Università di Trieste
LAUREA MAGISTRALE IN GEOSCIENZE
Curriculum Geologico Ambientale

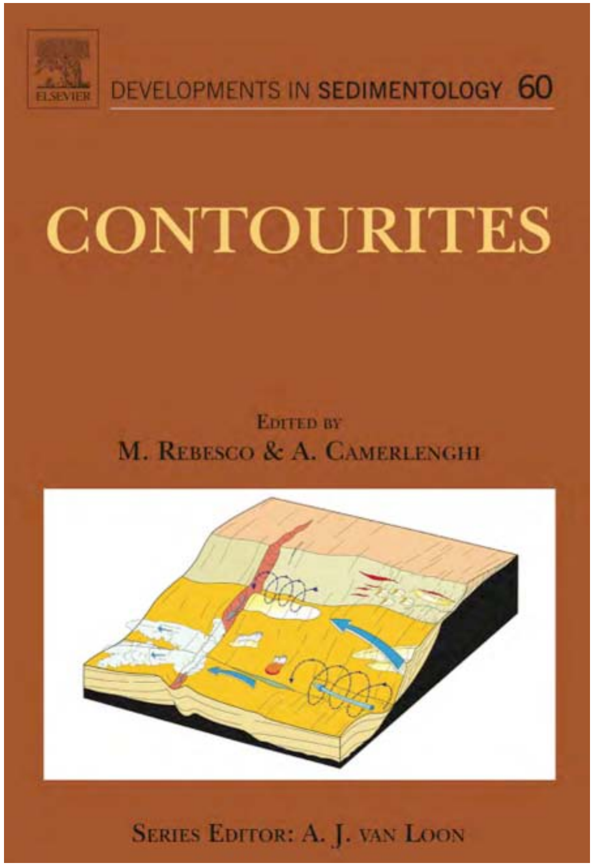
Anno accademico 2020 - 2021

Geologia Marina

<u>Parte III</u>

Modulo 3.2 Trasporto e deposizione per correnti di fondo
(*Alongslope processes*)

Docente
Michele Rebesco



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 50th 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

Michele Rebesco – OGS

Name:	**Michele Rebesco (mrebesco@inogs.it)**
Education:	**Phd in Earth Sciences in 1996 @University of Parma**
Years of experiences :	**30 years following M.Sc. Degree in geological sciences**
Current job title:	**Senior researcher, geophysics department**
My job in a few words:	**geological exploration of polar continental slopes**

Research and Academic or professional Experiences

- 30 years of experience as marine geologist in deep sea clastic sedimentary processes
- Editor-in-Chief of the journal "Marine Geology" since 2014 and previously editorial board member
- Professor at the University of Trieste for the Marine Geology course and Earth Science PhD course
- Chair of the Scientific Liaison Panel of the EU ARICE "Arctic Research Icebreaker Consortium"

An achievement I am willing to share

- Understanding along-slope versus down-slope and interacting sedimentary processes
- Evaluation of scientific manuscripts, research proposals and applications for marine survey and drilling

my personal interests outside work

- Travelling, Trekking, Climbing, Swimming, Reading…

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

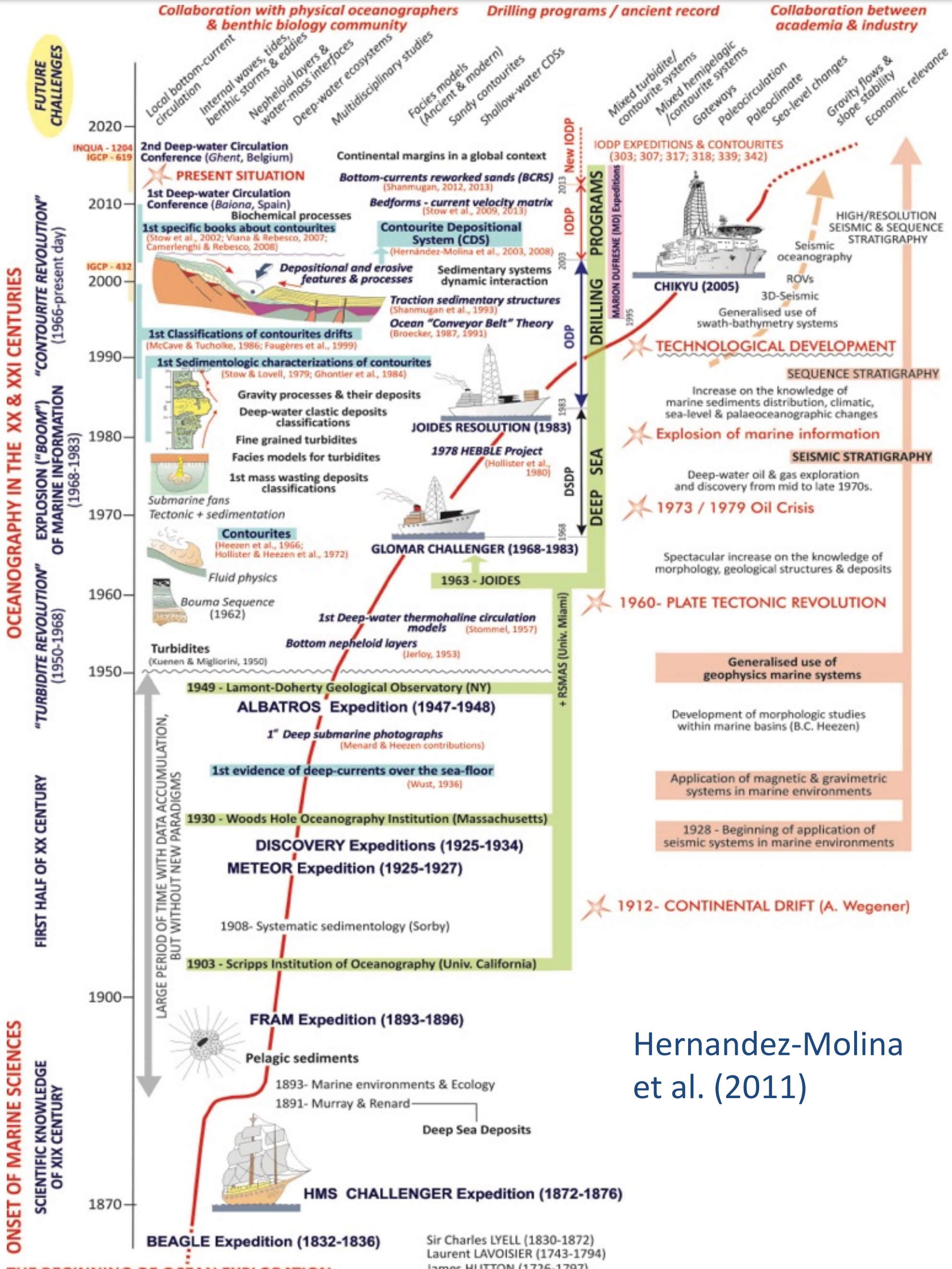
Sediment drift:
sediment body (sheeted or monded) produced by bottom currents.
Generally fine-grained, with large dimensions in many cases, typically separated from the slope by a moat

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.



Hernandez-Molina et al. (2011)

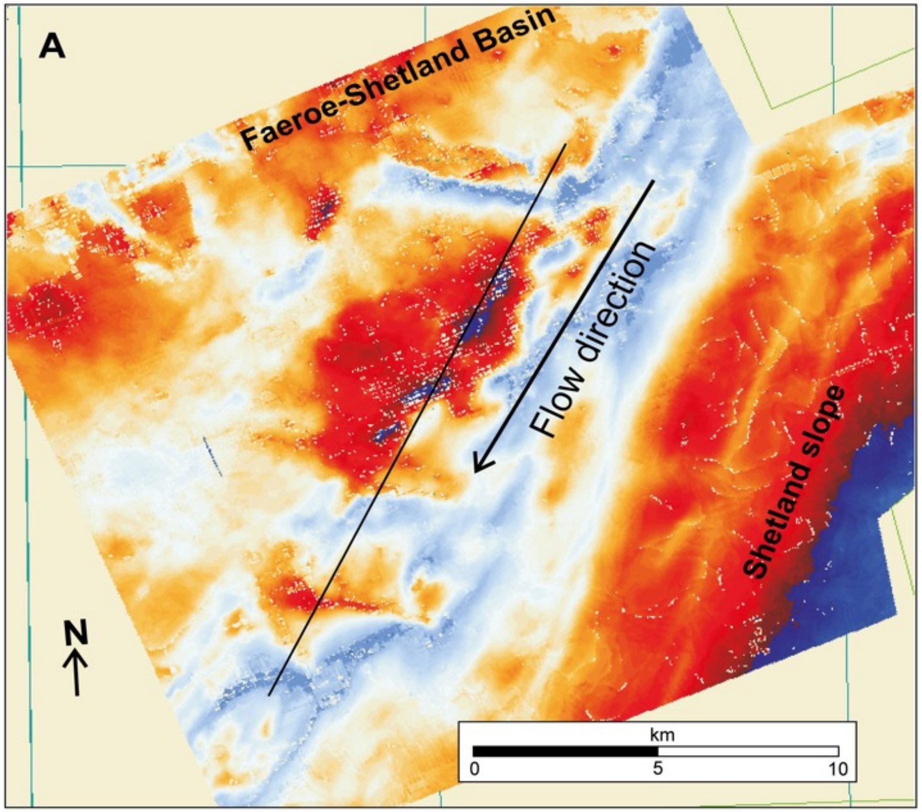
Evolution of knowledge

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

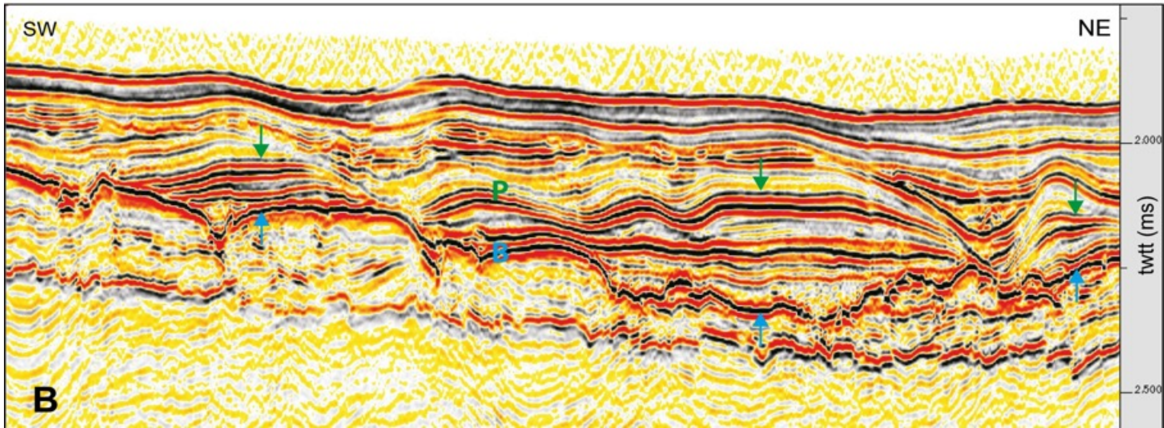
Though for many years associated research was the realm of a few specialists, contourites and bottom currents are of paramount importance in several areas of basic and applied research.

Significance for paloceanography (geophysics)

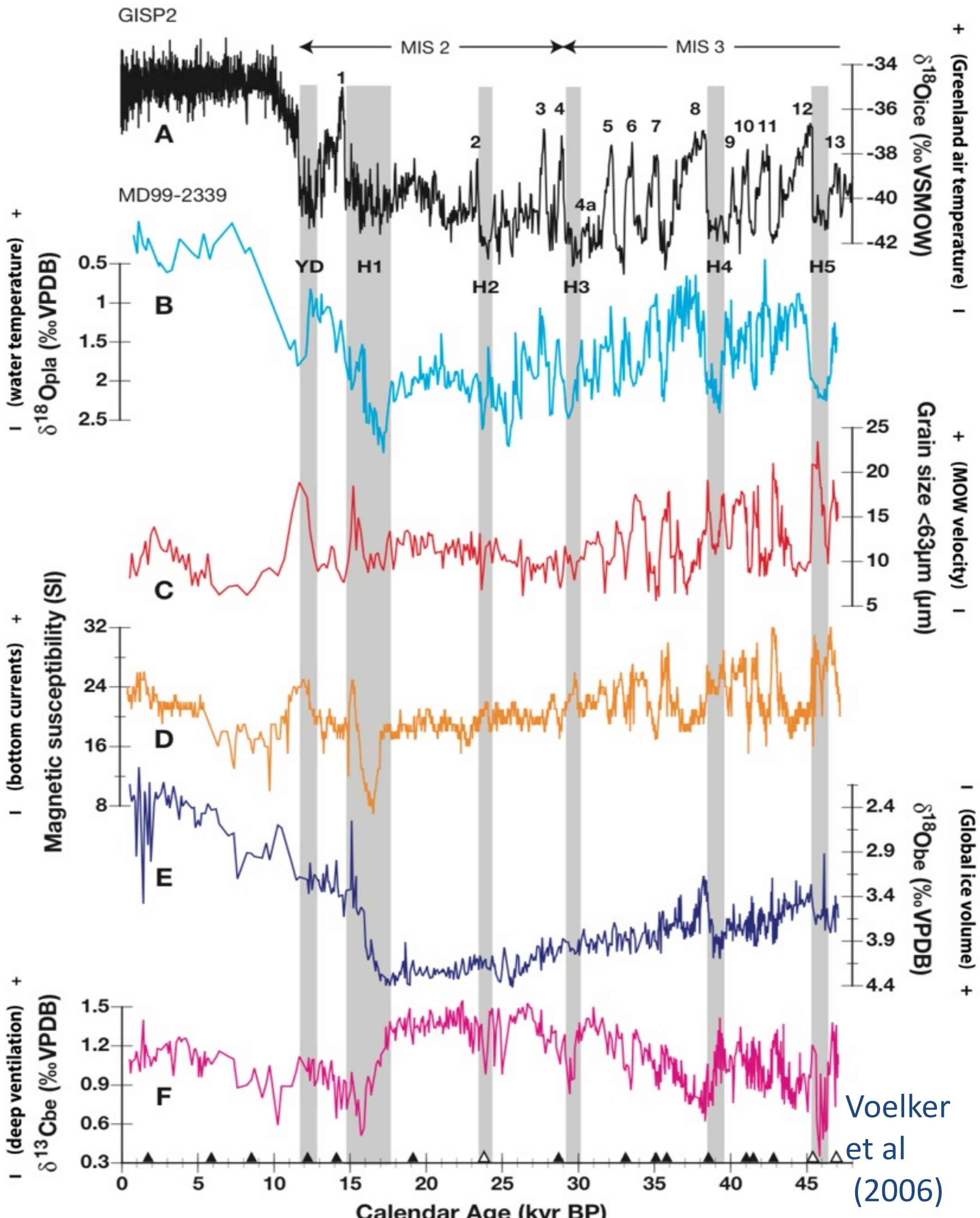
From contourite deposits, the history of ocean circulation and climate can be extracted using discrete sampling analyses (with geochemical, faunal, sedimentological techniques), continuous geophysical-chemical logging and seismic imaging. The latter allows to visualize drift geometry, internal reflections 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)



Significance for paloceanography (geology)



Voelker et al (2006)

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:

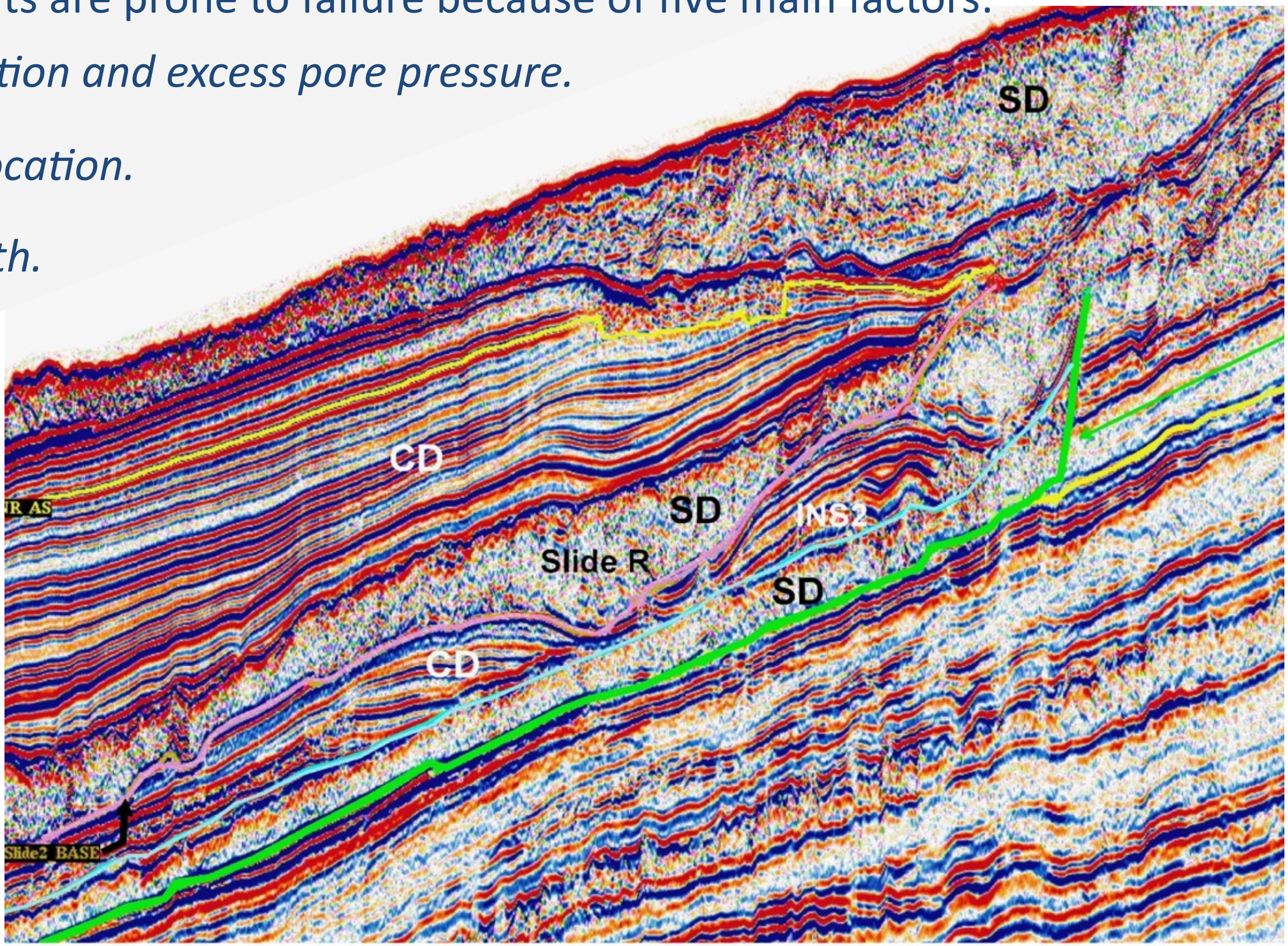
(a) under-consolidation and excess pore pressure.

(b) geometry and location.

(c) low shear strength.

(d) gas charging.

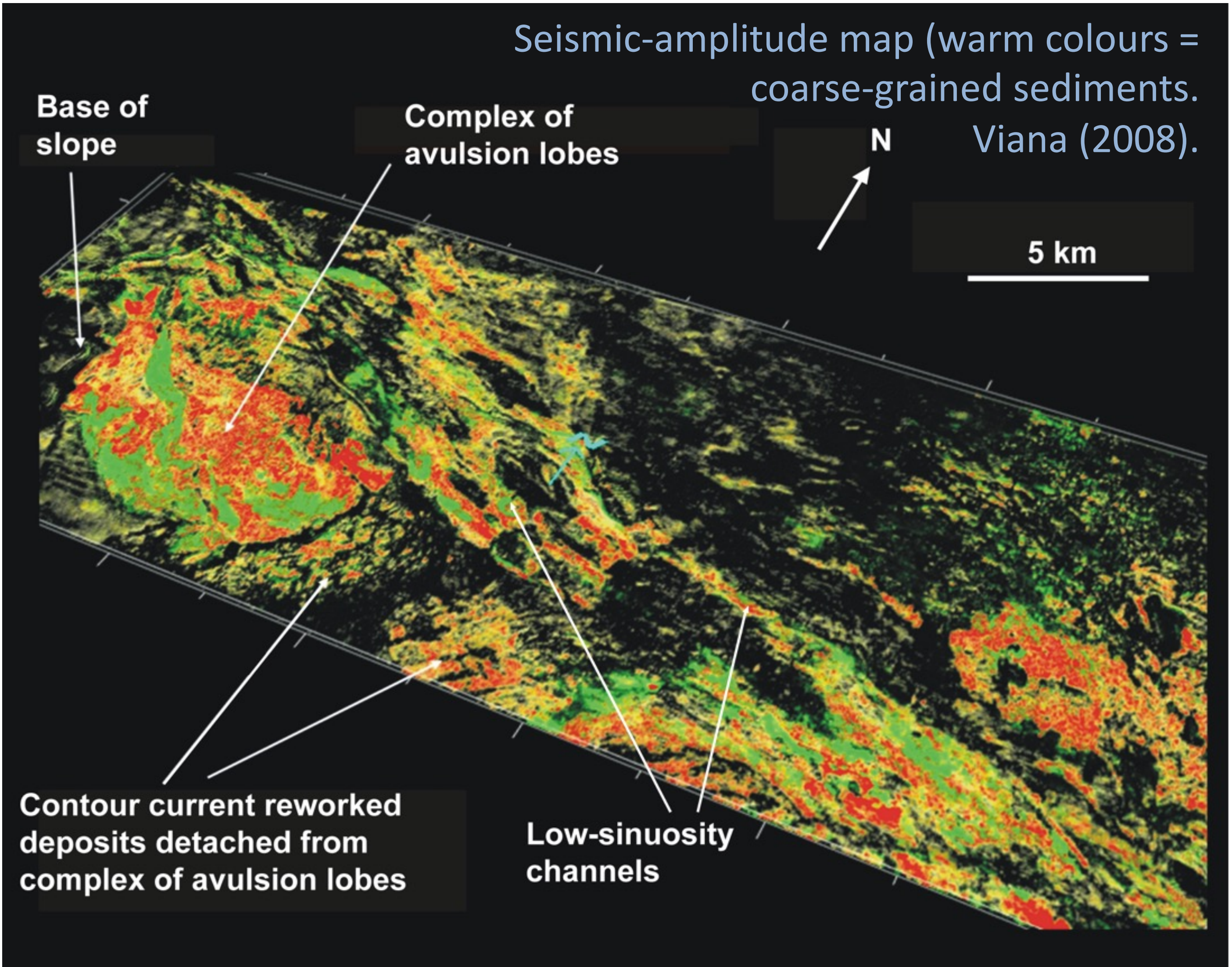
(e) loading.



