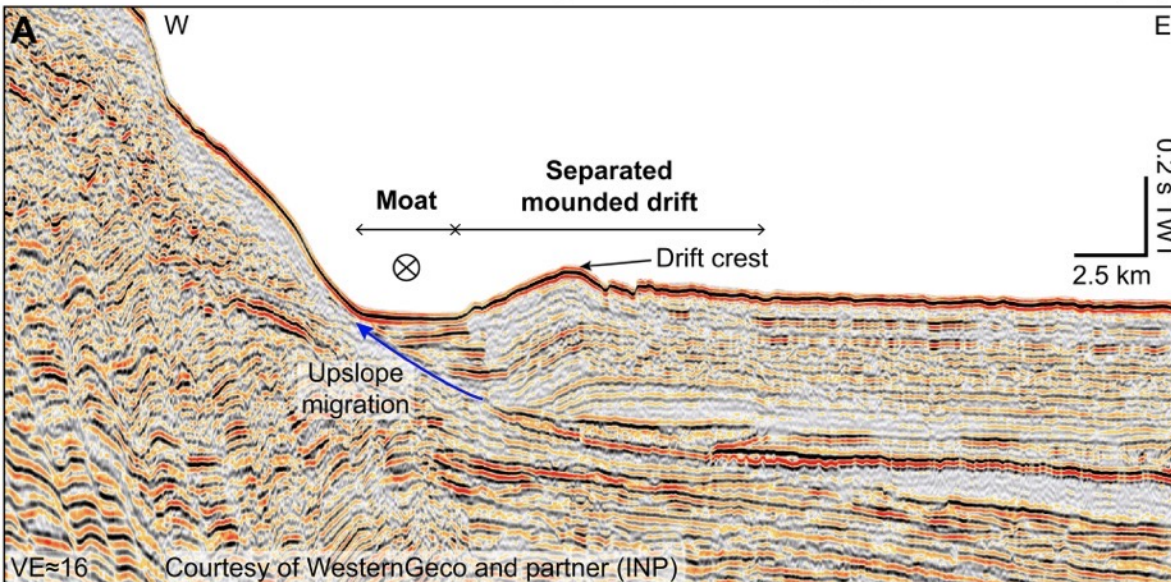
Deposits from currents

Link between geometry, sediment characteristics and modelled bottom currents, Mozambique Channel (Miramontes et al., 2021. Marine Geology 437, 106502.

Multi-channel seismic reflection profile showing a separated mound drift and a moat (courtesy of WesternGeco and partner. (B) Mean modelled bottom-current velocity at the foot of the Mozambican slope (modified from Thiéblemont et al., 2019).



**SEPARATED MOUNDED DRIFT and MOAT**





<b>Module</b>	<b>Topic</b>	<b>Teacher</b>	<b>Date</b>
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: 20 <sup>th</sup> October		
2.1	Sedimentary processes in river & deltas	Rebesco	24/10/22
	No lesson: 27 <sup>th</sup>		
2.2	Action of tides and waves, wind and ice	Rebesco	31/10/22
	No lesson: 3 <sup>rd</sup> 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: 14 <sup>th</sup> November		
3.2	Barrier systems and incised valleys	Rebesco	17/11/22
3.3	Continental shelves (waves, storms, tsunamis)	Rebesco	21/11/22
3.4	Mass transport deposits	Ford	24/11/22
3.5	Submarine fans (gravity flows on the continental slope)	Lucchi	27/11/22
3.6	Sediment drifts (bottom currents along the continental slope)	Rebesco	01/12/22
3.7	Abyssal plains (hemipelagic fallout) and continental margins	Rebesco	05/12/22
	No lesson on Thursday 8 <sup>th</sup> December		
3.8	Glacial depositional systems	De Santis	12/12/22
3.9	Carbonatic environments, faults, volcani	Rebesco	15/12/22
4.1	Sequence stratigraphy: introduction	Rebesco	19/12/22
	No lessons from 23 <sup>rd</sup> December to 8 <sup>th</sup> 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	13/01/23
6.2	Visit to OGS and SEISLAB (along with Geologia Marina)	Rebesco	20/01/23
6.3	Visit to CoreLoggingLAB (along with Geologia Marina)	Rebesco	27/01/23