Laberg and Camerlenghi (2008)

Significance for hydrocarbon exploration

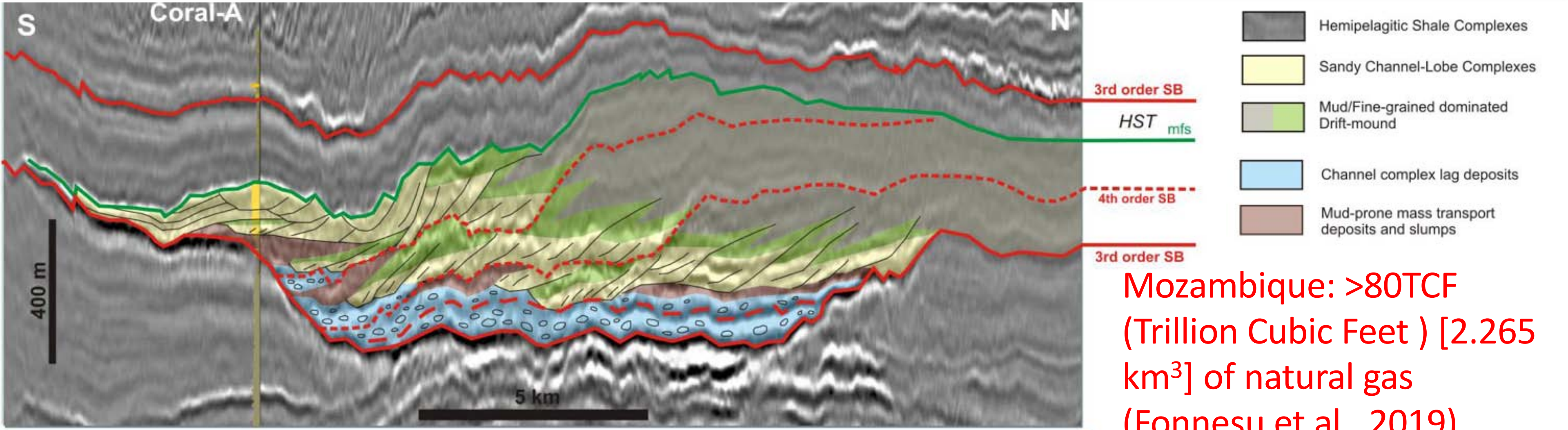
The action of contour currents has an impact on the petroleum systems in many aspects, including reservoir geometry and quality, and the distribution of sealing rocks.



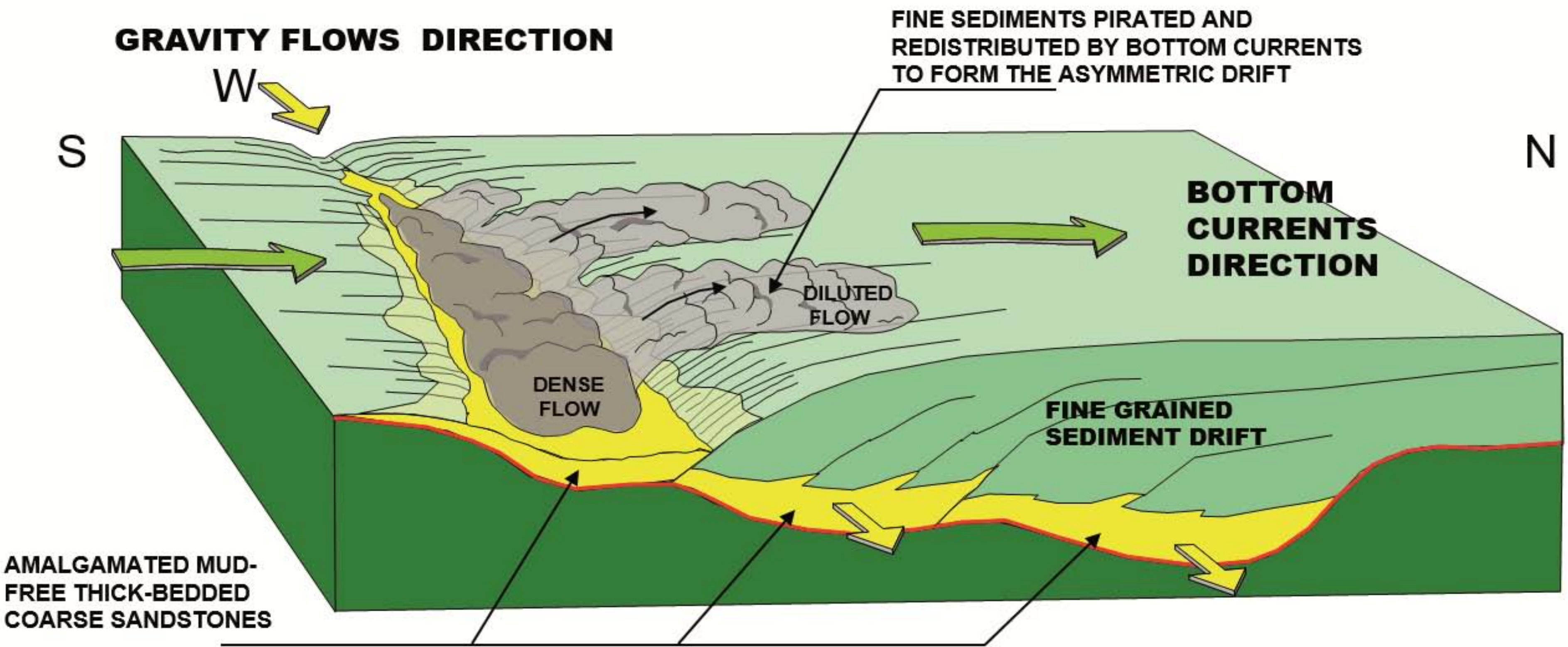
Seismic-amplitude map (warm colours = coarse-grained sediments. Viana (2008).

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.



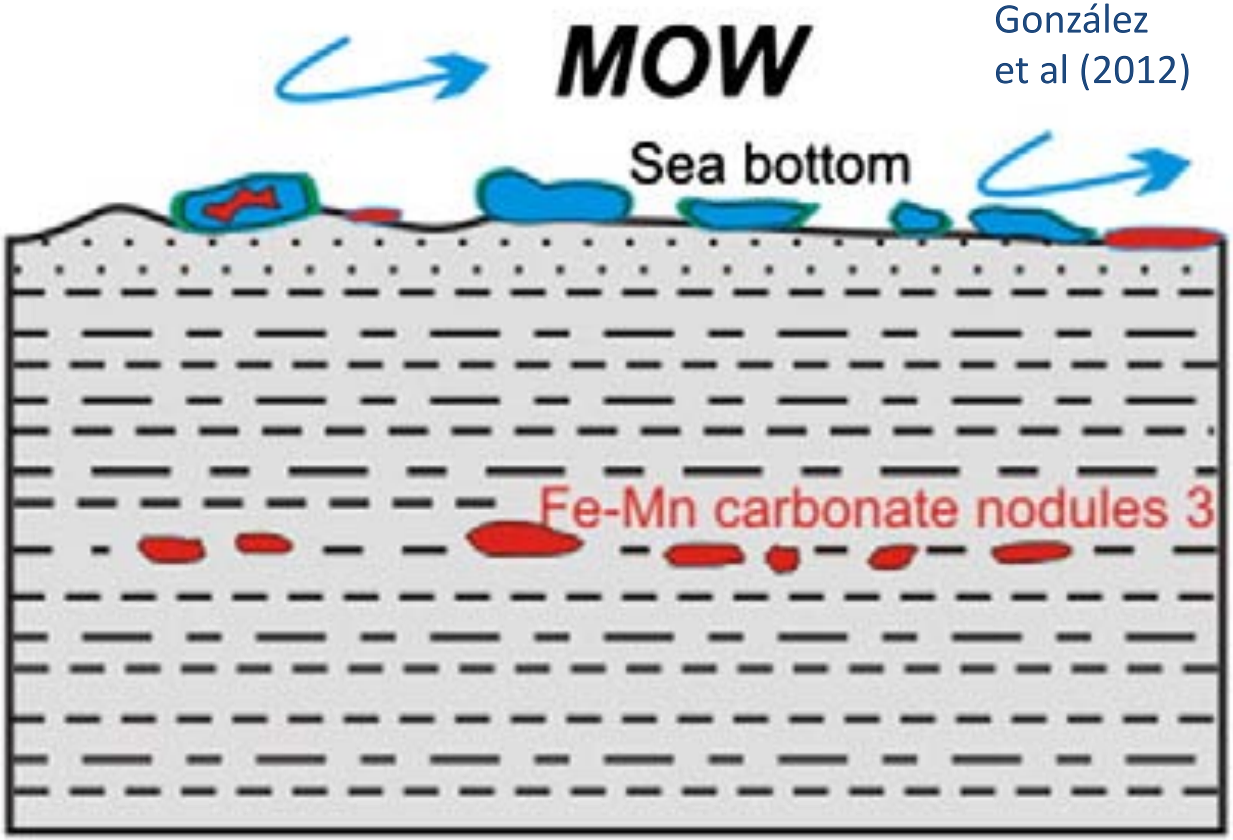
Mozambique: >80TCF (Trillion Cubic Feet) [2.265 km^3] of natural gas (Fonnesu et al., 2019)



Significance for polymetallic nodules

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 erosionall lag on the seafloor, while the newest ones will form at depth.

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

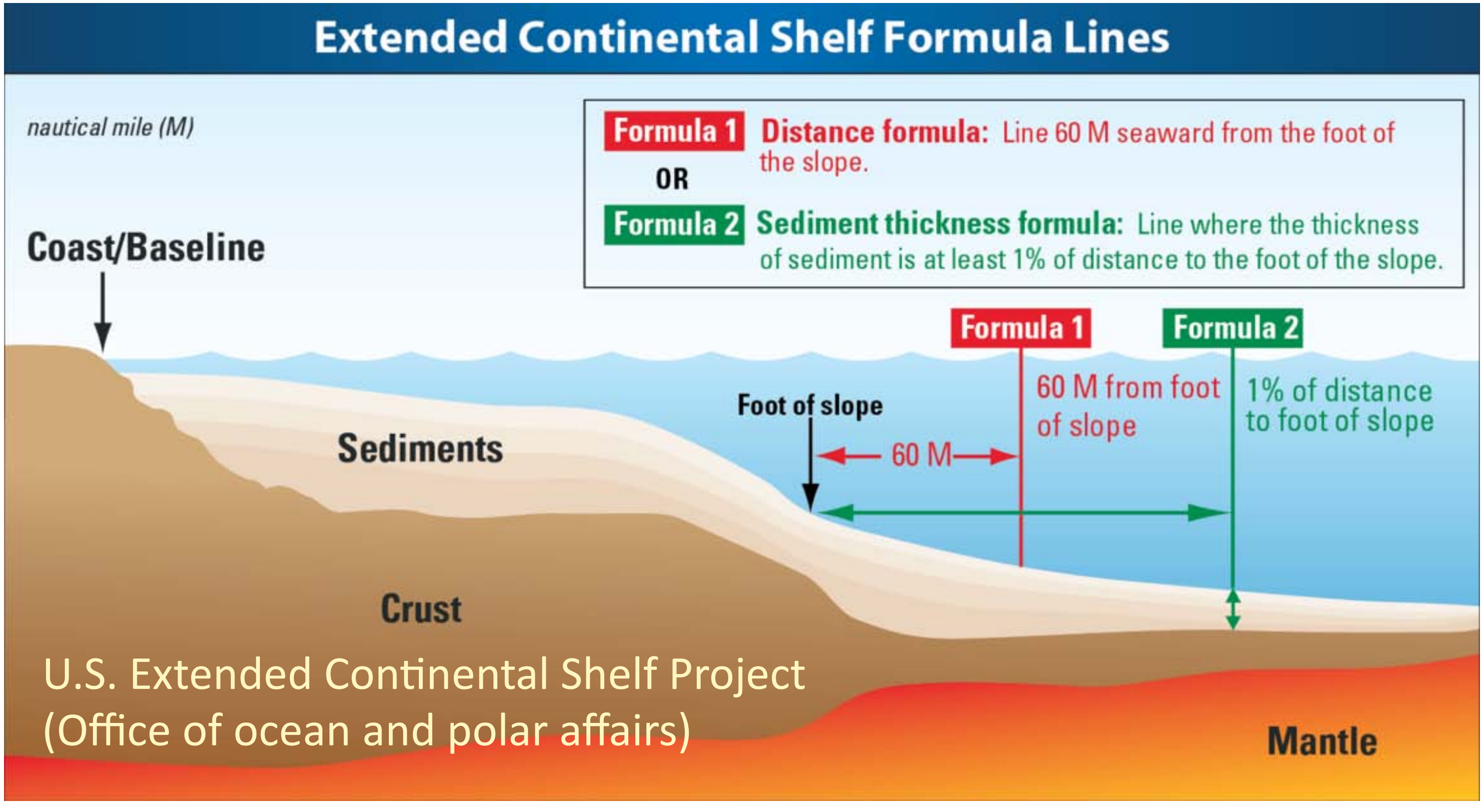


González et al (2012)

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 it 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)

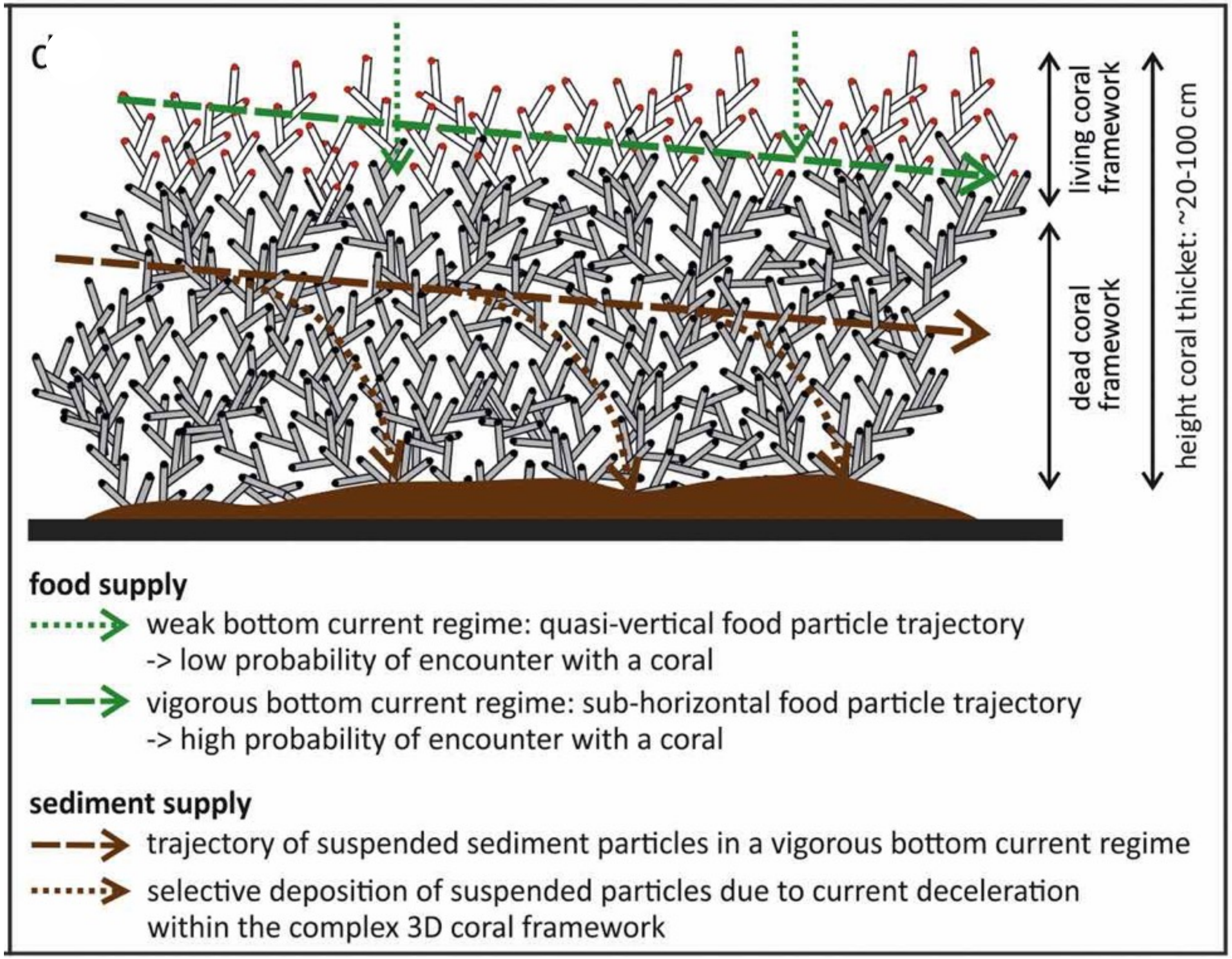


U.S. Extended Continental Shelf Project (Office of ocean and polar affairs)

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)

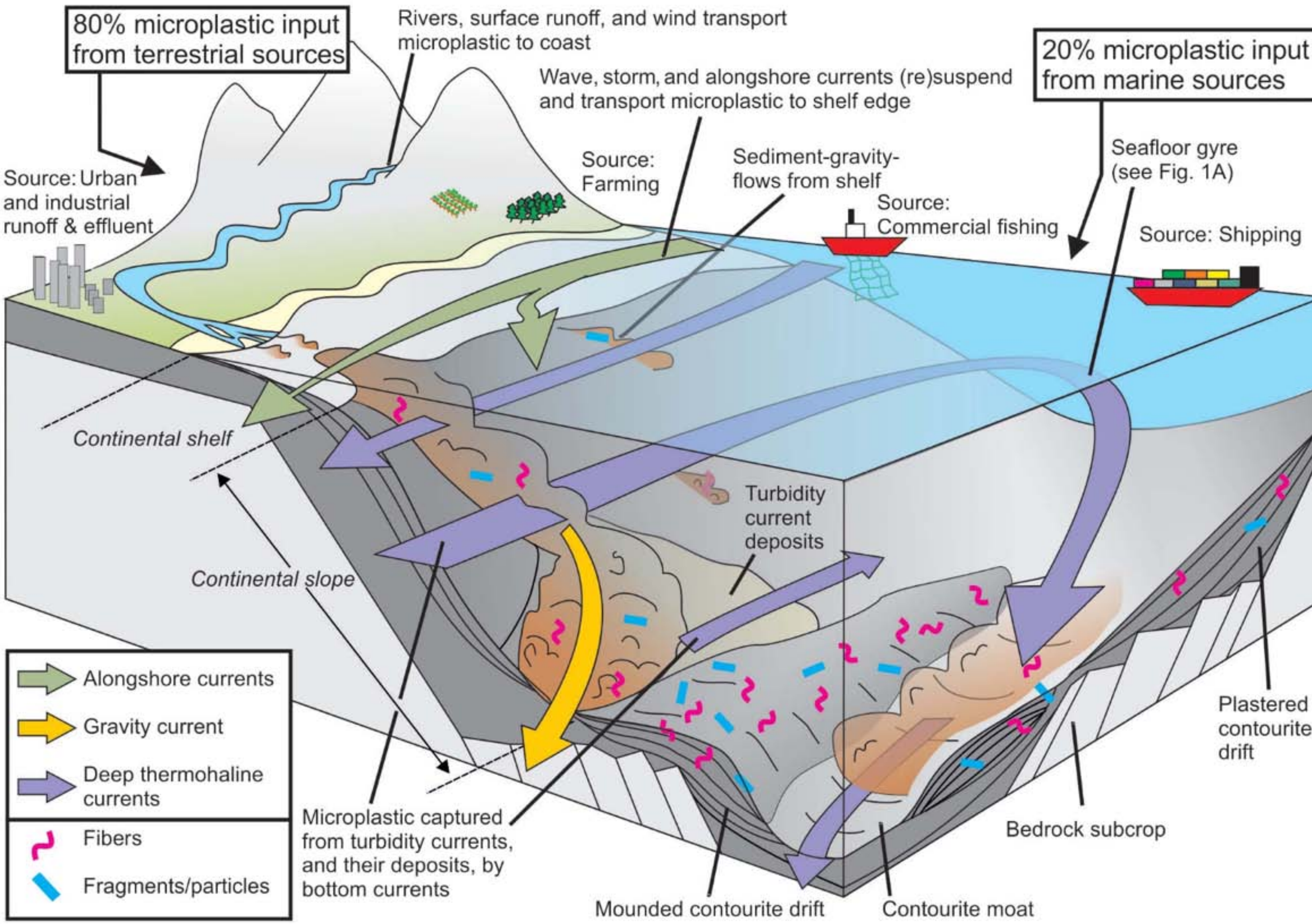
Significance for the ecological health of deepwater ecosystems

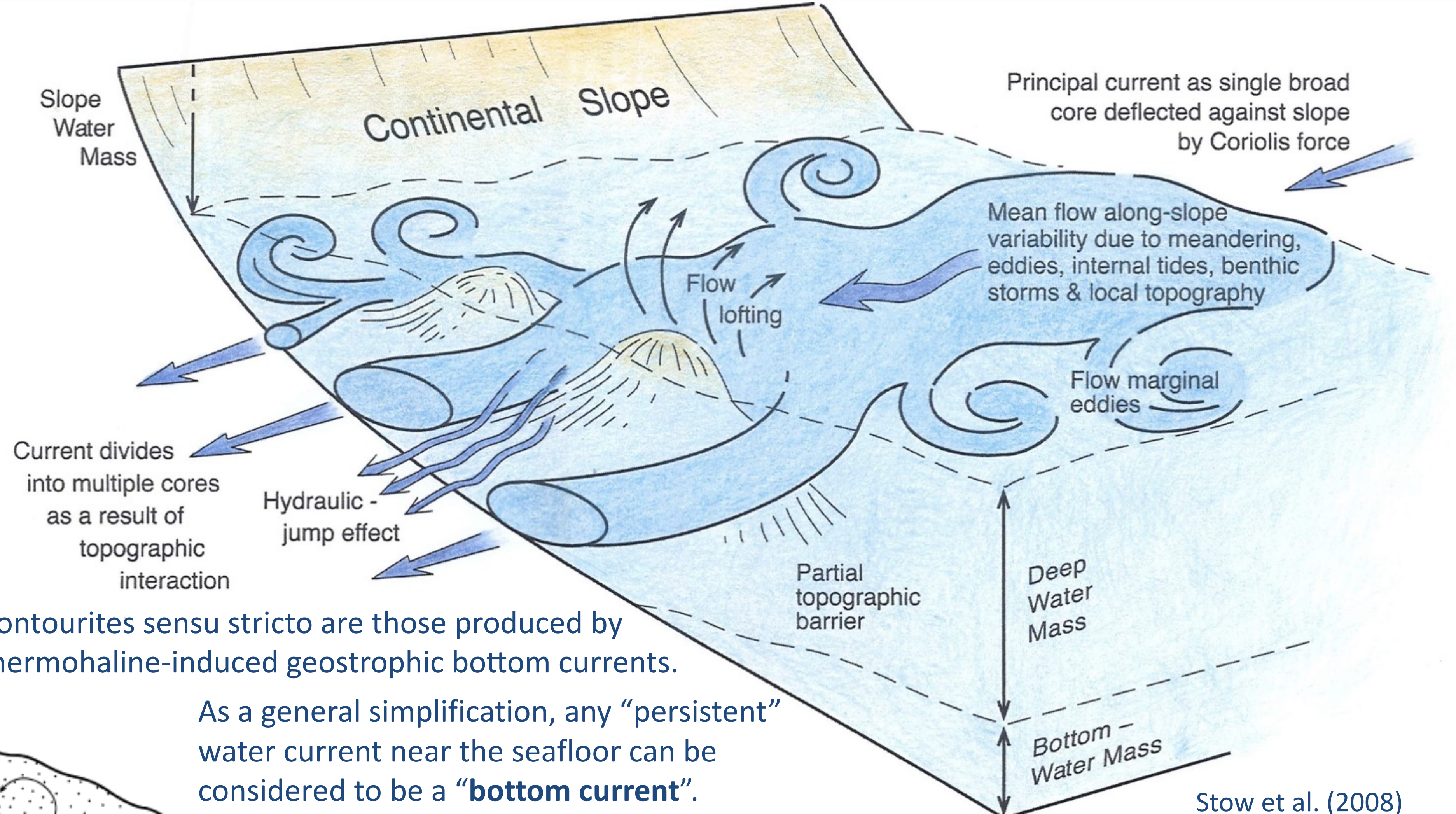
Hebbeln et al. (2016)



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)

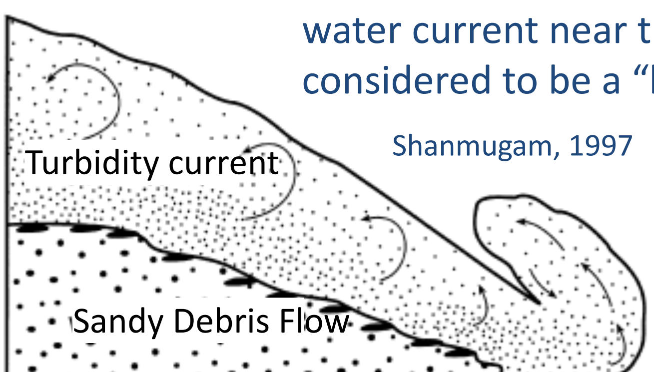




Stow et al. (2008)

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

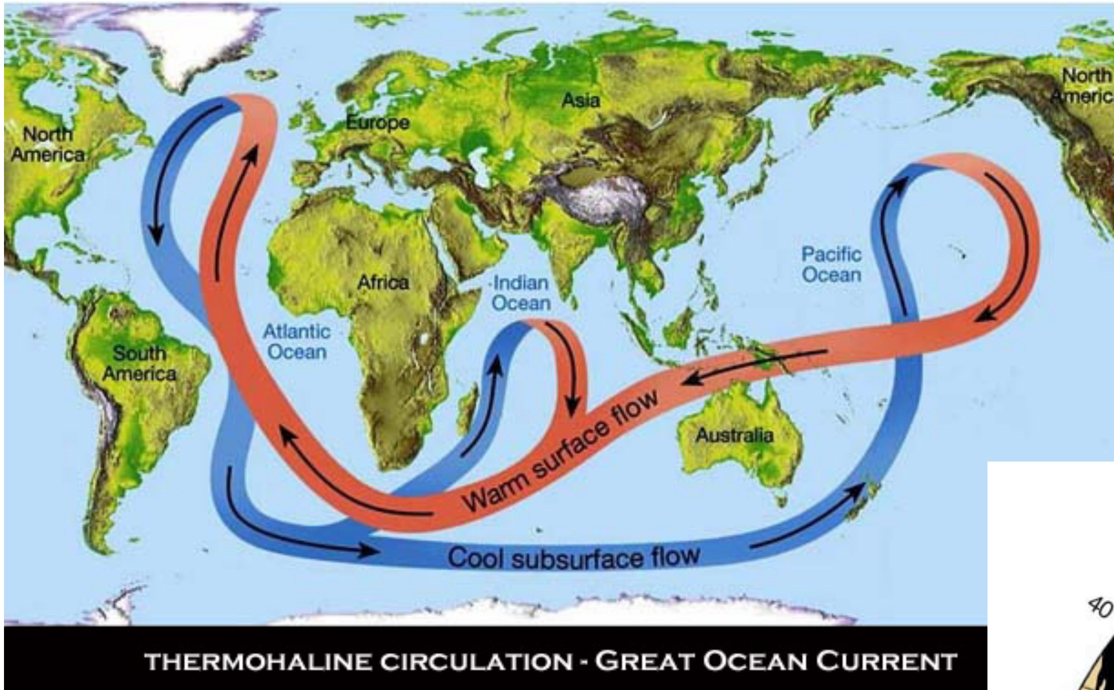
As a general simplification, any "persistent" water current near the seafloor can be considered to be a "**bottom current**".

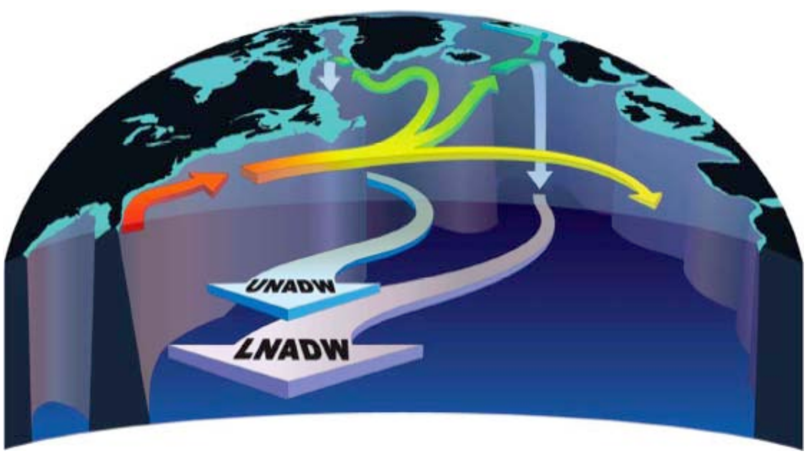


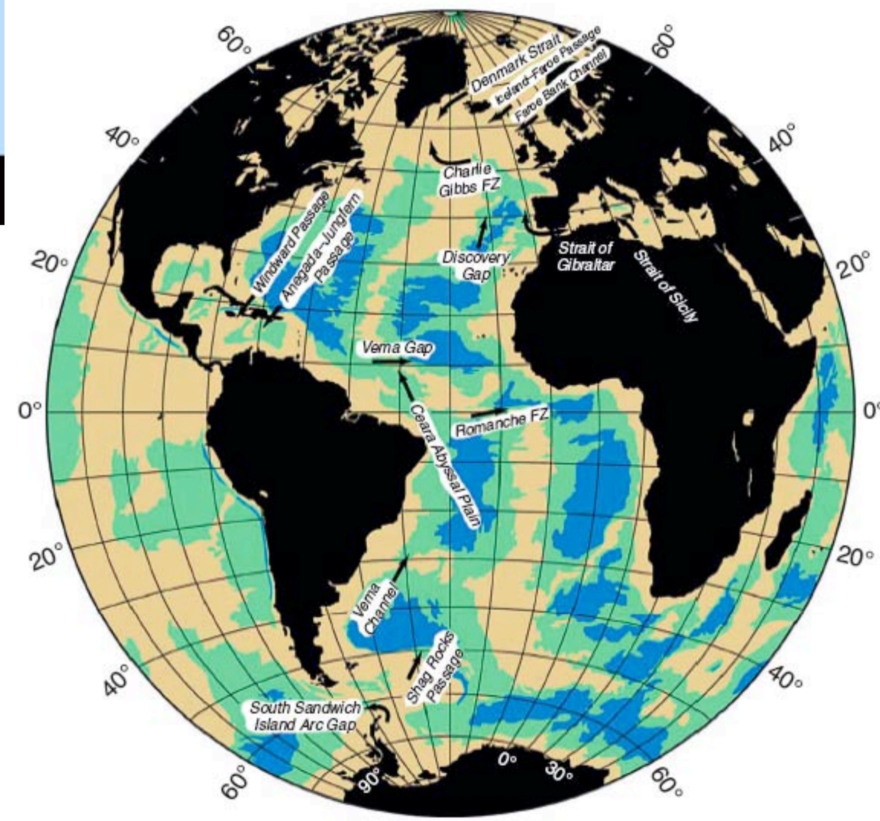
Shanmugam, 1997

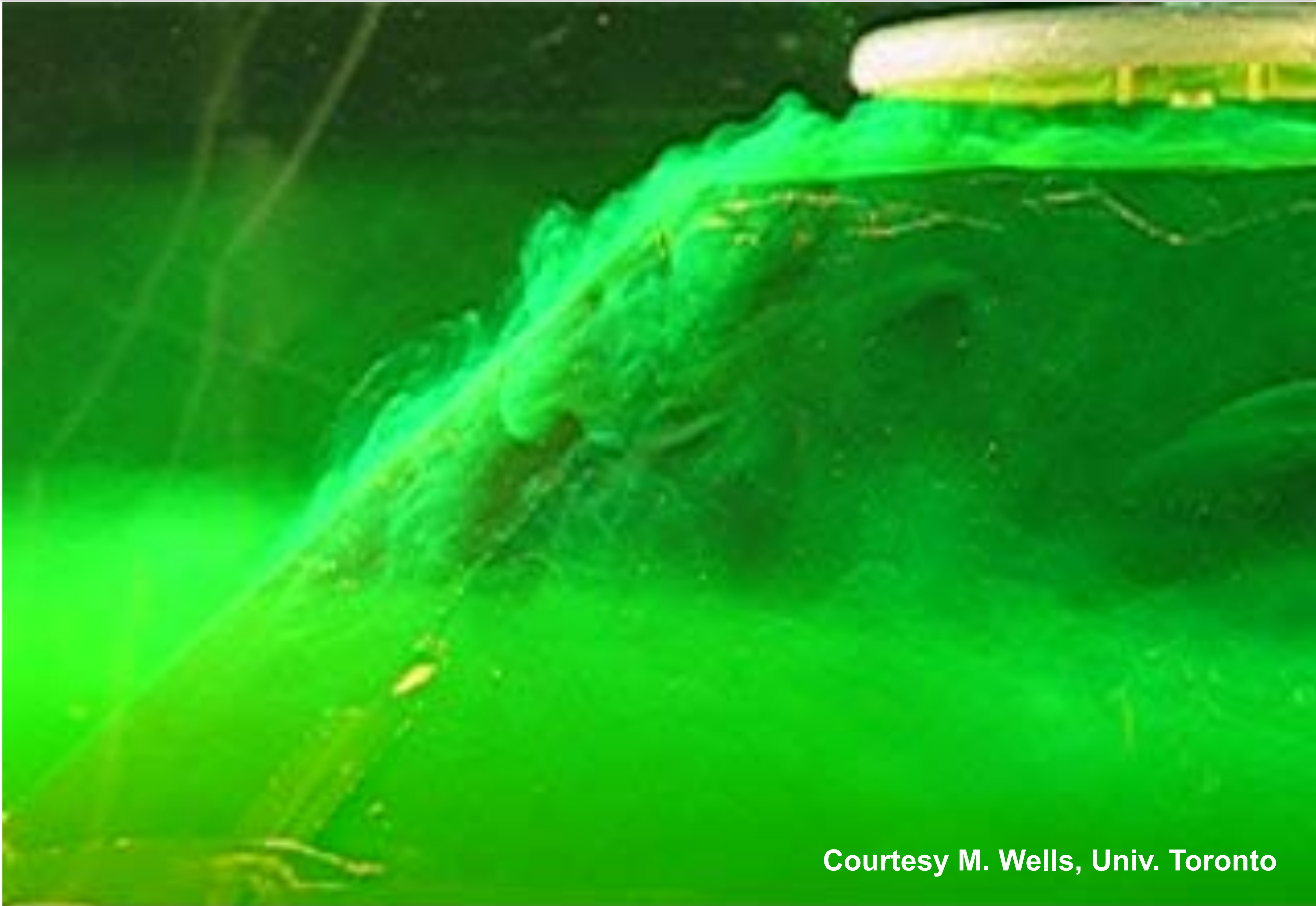
In addition, a number of associated processes are: benthic storms; overflows; interfaces between water masses; vertical eddies; horizontal vortices; tides and internal tides; internal waves and solitons; tsunami related traction current and rogue or cyclonic waves.

Thermoaline circulation

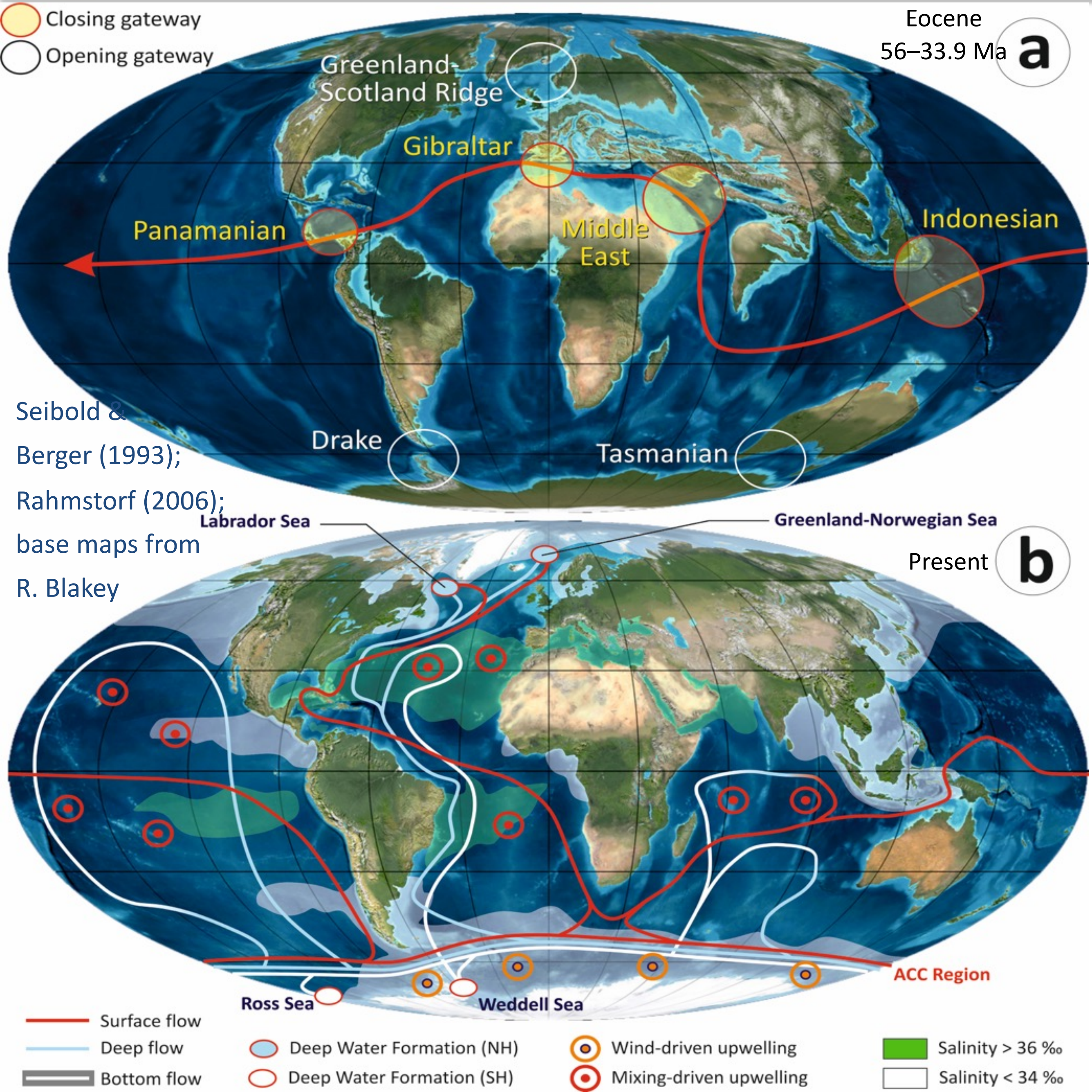






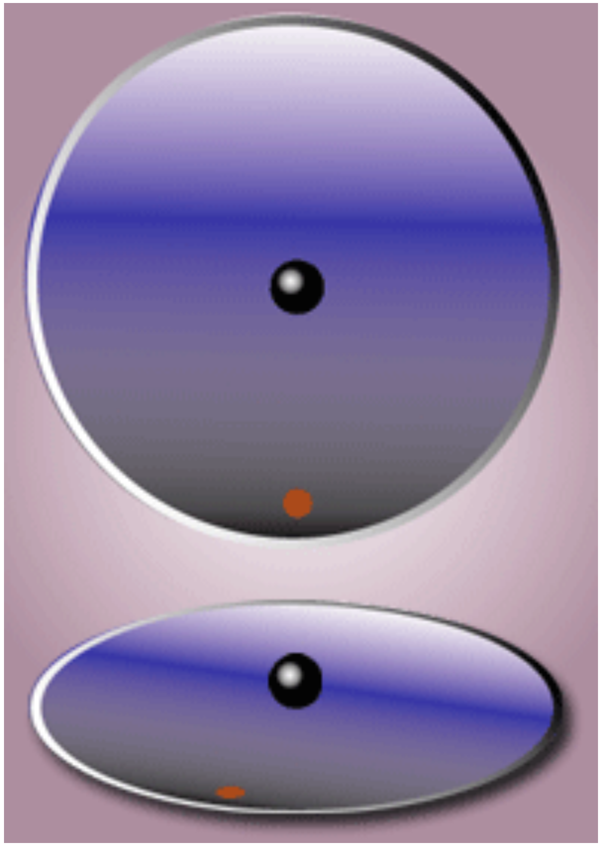


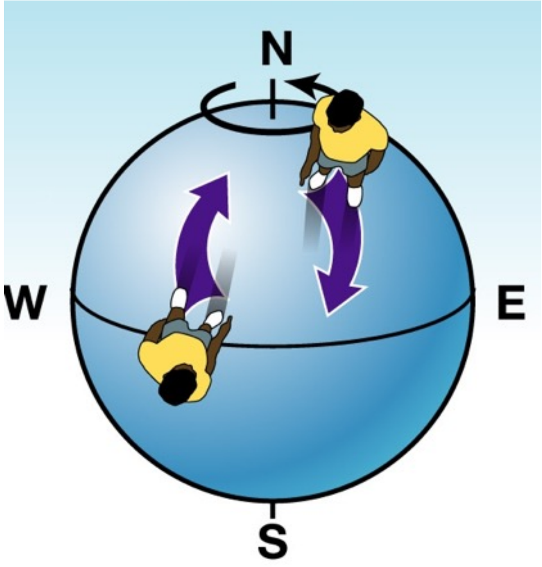
Courtesy M. Wells, Univ. Toronto



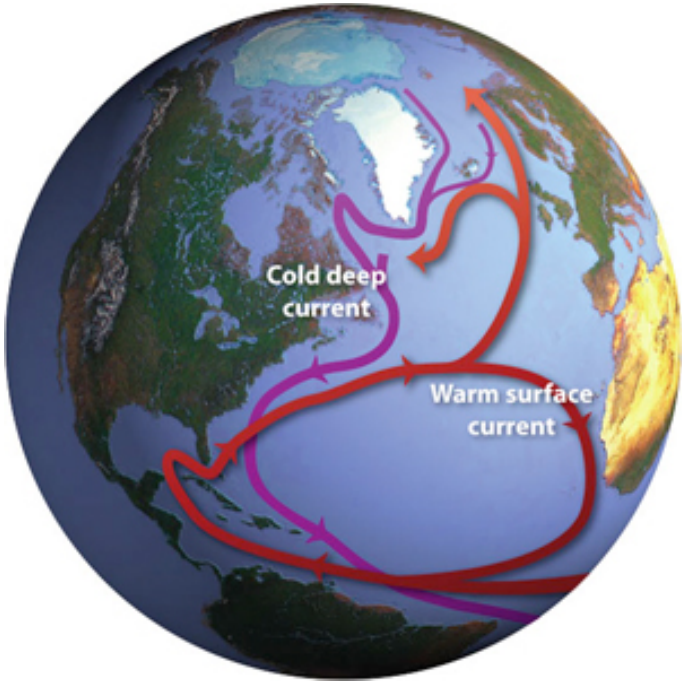
Seibold & Berger (1993); Rahmstorf (2006); base maps from R. Blakey

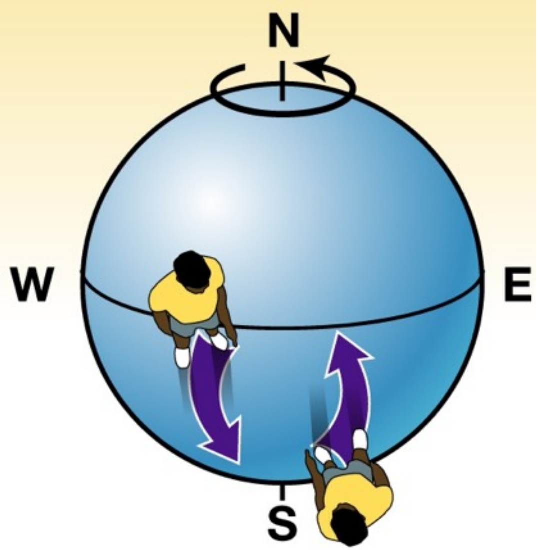
The deep waters of the oceans are primarily formed in marginal seas or shallow shelf regions where cooling and/or ice formation makes the water cold and dense, or strong evaporation makes the water highly saline. The relatively dense water thus formed flows out into the ocean via narrow or shallow straits 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.





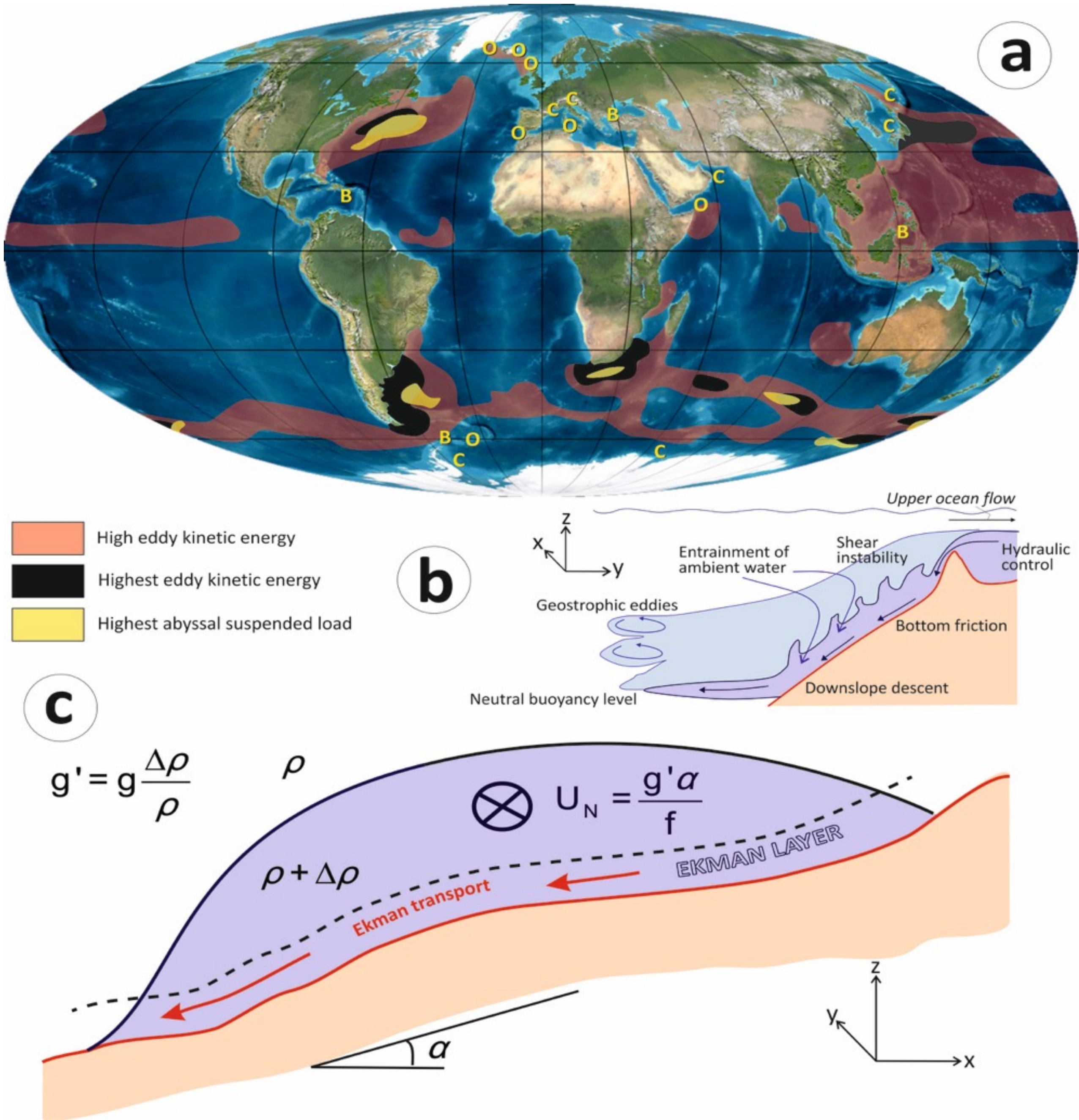
Coriolis effect

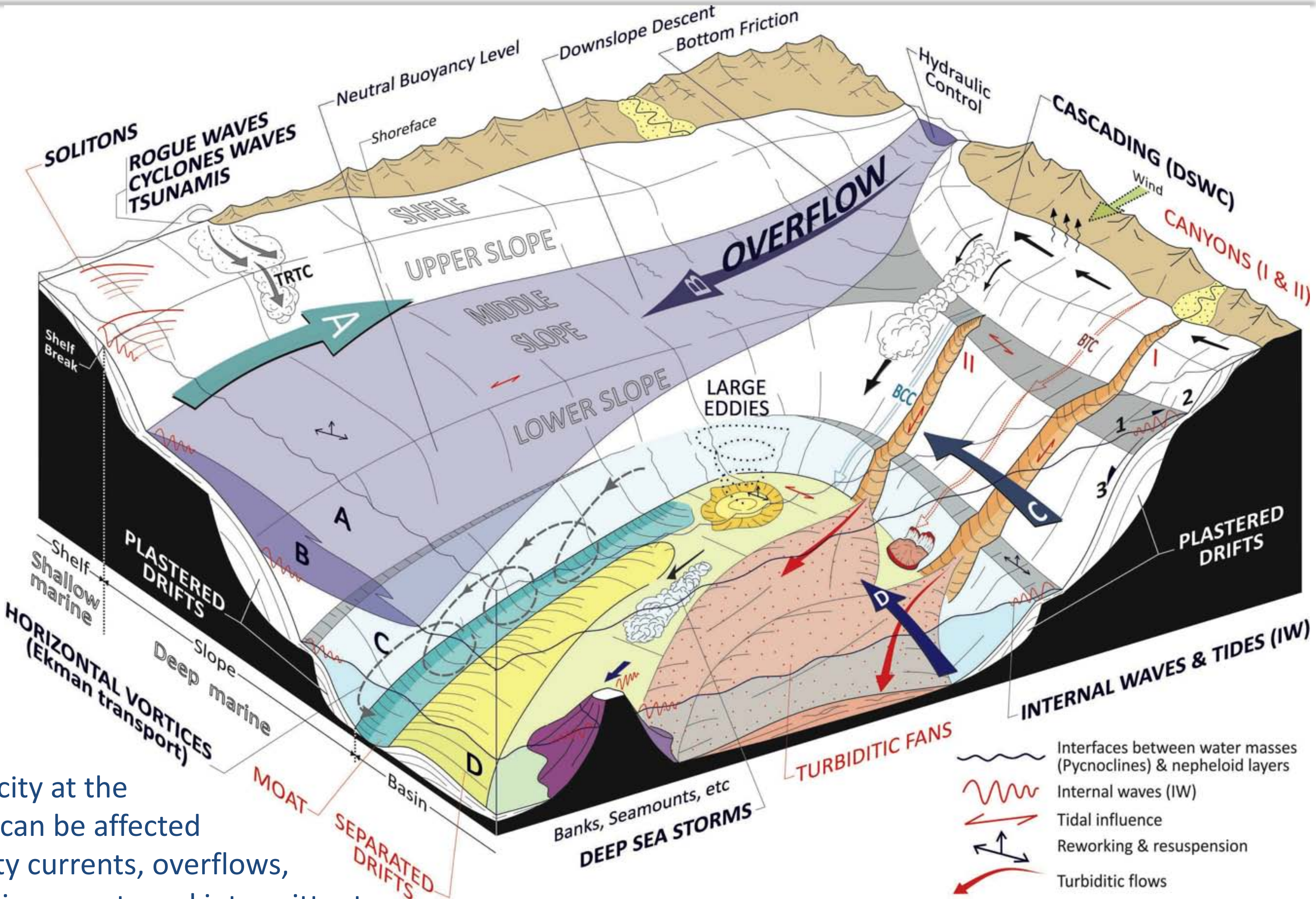




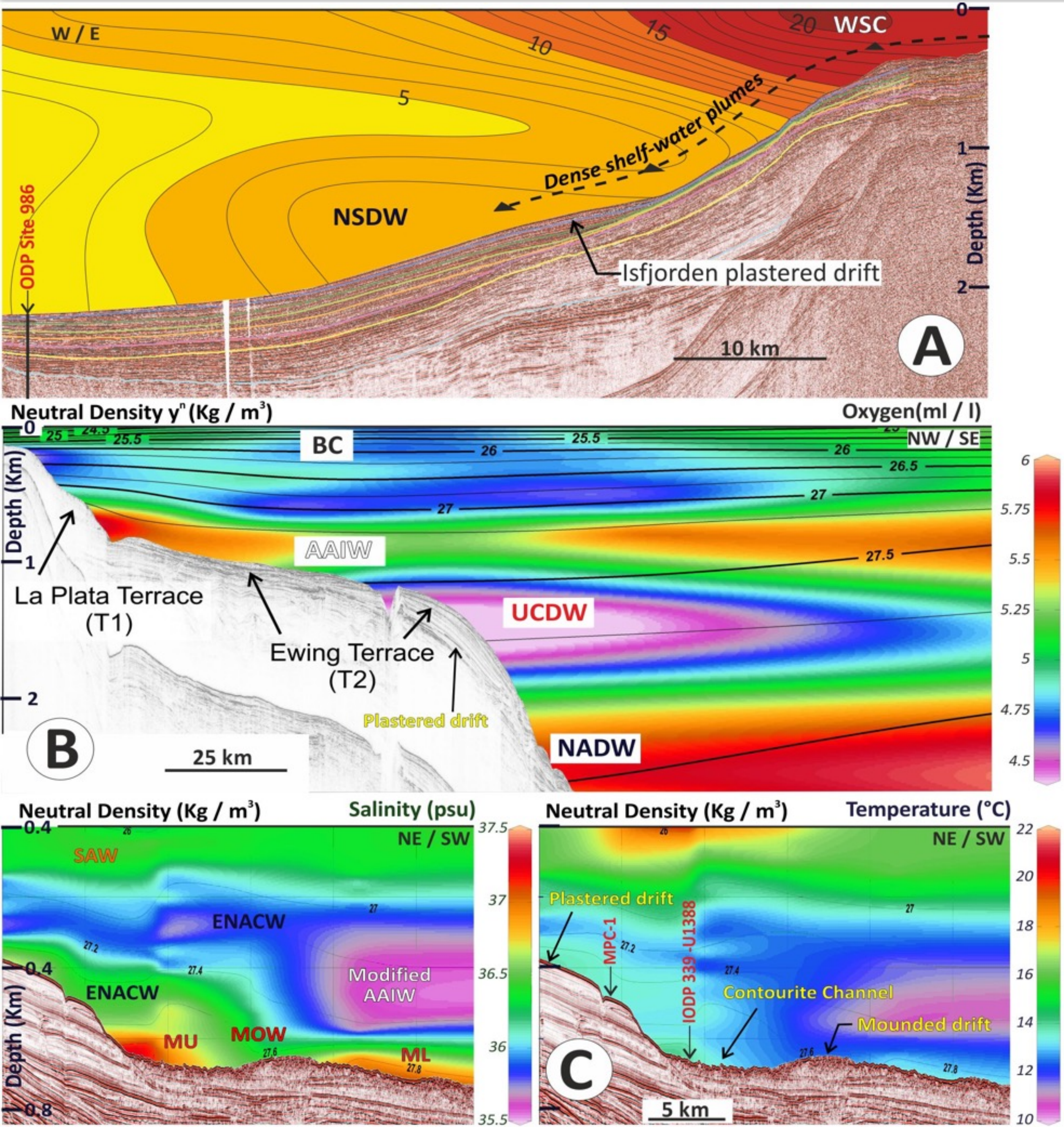
In physics, the Coriolis effect is a deflection of moving objects when they are viewed in a rotating reference frame

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: ρ; plume density: ρ+Δρ; reduced gravity: g'; bottomslope: α; Coriolis parameter: f; and Nof velocity: UN). Also shown are the Ekman layer and the benthic Ekman transport.



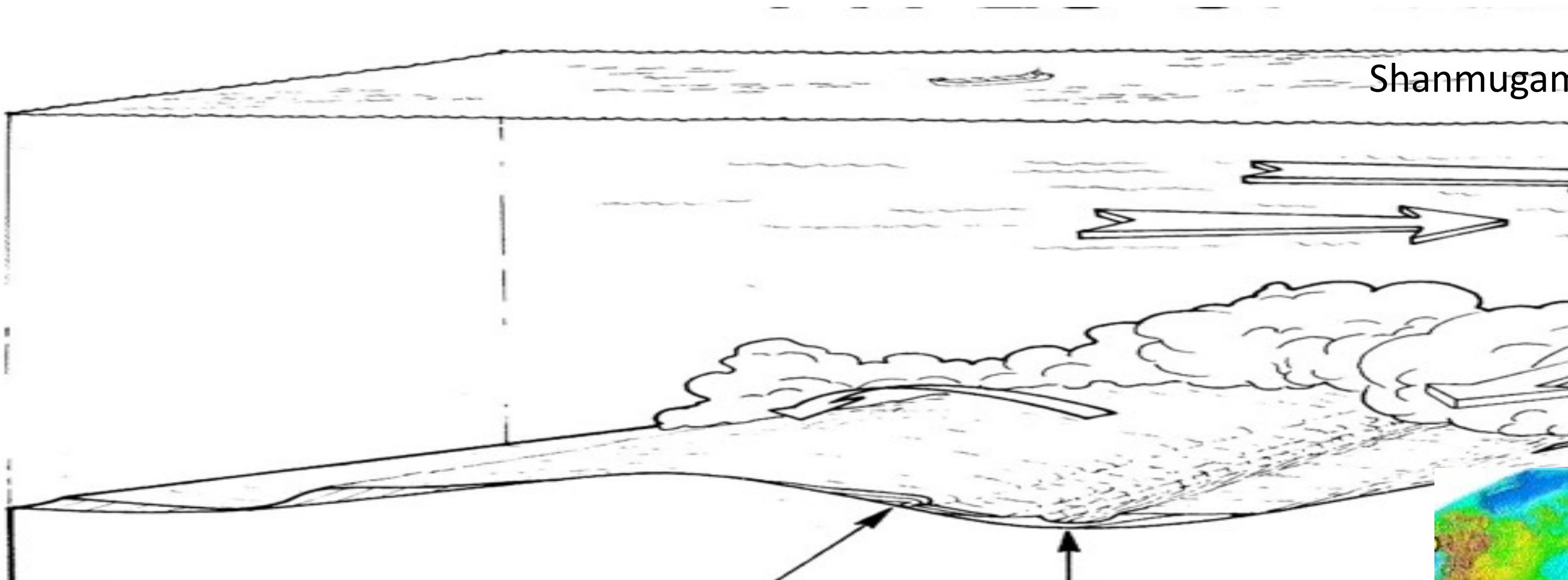


The velocity at the seafloor can be affected by density currents, overflows, barotropic currents and intermittent processes (cascading, giant eddies, deep sea storms, vortices, internal waves, internal tides, tsunamis, cyclone waves, and rogue waves)

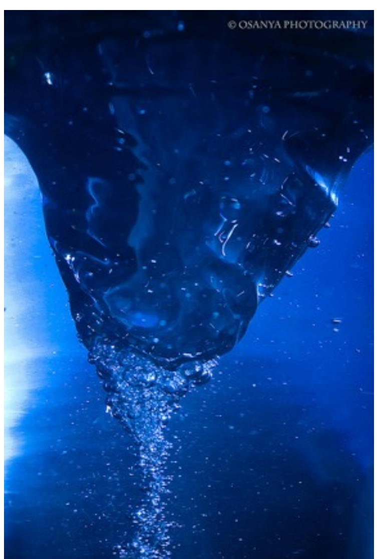


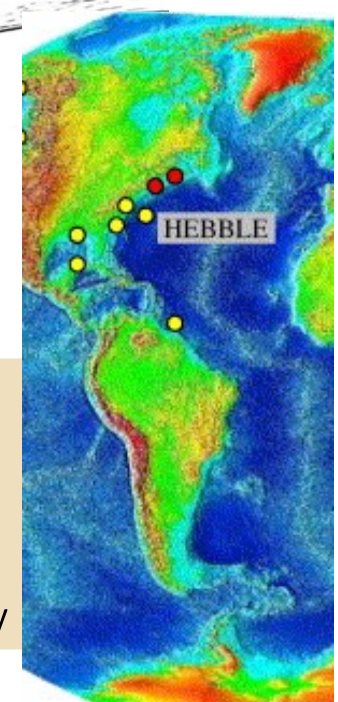
Examples of combining physical oceanographic data with geologic/geophysical data, showing the relationship amongst the long-term current regime, the seafloor morphology and the sub-bottom sediment geometry. A) Western Spitsbergen margin (Rebesco et al., 2013); B) Argentine margin, North of the Mar del 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 (kg/m3).

Sediment entrainment



Shanmugam, 2000

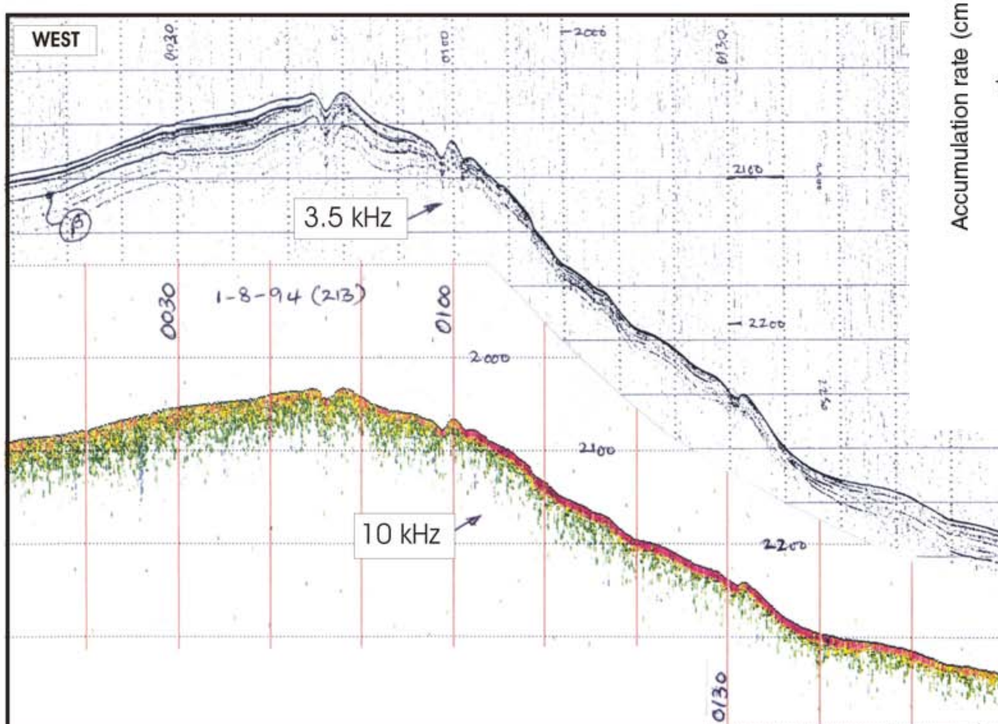


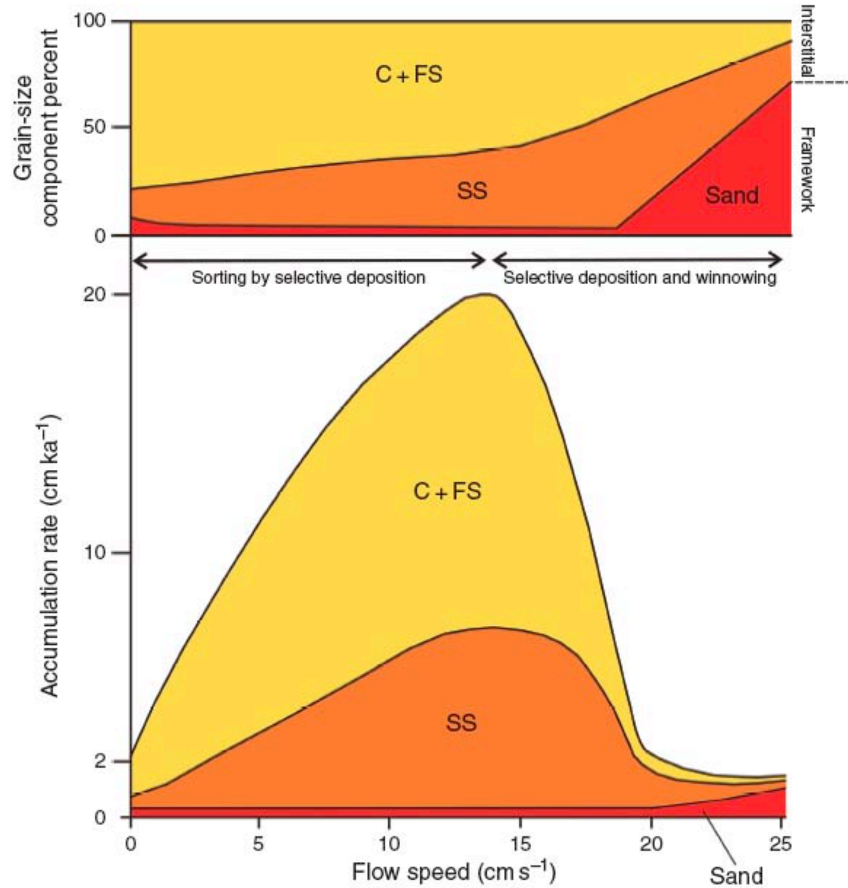


Benthic storm characteristics in the HEBBLE area

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 cm3 /m2 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.

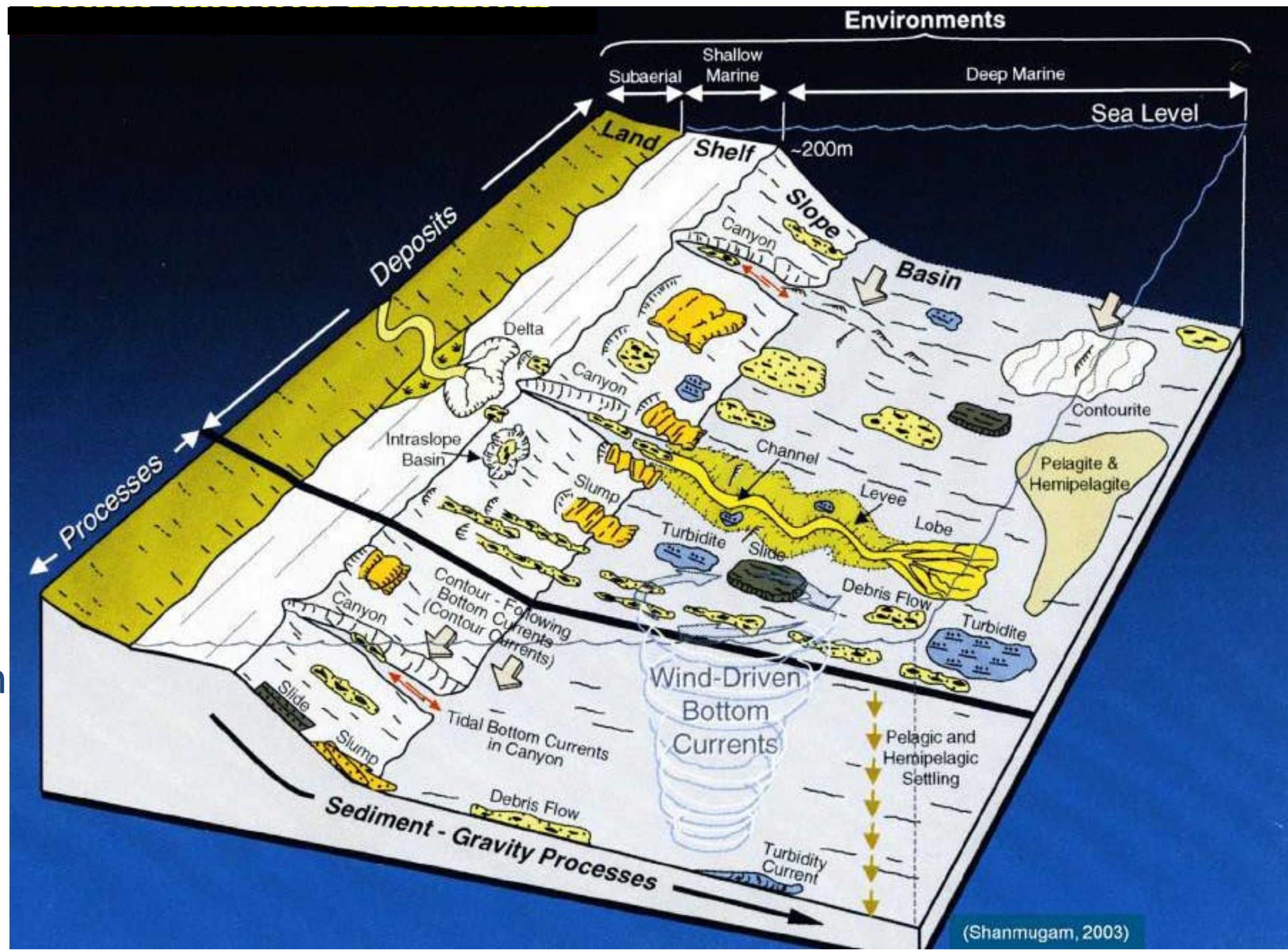




Deposits from currents

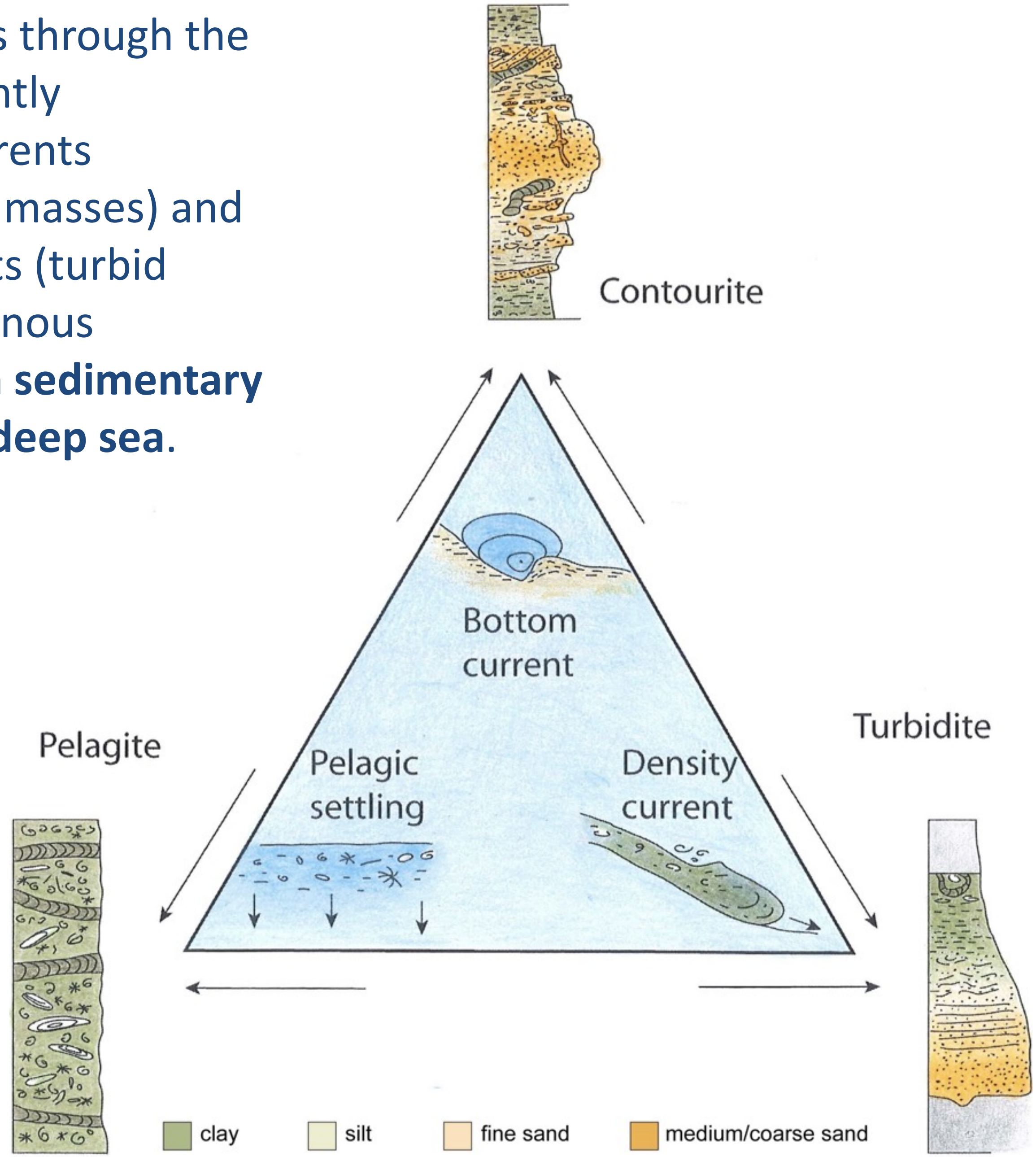
Deep sea depositional processes

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.

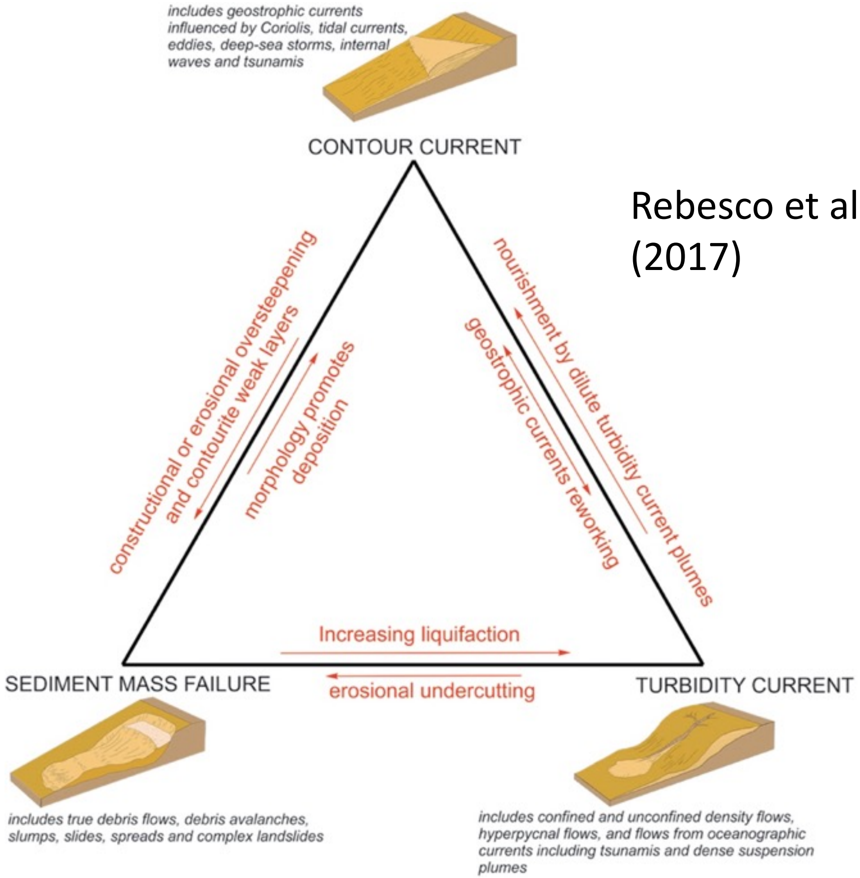


The settling of pelagic particles through the water column, the predominantly alongslope flow of bottom currents (relatively clean bottom water masses) and the downslope density currents (turbid flows of predominantly terrigenous sediments) are **the three main sedimentary processes taking place in the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

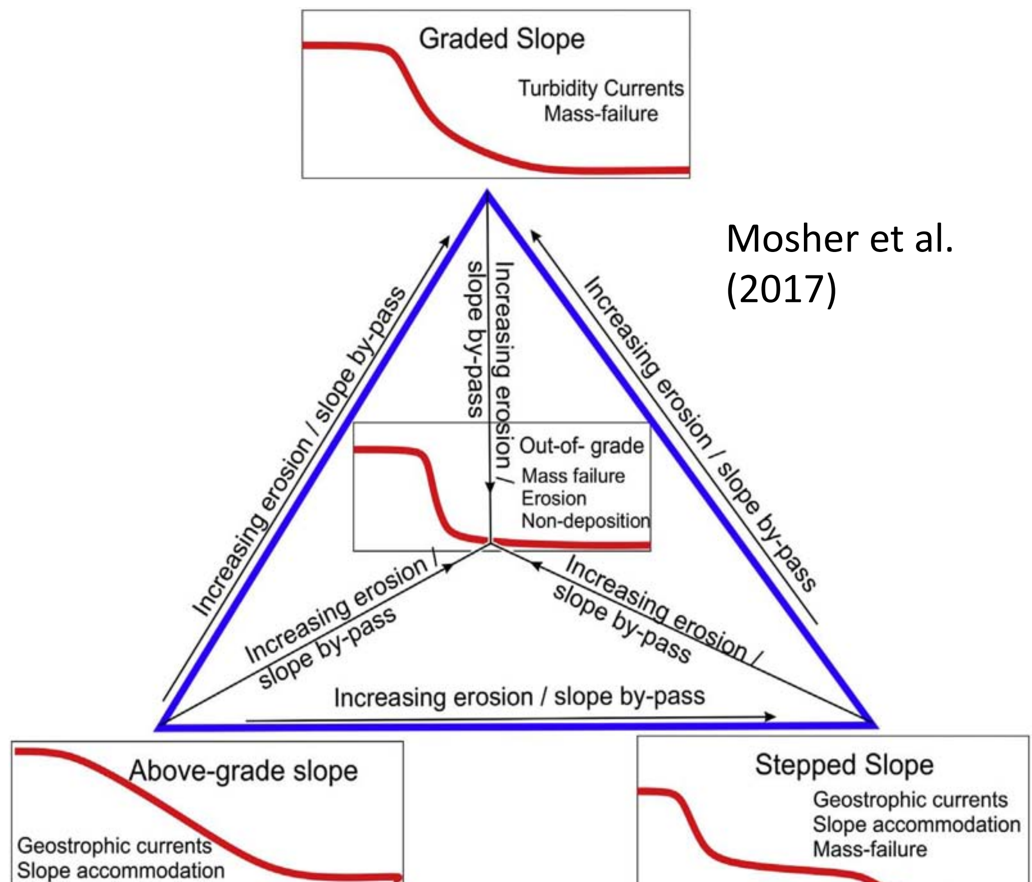
While the first represent a "background" process that becomes dominant only in very remote abyssal areas, episodic, high-energy density flows are commonly superposed to permanent flow of bottom currents on many continental margins.



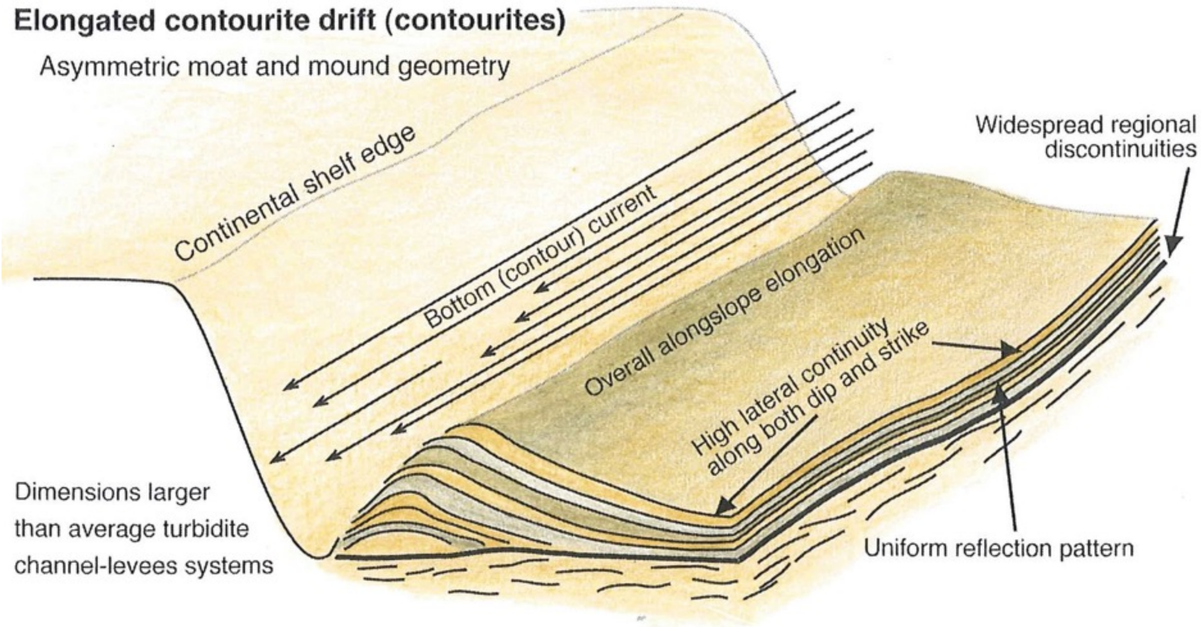
Clastic sedimentary processes on continental margins and morphotypes



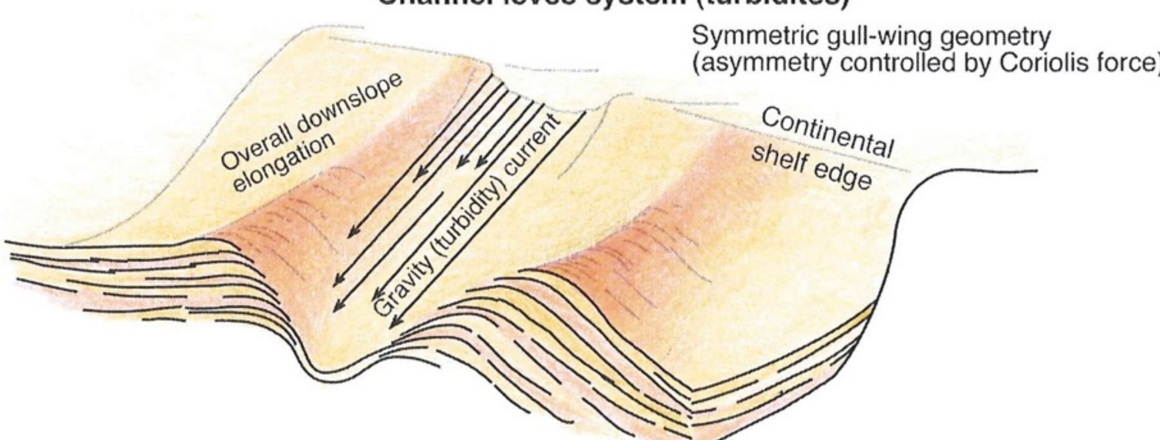
Rebesco et al. (2017)



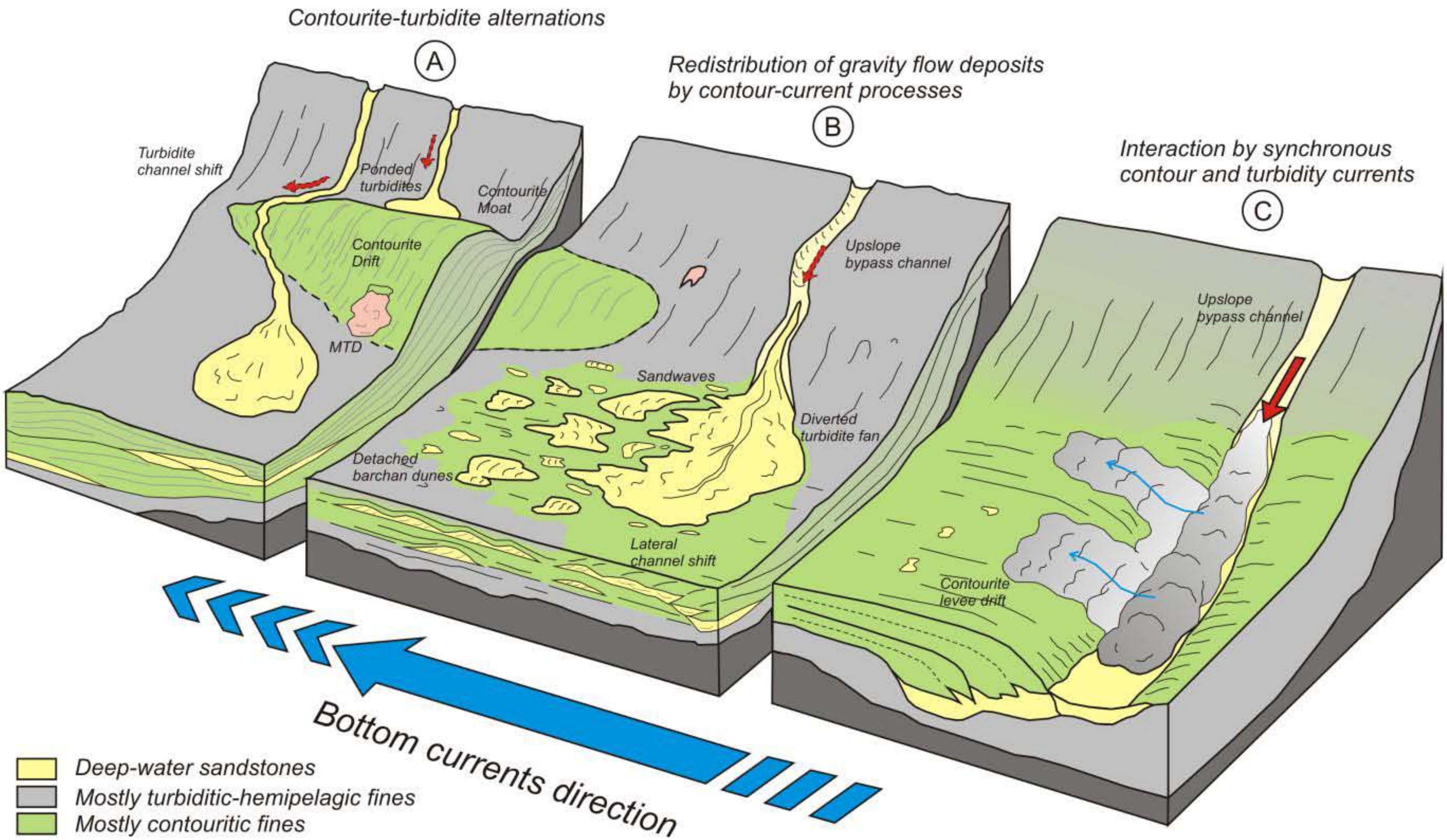
Mosher et al. (2017)



Rebesco (2005)

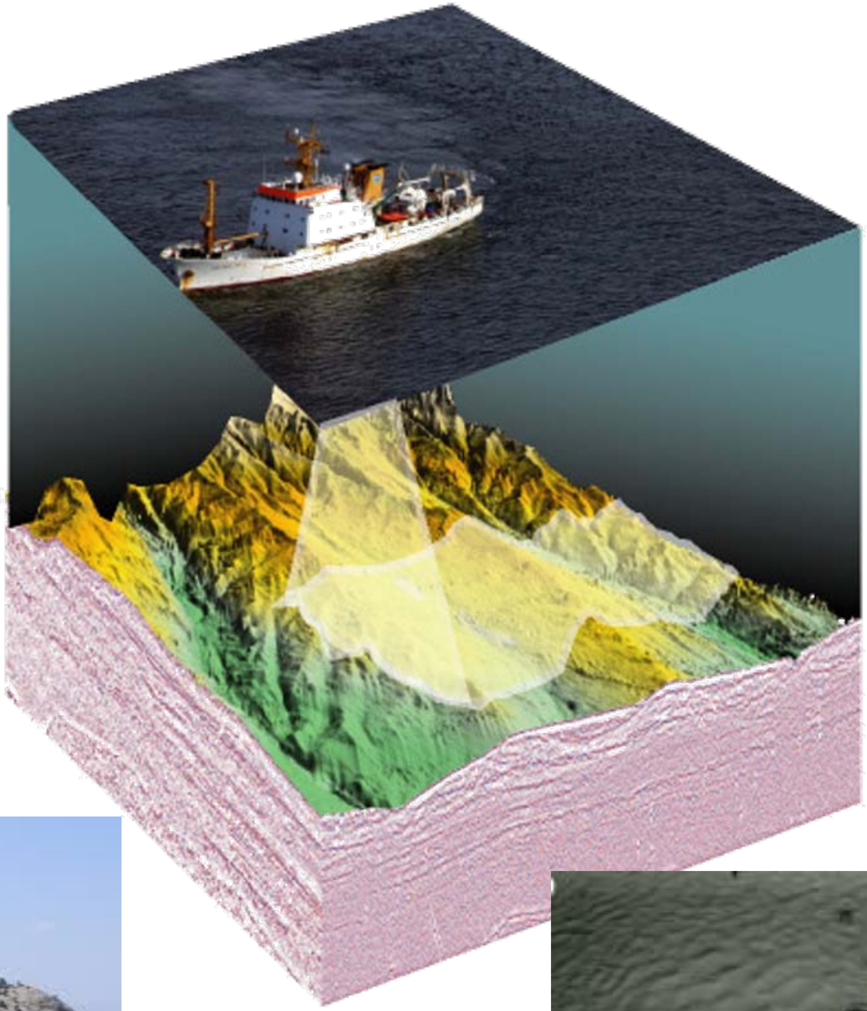


Bottom currents are capable of building thick and extensive accumulations of sediments ("contourite drifts"). Similarly to channel-levee systems generated by turbidity currents, such large bodies normally have a noticeable mounded geometry, which is generally elongated parallel, or lightly oblique to the margin. Besides this, bottom currents and associated processes generate also a wide range of other depositional and erosional or non-depositional structures at different scales.



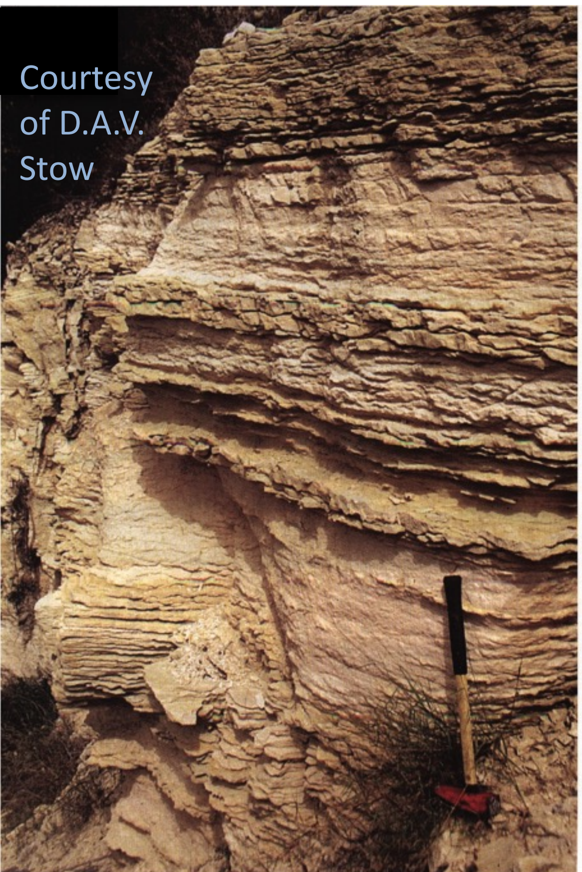
(Fonnesu et al., 2019)

Methods to study contourite deposits

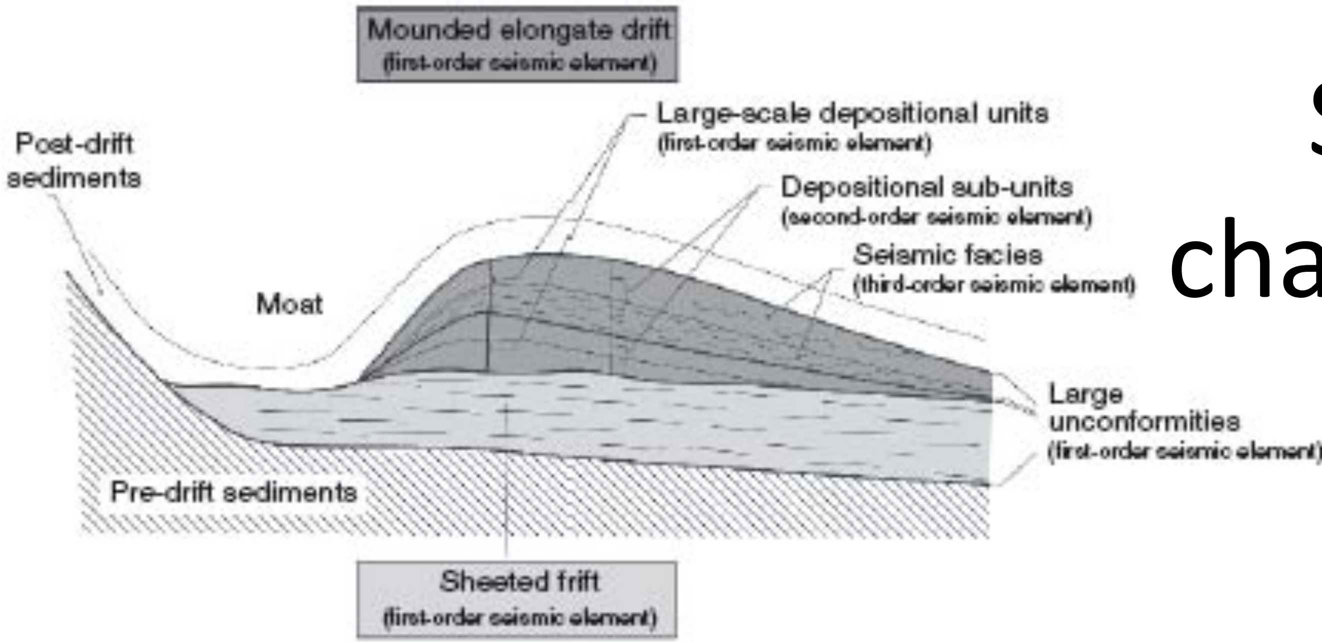


Three scale approach

Diagnostic criteria are their **facies and ichnofacies, texture and sequences, microfacies and composition**. **Sedimentary structures** are also “diagnostic indicators”, but for their interpretation its full context should always be considered. **Medium-scale criteria** (hiatuses and condensed deposits, variation in the thickness, geometry, palaeowater depth, geological context) can be definitive. **Large-scale criteria** (palaeoceanographic features and continental margin reconstructions) are essential, but generally more problematic to apply on outcrops.



Recognizing contourite deposits in ancient sedimentary series presently exposed on land, is a difficult task. The distinction between contourites and reworked turbidites is controversial.



Seismics characteristics

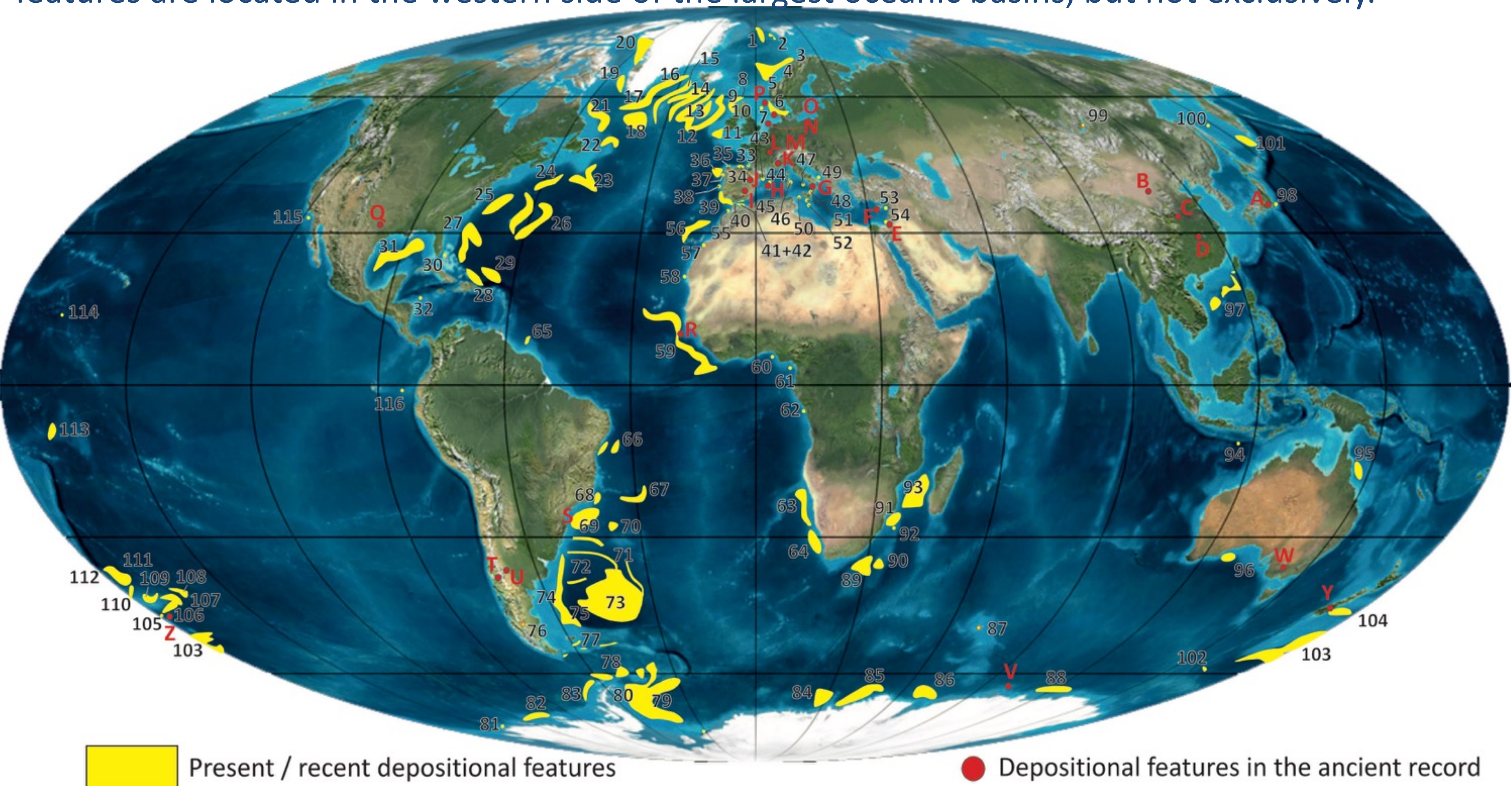
triple-scale approach that involves 3 ‘‘orders of seismic elements’’.

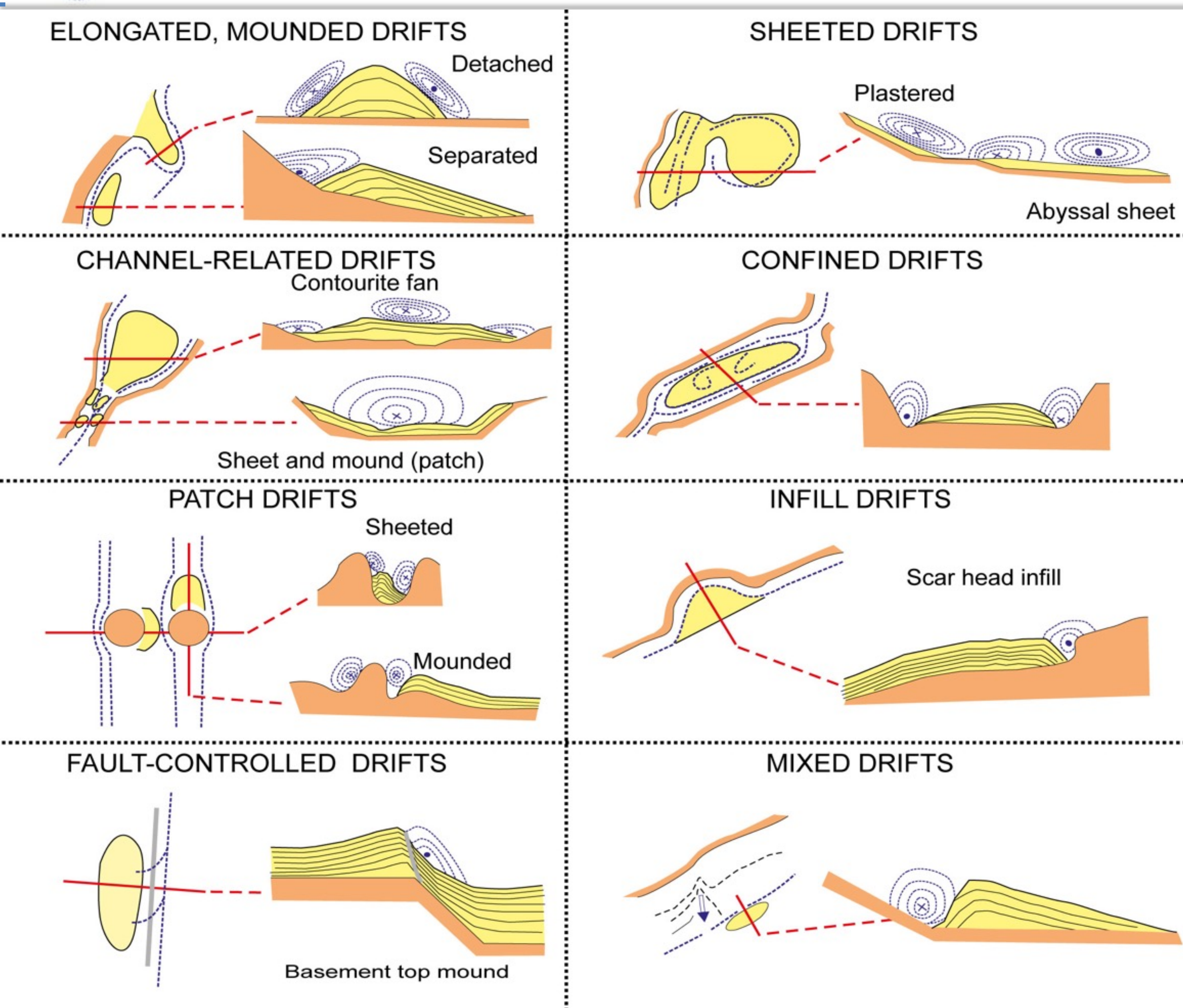
Large scale (overall architecture): I-order elements (major changes in current strength and sediment supply): External geometry, Bounding reflectors, Gross internal character.

Medium scale (internal architecture): II-order seismic elements (reflecting smaller fluctuations): lens-shaped, upward-convex geometry; uniform stacking pattern; down-current migration or aggradation;downlapping reflector terminations

Small scale (internal acoustic character): III-order seismic elements:
facies analysis (continuous, (sub)parallel, wavy, structureless),
and attribute analysis (bedforms).

This **updated compilation of contourite occurrence** was done specifically for the present review, but was subsequently archived and visualised on the Marine Regions website (http://www.marineregions.org). It demonstrates that contourite features are ubiquitous within the oceanic basins (different settings and different water masses from the outer shelf to the abyssal plains. The highest numbers of described large contourite depositional and erosional features are located in the western side of the largest oceanic basins, but not exclusively.





All **contourite drifts** are characterised by a variable degree of mounding and somewhat evident elongation

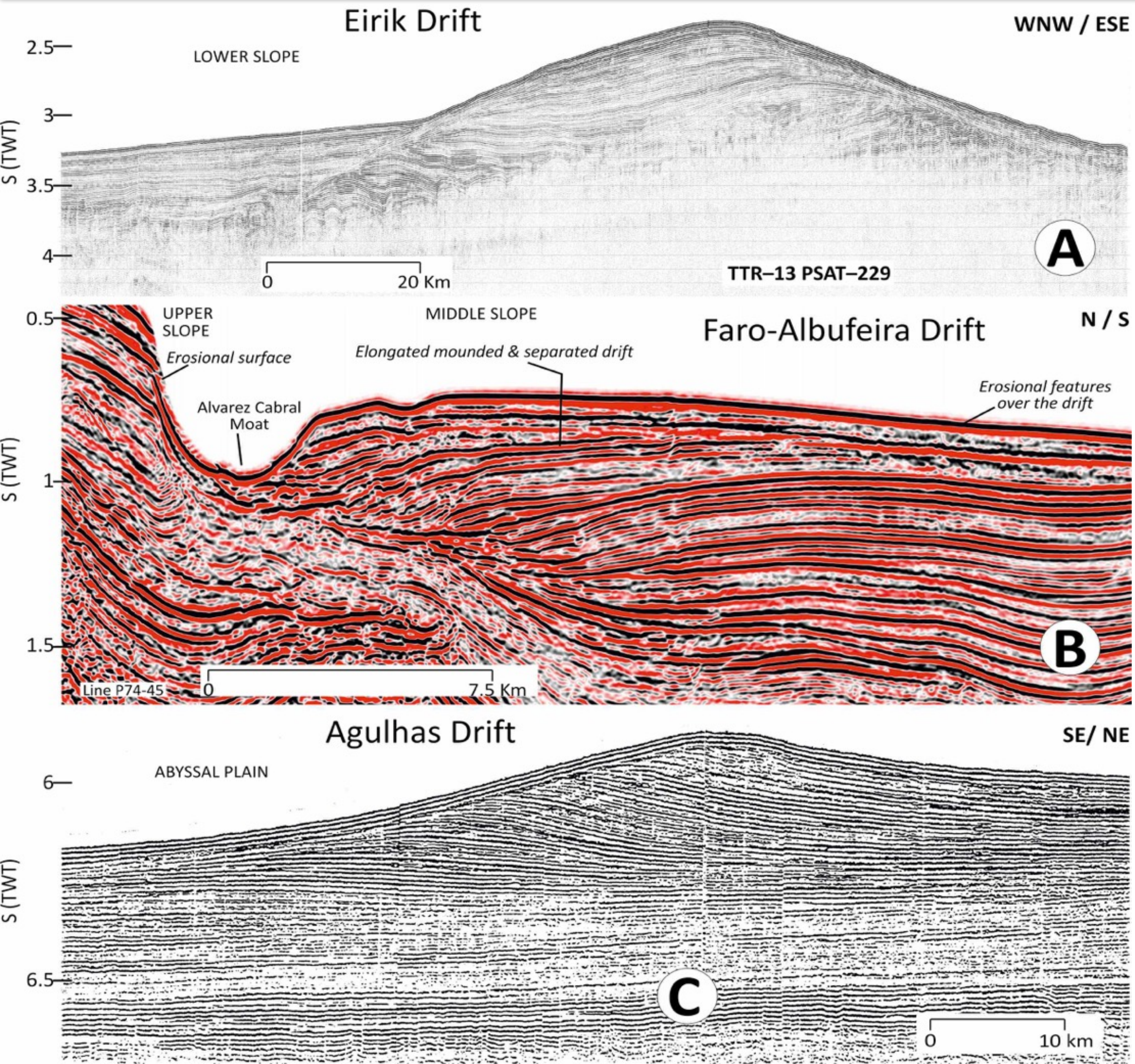
Sediment drift types and inferred bottom-current paths. From Rebesco (2005) after Stow et al., 2002).

Faurgères and Stow, 2008: Factors controlling drift location, morphology and depositional pattern

Large-scale features of drifts are controlled by a number of interrelated factors, including

(1) the bathymetric framework (water depth and morphological context),
(2) the current conditions (velocity, variability, and Coriolis force),
(3) the sediment supply (amount, type, source, input, variability),
(4) interaction with other depositional processes (in time and space),
(5) sea level and sea-level fluctuations,
(6) climate and climate change,
(7) tectonic setting and activity and
(8) the length of time over which these various processes and controls have operated and varied.

It is not a simple matter to disentangle these various controls as many clearly overlap and are interrelated. Neither is it always certain just what effect a particular control exerts.



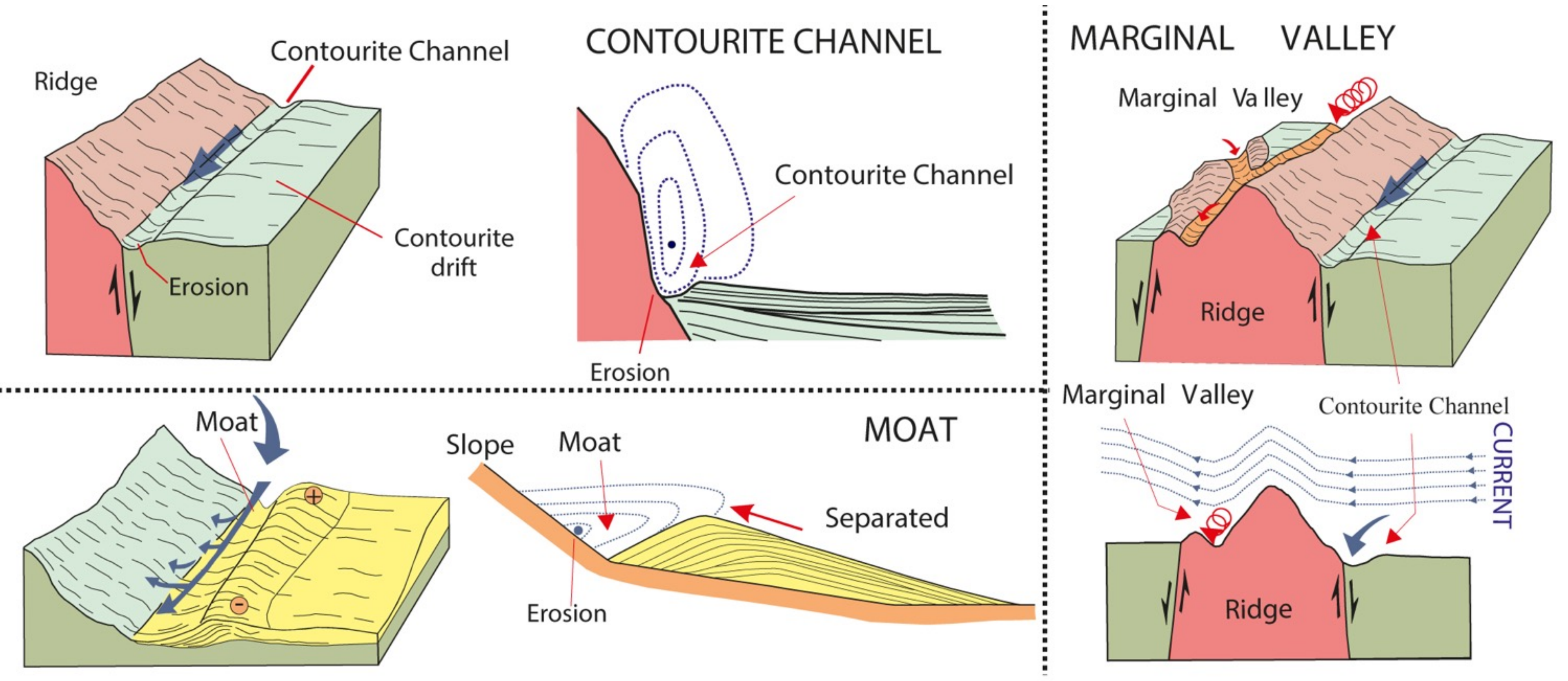
Examples of large contourite drifts:

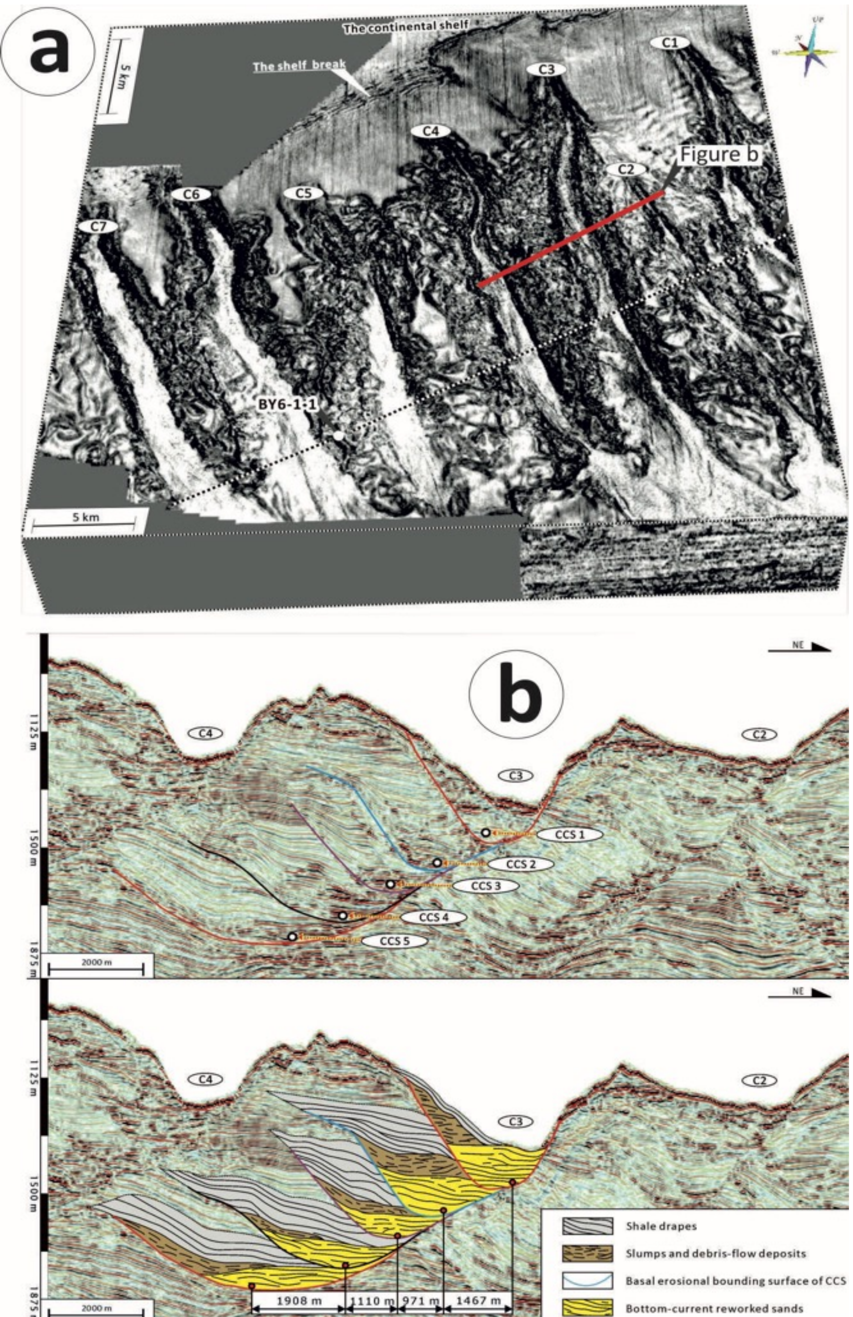
A) Eirik Drift, Greenland margin, northern hemisphere (Hunter et al, 2007);

B) Faro-Albufeira Drift, Gulf of Cádiz margin, northern hemisphere (courtesy of REPSOL Oil);

C) Agulhas Drift, Transkei Basin, southern hemisphere (Niemi et al., 2000).

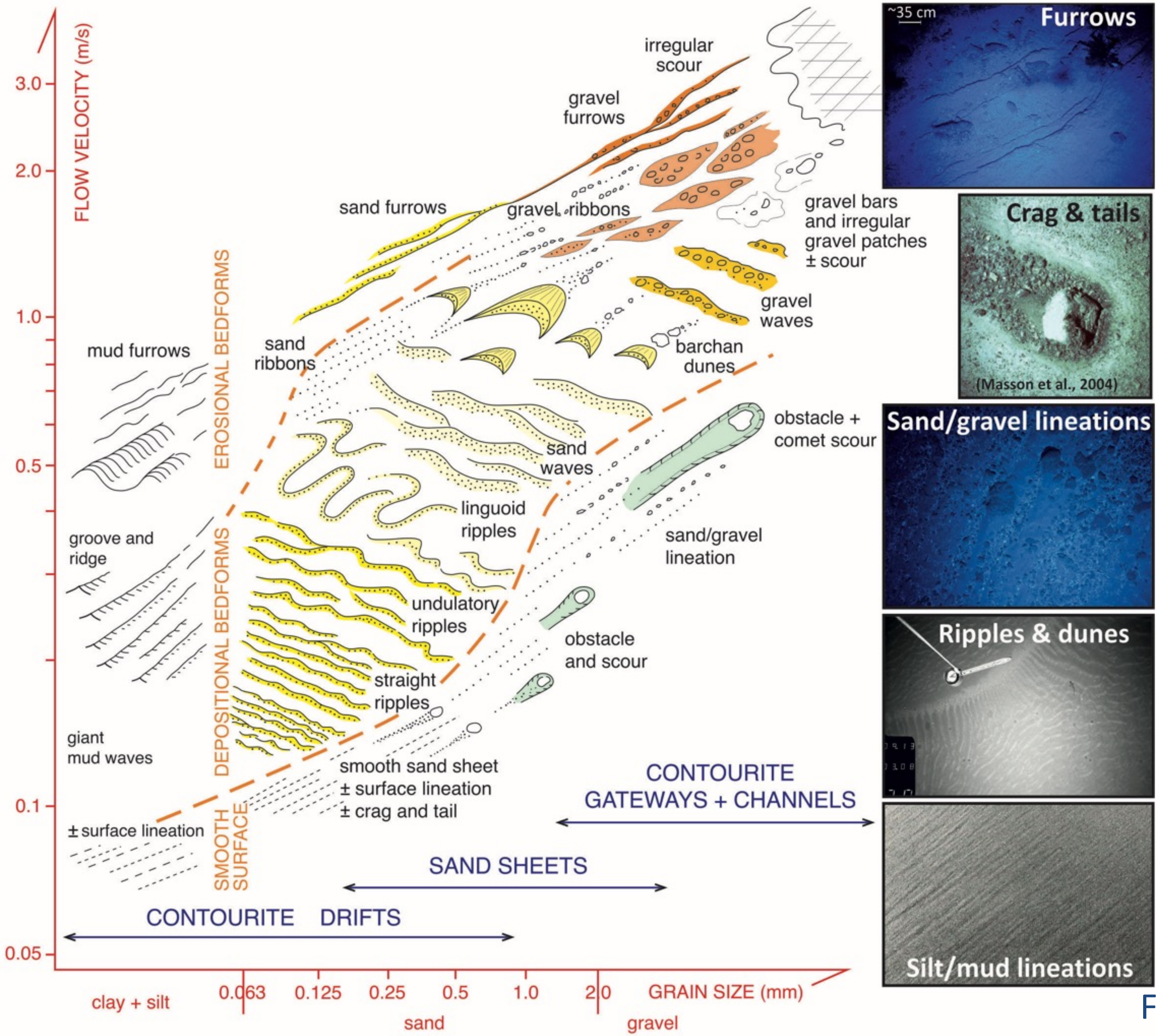
Large-scale **erosional features** are also common in Contourite Depositional Systems, though less studied with respect to depositional ones. Most commonly they occur just in association with contourite drifts, but may also characterize a broad area of continental slopes. We propose here a reconsideration of the only systematic classification of large-scale erosional features attempted so far (Hernández-Molina et al., 2008; García et al., 2009).





Three-dimensional (3D) coherence volume showing unidirectionally migrating deep-water channels (C1 to C7). B) Facies and architecture within unidirectionally migrating deep-water channel 3 (C3). Five channel-complex sets (CCS1 to CCS5), are identified, each of which comprises **bottom-current reworked sands** (BCRS) in the lower part, grading upward
into slumps and debris-flow deposits and, finally, into shale drapes. The BCRS are represented by subparallel and high-amplitude reflections with external lens shapes and are systematically nested in the direction of channel migration (Gong et al., 2013; with permission from the AAPG).

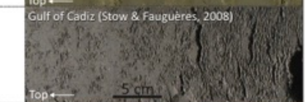
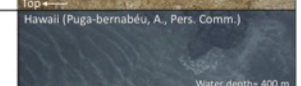
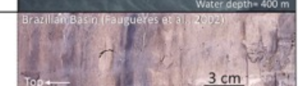
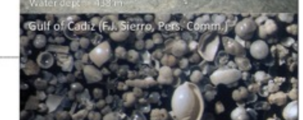
BCRS from previous turbiditic deposits may represent a pragmatic alternative to the application of conventional turbidite concepts, and a new concept for understanding the origin and predicting the distribution of deep-water sandstones. BCRS frequently contain different seismic facies and sedimentary structures.



Various depositional and erosional bedforms are generated by bottom currents. hey are highly variable in terms of sediment composition, morphology and dimension, from decimetres to kilometres. The detection of bedforms can be important for the reconstruction of bottom-current velocity and for geohazard assessment (where velocities can damage seafloor infrastructure, including pipelines and telecommunications cables).

From Stow *et al.*, 2013.

CLASSIFICATION FOR CONTOURITE DEPOSITS

Group	Type of deposits	Grain size	Characteristics	Sed. Structures	Examples
CLASTIC CONTOURITES	**Muddy contourites**	5 - 11 Ø < 0.31 mm	50 % Clays < 15 % of sands ≤20 -30 % of bioclastic and / or carbonate components Homogeneous & highly bioturbated Poor sorting	Rare laminations Bioturbatiion Indistinct mottled appearance	 Rockall Trough (Stow & Fauguères, 2008)
CLASTIC CONTOURITES	**Silty contourites**	4 - 8 Ø 0.063-0.004 mm	40 - 60 % Silts Interbedded between muddy & sandy contourites Poor sorting Sharp to irregular tops and bases	Tractive structures (ripples, sed.waves) Bioturbational mottling Ichonofacies	 Gulf of Cadiz (Stow & Fauguères, 2008)
CLASTIC CONTOURITES	**Sandy contourites**	-1 - 4 Ø 2 - 0.063 mm Normally does not exceed fine sands	Sheeted to wedge beeding Well-sorted deposits, but can be poor to moderate Mixed siliciclastic / biogenic composition Heavy mineral concentration Both positive & negative grading Gradational or erosive contacts	Tractive structures (e.g.: horizontal lamination, cross-lamination, ripples, etc) Bioturbation (sub.vertical burrows) Massive layers (structureless) Erosional or gradational contacts	 Gulf of Cadiz (Stow & Fauguères, 2008)
CLASTIC CONTOURITES	*Bottom current reworked sands (BCRS)*		From previous turbiditic deposits Rhytmic layers Lenticular bedding Well sorted Coarsening upward sequences Sharp to gradational bottom contact and sharp (nonerosiona) upper contactl	Tractive sturctures (e.g.: horizontal lamination, low-angle cross lamination; mud-offshoots in ripples, mud-drapes, flaser, etc)	 Gulf of Mexico (Shanmugam, 2006; 2012)
CLASTIC CONTOURITES	**Gravel contourites**	< -1 Ø > 2 mm	Winnowing & erosion (channels, moats, etc) Irregular layer and lenses Poorly to very poorly sorted	Sandy gravel lag	 Faeroe-Shetland Channel (Akhurst et al., 2002)
VOLCANOCLASTIC CONTOURITES		Mud, silt or sands	Similar to the siliciclastic facies Composition is dominated by volcaniclastic material	Similar to the clastic contourites	 Hawaii (Puga-bernabéu, A., Pers. Comm.)
SHALE-CLASTS OR SHALE-CHIP LAYERS		Shale clasts generally mm in size	Developed in muddy & sandy contourite facies From substrate erosion by strong bottom currents Burrowing on the nondeposition surface	Clats axes sub-parallel both to beeding and to the current direction	 Brazilian Basin (Fauguères et al., 2002)
CALCAREOUS CONTOURITES	**Calcareous muddy & silty contourites**	> 4 Ø < 0.063 mm Silty clay to clavey silts	>70 % of bioclastic and / or carbonate components Dominant biogenic input Poorly sorted Distint sand-size fractions (biogenic particles) Composition: pelagic to hemipelagic, including nannofossils & foraminifers as dominat elements Admixture of siliciclastic or volcanicclastic material	Bedding is indistint, but may be enhanced by cyclic variations in composition / grain size. Bioturbation	 Ortegal Spur (Belgica GENESIS Cruise)
CALCAREOUS CONTOURITES	**Calcareous sandy contourites**	-1 - 4 Ø 2 - 0.063 mm Sands	Equivalent of sandy contourites Both well-sorted to poorly sorted Particles from pelagic, benthic, off-shelf & off-reef sources Admixture of siliciclastic, volcanic & silicieous material	Thin-bedded cross-laminated foraminera contourite. Lenticularity Hardgrounds.non de`positional surfaces Bioturbation & burrowing	 Gulf of Cadiz (F.J. Sierro, Pers. Comm.)
CALCAREOUS CONTOURITES	**Calcareous gravel lag contourites**	< -1 Ø > 2 mm Gravel	Clasts or chips derived from erosion of the subtrate		
SILICEOUS BIOCLASTIC CONTOURITES		Mud, silt or sands	Rich in diatomaceous & radiolarian material	Laminated and / or cross-laminated sands	 Blake-Bahama Basin (DSDP, Site 534, Sheridan et al 1983)
CHEMOGENIC CONTOURITES	**Manganíferous contourites**		Manganiferous or ferro-manganiferous horizonts Areas with ferro-manganese nodules & pavements	Bioturbation & burrowing	 Brazilian Basin (Gonthier et al., 2003)
CHEMOGENIC CONTOURITES	**Chemogenic gravel-lag contourites**		Deep-water chenoherms (chemical - biogenic precipitates) of metal - carbonate chimneys, mounds & encrustations Winnowed and aligned into chemogenic gravel-lags	Strewn od debris Alineation of gravel-lag	 Bellingshausen Basin (Heezen & Hollister, 1971)

Stow and Faugères (2008) + BCRS from Shanmugam, 2012

Martín-Chivelet et al., 2008 Traction structures

40 years of controversy

1950s: discovery of current ripples = establishment of the contourite facies

1970s: discovery of fine-grained turbidites = seed of controversy since similar sedimentary structures of contourites.

1980s: concept that bioturbation destroy traction structures = reinterpretion of contour-current deposits as fine-grained turbidites

1990s: few workers provided convincing evidence of traction structures = most workers reject this criterium

Setting the stage for sedimentary structures in contourites

In the time interval between deposition and significant lithification, burrowing can be sufficiently intense to destroy previous traction structures.

Traction structures are abundant on recent ocean floors.

Traction structures are more abundant and easily preserved in sandy contourites.

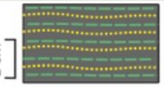
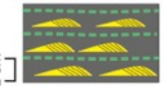
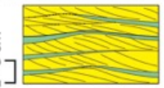
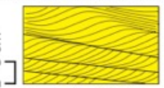
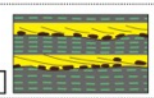
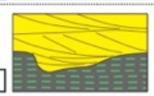
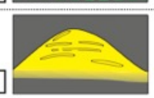
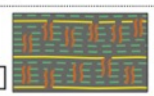
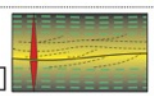
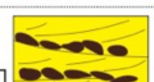
Thermohaline circulation in older, greenhouse times, was probably driven by active sinking of saline waters in intertropical seas

studies from boreholes or small outcrops might be biased by partial observation of bedform geometry,internal architecture and lateral arrangement.

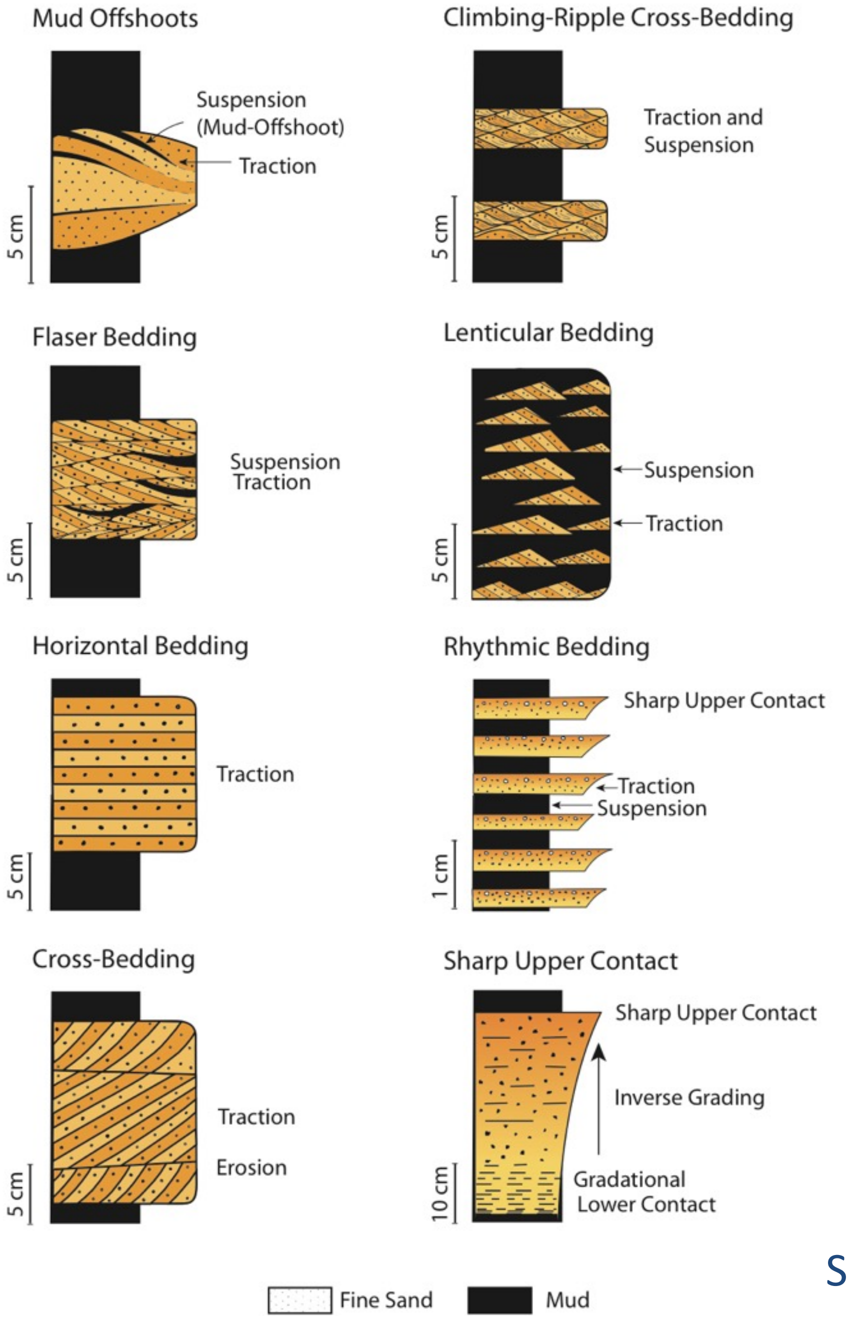
turbidity currents are sediment gravity flows contour currents are water flows.

Various **sedimentary structures** have been described for contourites in present and ancient deposits (Martín-Chivelet *et al.*, 2008). However, in areas of intense bioturbation from benthic activity, the preservation potential of some of these structures can be low.

MAIN TYPES OF PRIMARY SEDIMENTARY STRUCTURES IN CONTOURITE DEPOSITS

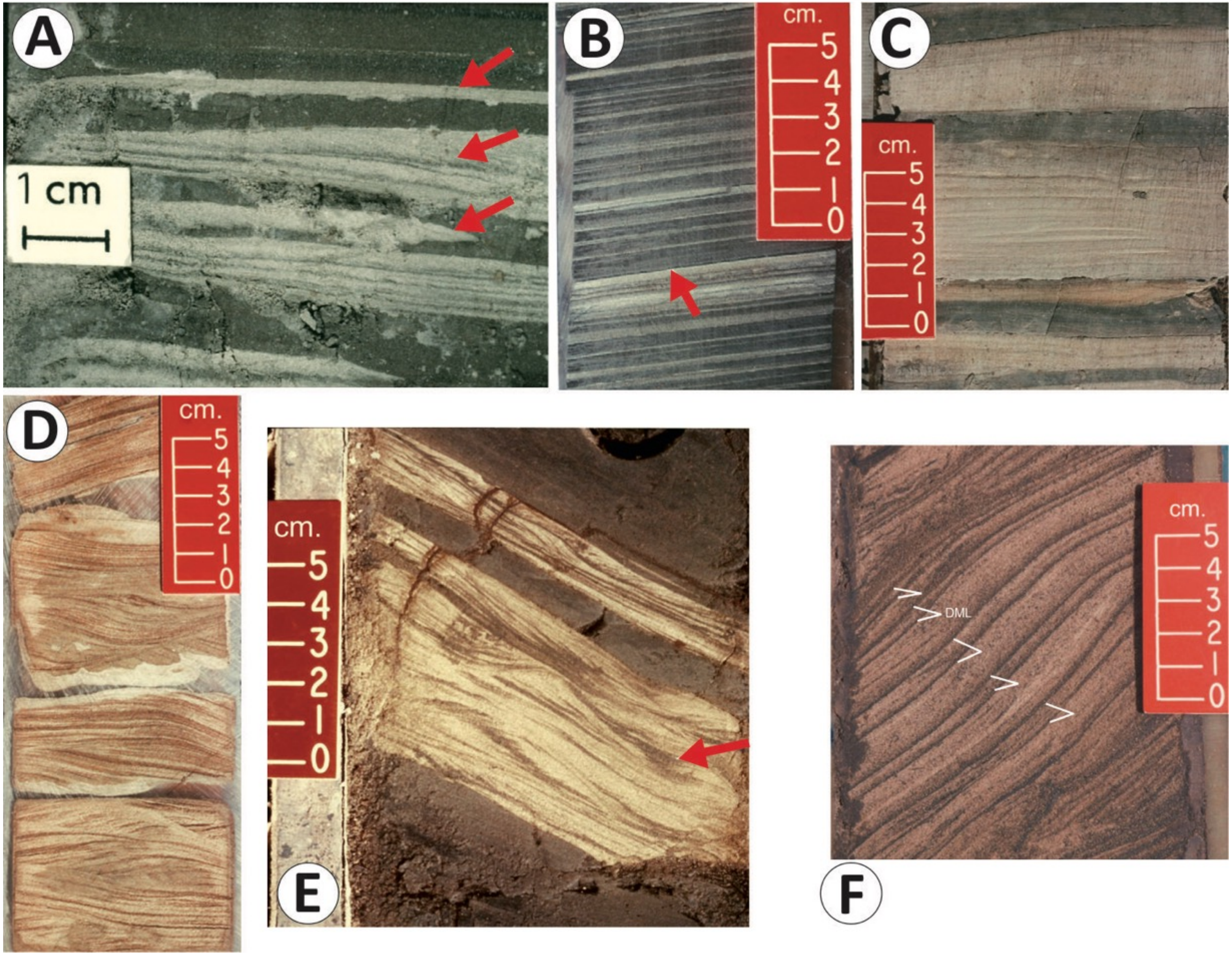
Sketch	Sed. structures	Dominant grain size	Enviromental implications
1 cm 	Horizontal or sinusoidal lamination, stripped, fine-grained deposits; "wispy" lamination	Fine sand, silt & mud < 2 Ø < 0.250 mm	Low current strength Predominance of deposition from suspension
1 cm 	Lenticular bedding starved ripples	Fine sand, silt & mud < 2 Ø < 0.250 mm	Alternating flow conditions, low to moderate current strength, winnowing
1 cm 	Wavy bedding, flaggy chalks	Fine sand, silt & mud < 2 Ø < 0.250 mm	Alternating flow conditions, low to moderate current strength
1 - 5 cm 	Flaser bedding, mud offshoots	Fine sand to silt 8 - 2 Ø 0.004 - 0.250 mm	Alternating flow conditions, Current speed = 10 - 40 cm / s
1 - 5 cm 	Climbing ripples (subcritical to supercritical)	Very fine to medium sands 4 - 1 Ø 0.063 - 0.5 mm	Current speed = 10 - 40 cm / s High suspension load
10 - 50 cm 	Large-scale cross-bedding, megaripples, dunes, sandwaves	Medium sands 2 - 1 Ø 0.250 - 0.5 mm	Current speed = 40 - 200 cm / s Barchan dunes usually form at 40-80 cm / s
1 cm 	Parallel lamination (upper stage plane beds), presence of primary current lamination	Very fine to medium sands 4 - 1 Ø 0.063 - 0.5 mm	Current speed = 40 - 200 cm / s
1 cm 	Minor erosive surfaces, mud rip-up clasts, upper sharp contacts	Sand, silt & mud < -1 Ø < 2 mm	Alternating flow conditions, low to moderate current strength
1 - 5 cm 	Sole marks: flutes, obstacle scours & longitudinal scours, cut & fill structures	Sand, silt & mud < -1 Ø < 2 mm	Flow speed peaks
5 cm 	Longitudinal ripples	Coarse sandy muds (20 % sand)	Low current speed = 2 - 5 cm / s Winnowing
1 - 10 cm 	Bioturbation (strongly variable)	Sand, silt & mud	Low current speed Strong paleoecological control, Low to moderate accumulation rates
3 - 20 cm 	Normal & reverse grading at different scales and within different types of deposits	From coarse sand to mud Usaully fine sand, silt & mud	Gradual changes in flow strength
0.1 - 2 cm 	Pebble lags, furrows	Coarse sand, microconglomerate	Current speed over 200 cm / s

Clay and / or mud — Silt — Sand — Pebbles & cobbles



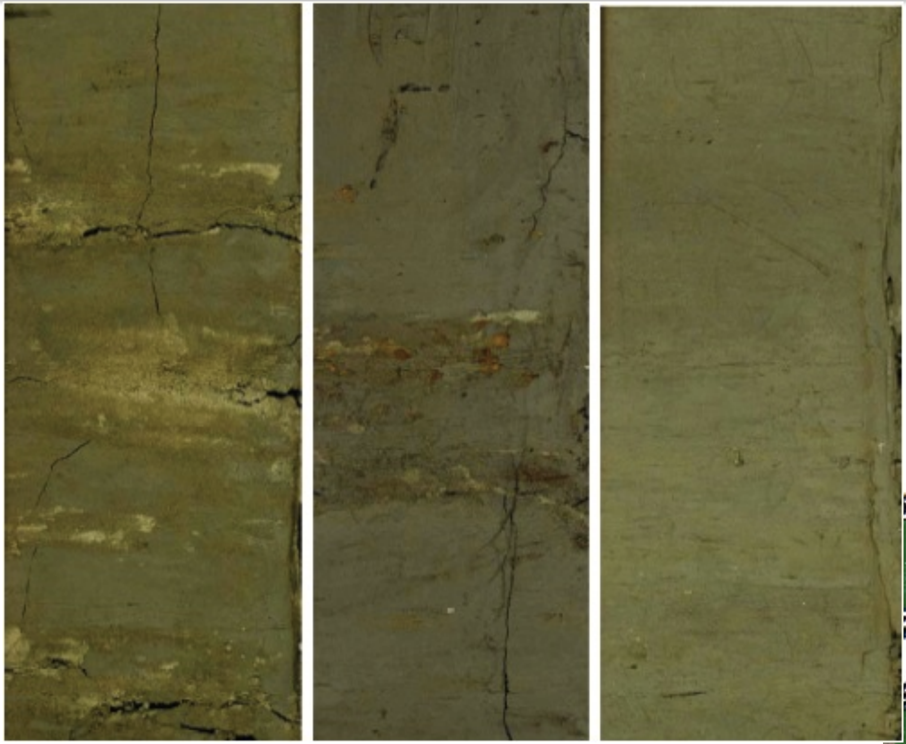
Most of these structures are also present in other deep-water deposits (*e.g.* turbidites), but some have been suggested to be a clear diagnostic feature for bottom-current deposits, such as: *negative grading*; *longitudinal triangular ripples*; and *double mud layers and sigmoidal cross-bedding*, which are unique to deep-water tidal deposits in submarine canyons (Shanmugam, 2006; 2012).

Shanmugam et al., 1993



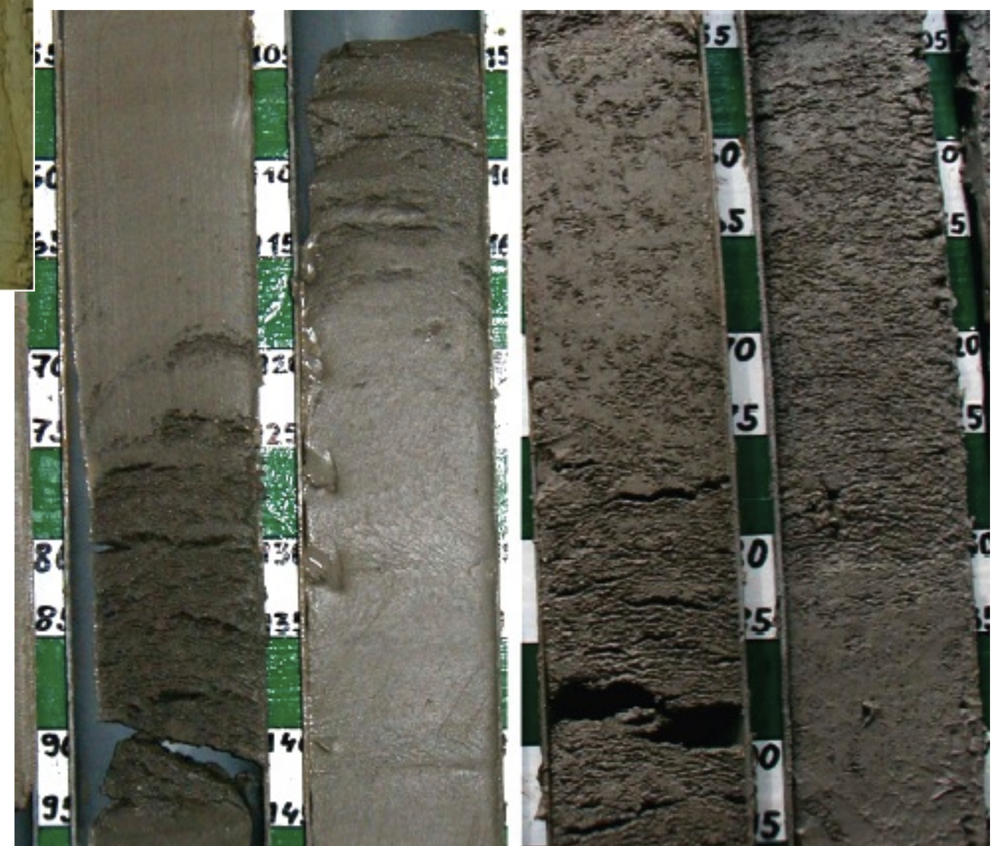
Sedimentary structures in bottom-current reworked sands (BCRS): A) Discrete thin sand layers with sharp upper contacts; B) Rhythmic layers of sand and mud, inverse grading, and sharp upper contacts; C) Horizontal lamination with gradational upper contact; D) Convex-up and concave-up laminae; E) Flaser bedding; and F) Double mud.

Shanmugan, 2008; Shanmugam *et al.*, 1993; Shanmugam, 2012



Stow and Faurgères, 2008: Silty-Muddy contourites

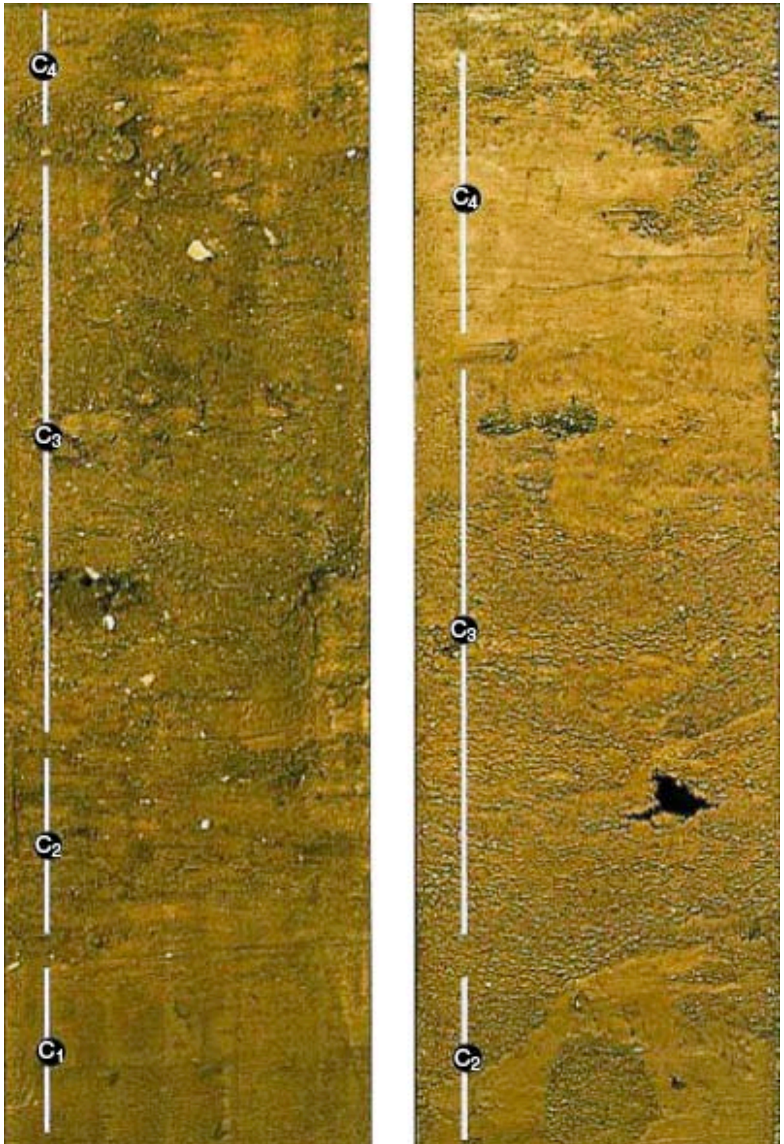
Homogeneous, featureless, poorly bedded units in some cases showing cm-dm banding marked by subtle colour and core logging changes.



Highly bioturbated (mottled with burrows). Rare primary indistinct lamination (marked by colour change and/or irregular winnowed concentrations of coarser material). Rarely, remnants of thin cross-laminated beds. Silty–clay grain size and poor sorting, with dominantly siliciclastic composition with some biogenic fraction. Either local and far-travelled components

Sandy contourites

Either as thin irregular layers and much thicker units within the finer grained facies, may display either distinct or gradational contacts. Thoroughly bioturbated, appear massive (structureless). The mean grain size normally does not exceed fine sand (apart from coarser grained horizons and lags), and sorting is mostly poor to moderate, in part due to bioturbational mixing.

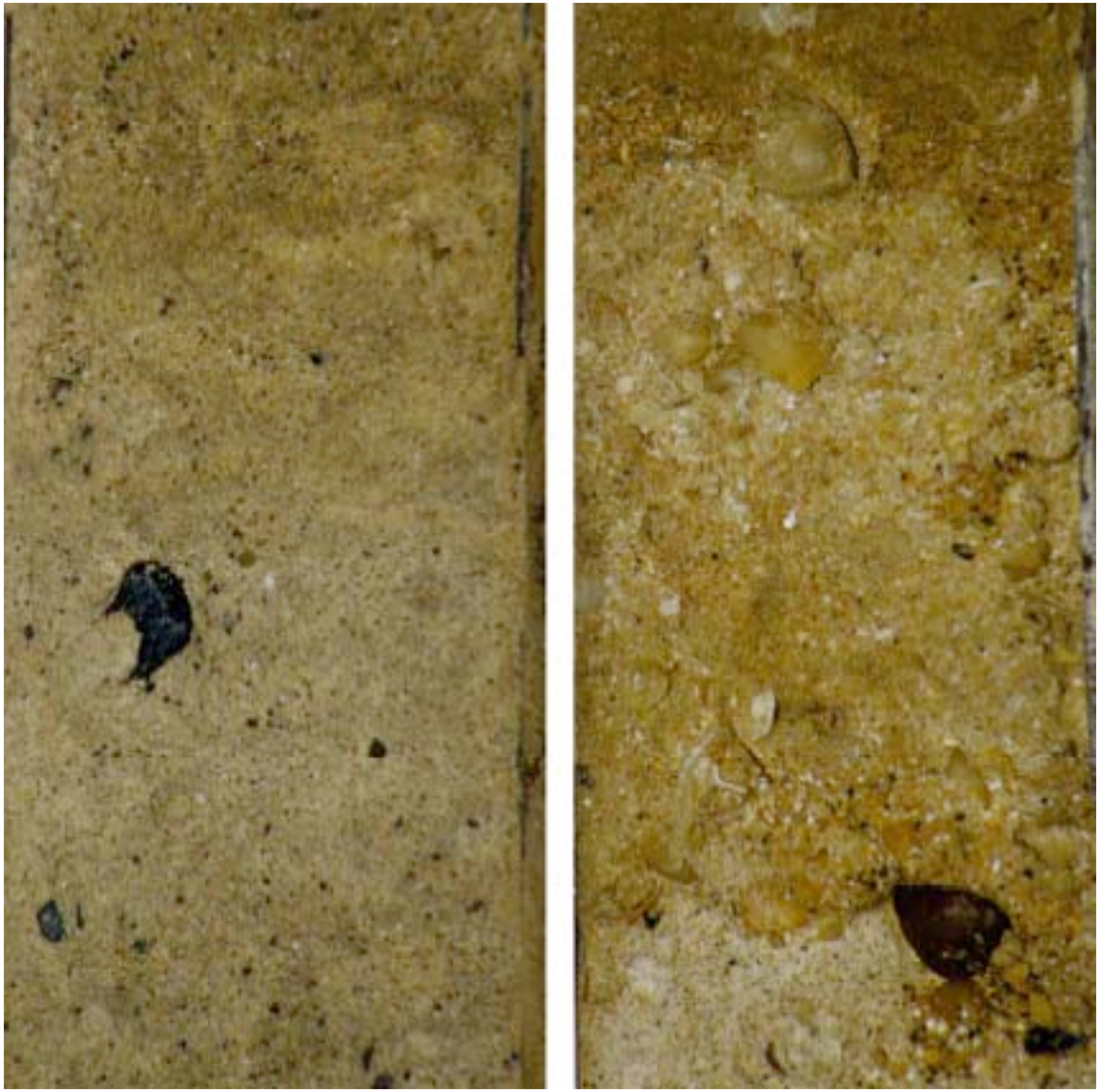


Both positive and negative grading may be present. A mixed siliciclastic–biogenic composition is typical, with evidence of abrasion, fragmented bioclasts and iron-oxide staining.

Laminated sandy contourites

Less common than their bioturbated counterparts and have been rarely documented, but do occur where high-energy (high-velocity) bottom currents are especially dominant and larger-scale bedforms (e.g. dunes) are evident on the sea floor. The few examples observed to date are thick to very thick-bedded and distinctly laminated. The lamination is relatively broad and diffuse, enhanced by slight colour variation, and parallel at the scale of the cores, although this may also be part of large-scale cross-bedding. Bioturbation is rare, but large sub-vertical burrows have been noted. The mean grain size is medium-grained sand, with moderately good sorting. The sediment has a mixed siliciclastic/biogenic composition, with evidence of abrasion, fragmented bioclasts and iron-oxide staining.

Gravel-rich contourites and gravel-bearing contourites

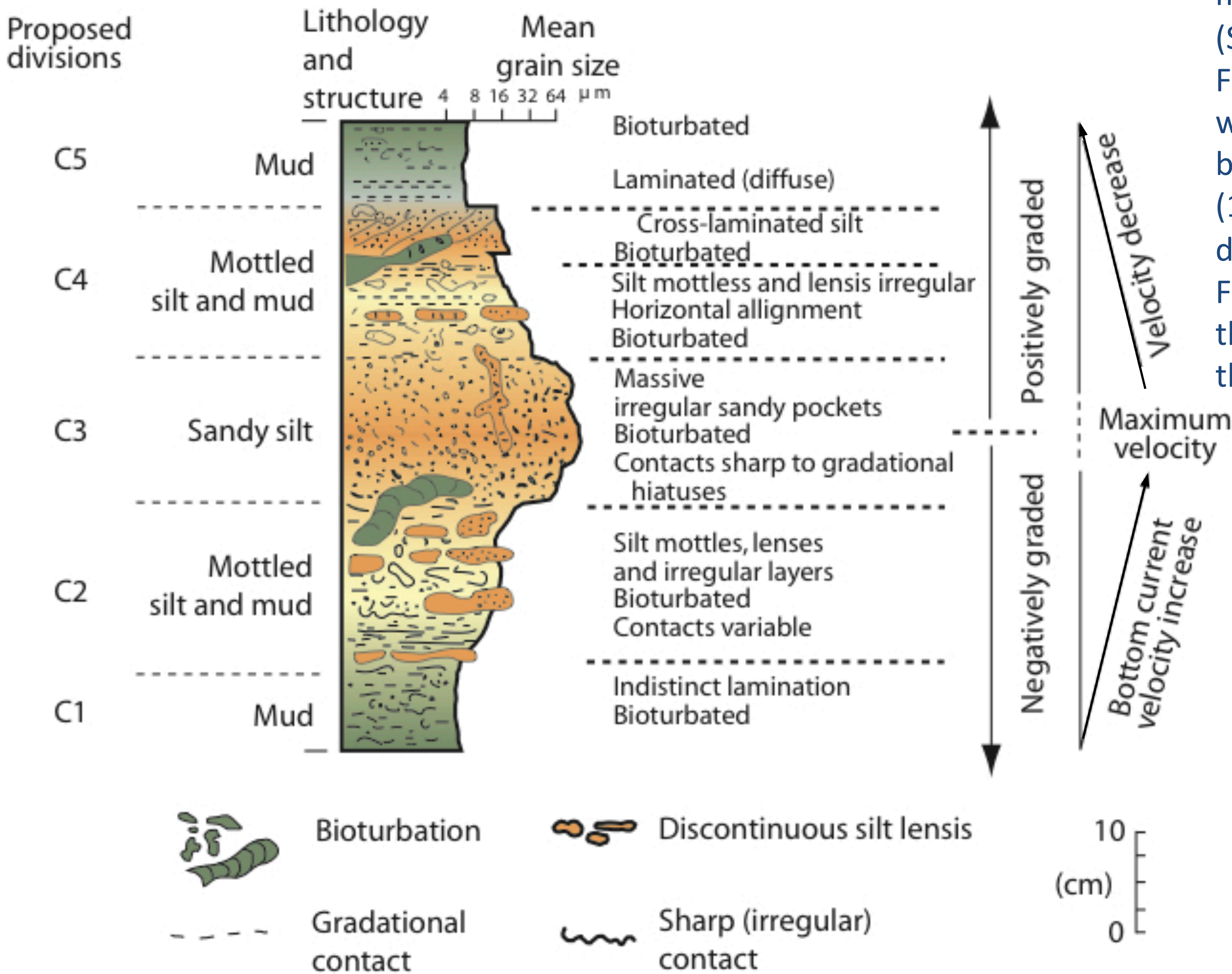


Common in drifts at high latitudes (ice-rafted debris). Under relatively low-velocity currents, IRD remains and is not subsequently reworked. This facies is often indistinguishable from glaciomarine hemipelagites.

Concentration of the coarser fraction occurs under higher-velocity currents and more extensive winnowing, yielding irregular layers and lenses of poorly to very poorly sorted, sandy gravel-lag.

Similar coarse-grained concentrations and gravel pavements are locally developed in response to high-velocity bottom-current activity in shallow straits, narrow contourite moats and passageways.

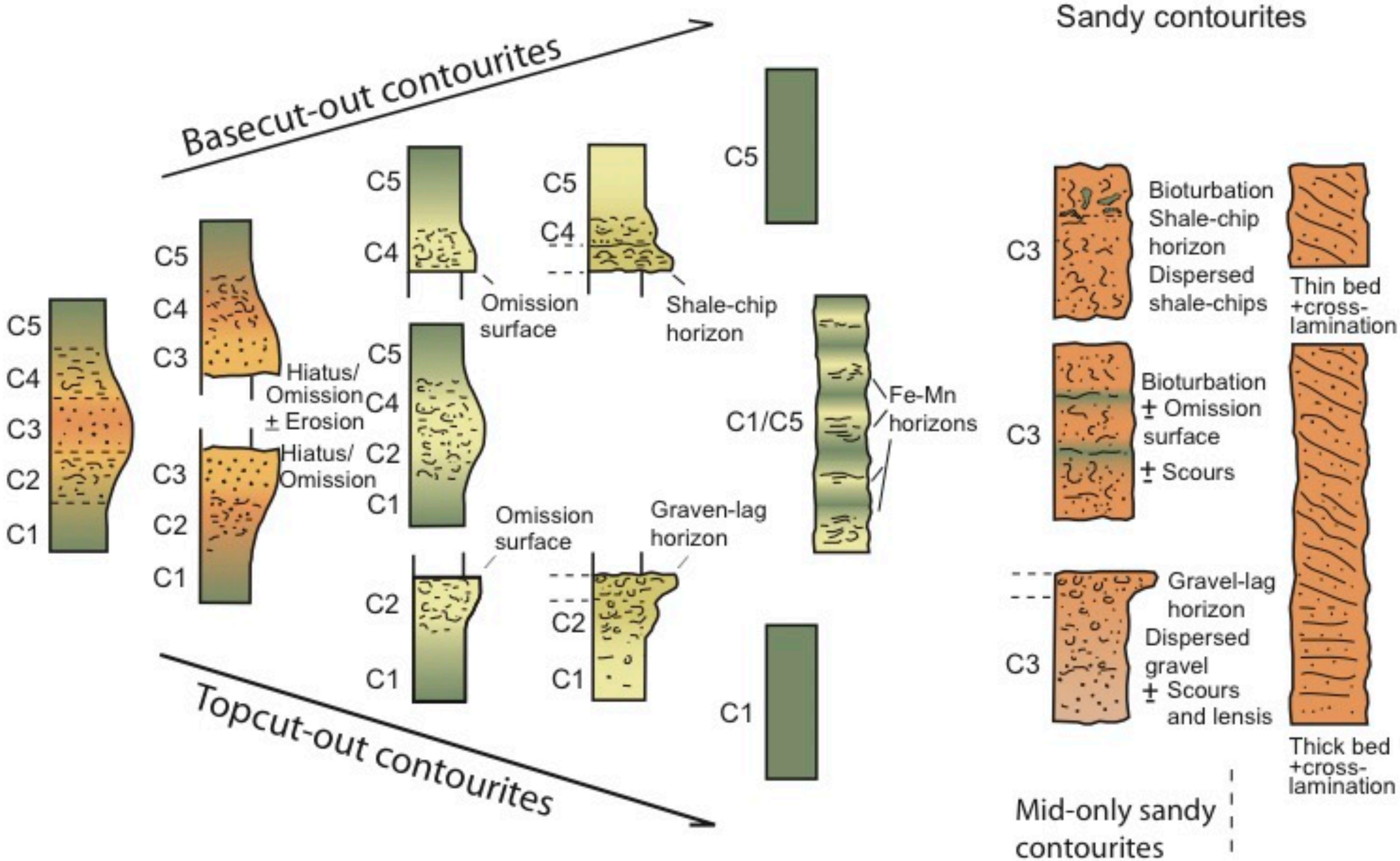
The creation of a definitive **facies model** for contourites poses major challenges.



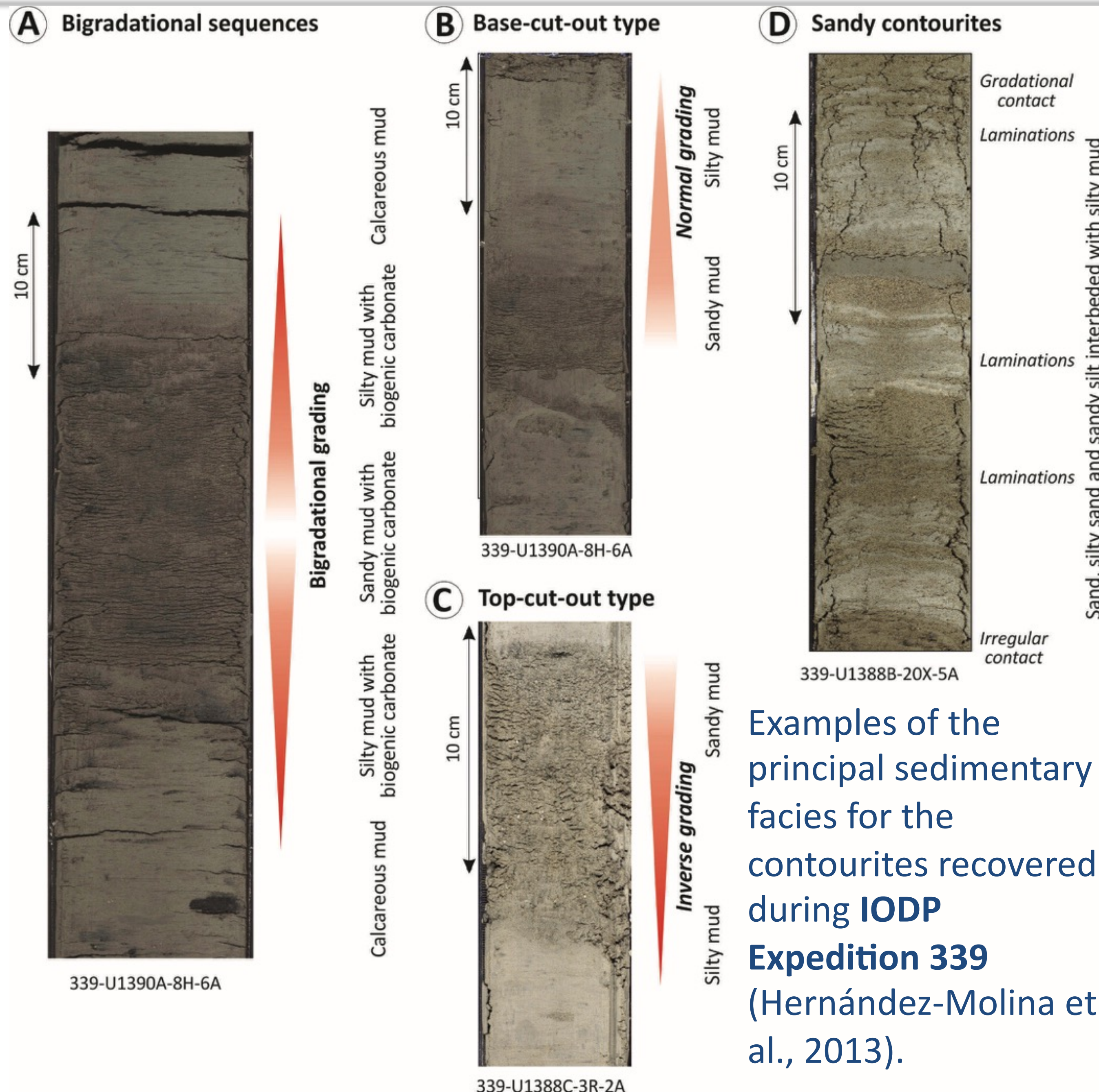
The standard contourite facies model sequence (Stow and Faugères, 2008) was first proposed by Gonthier *et al.* (1984) and was derived from the Faro Drift within the middle slope of the Gulf of Cádiz.

This model implies a cyclic trend, encompassing 3 main facies, linked to variation in contour-current velocity.

Facies and facies sequences associated to contourites vary greatly, making any singular, systematic characterisation of facies rather difficult for the moment. Stow et al. (2002) slightly modified the standard sequence by using five principal divisions (C1–C5), and Stow and Faugères (2008) later proposed a model for partial sequences ,which are equally or more common than the full bi-gradational sequence.



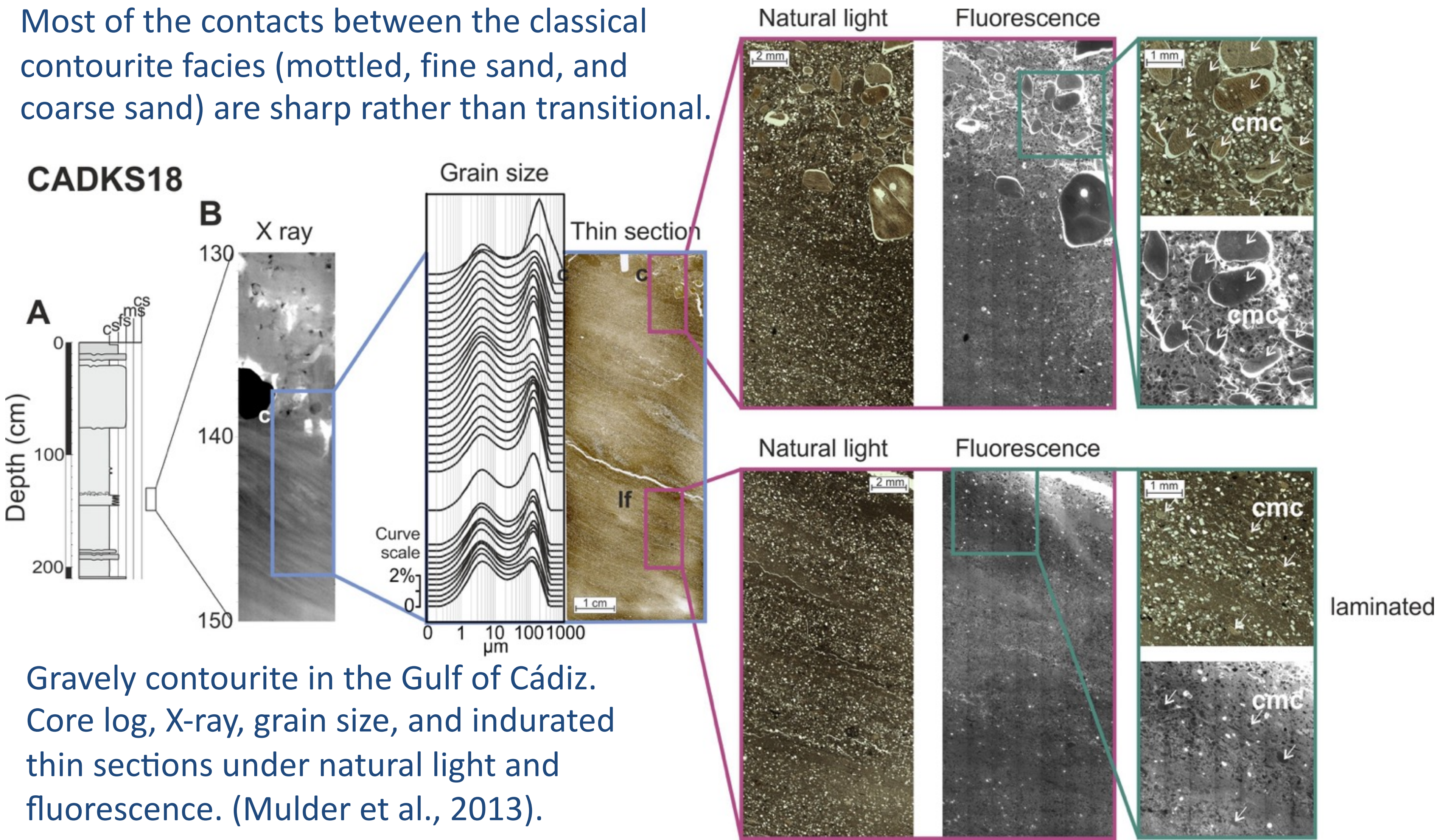
Preliminary results are in agreement with the previously proposed idea that there is a greater variety of facies sequences for bottom current deposits than what is presently represented in the most commonly accepted contourite facies model. Additionally, remarkable interactions between contourite and turbidite processes have been reported that are completely new and different from the current facies models.



Examples of the principal sedimentary facies for the contourites recovered during **IODP Expedition 339** (Hernández-Molina et al., 2013).

The main criticism for considering the Faro Drift deposits as the standard contourites facies sequence relates to two facts: this drift is predominantly muddy, and it is located in the distal part of a huge CDS. Moreover, other facies in other parts of the same depositional system have recently been reported, but it is difficult to apply the conceptual model to them.

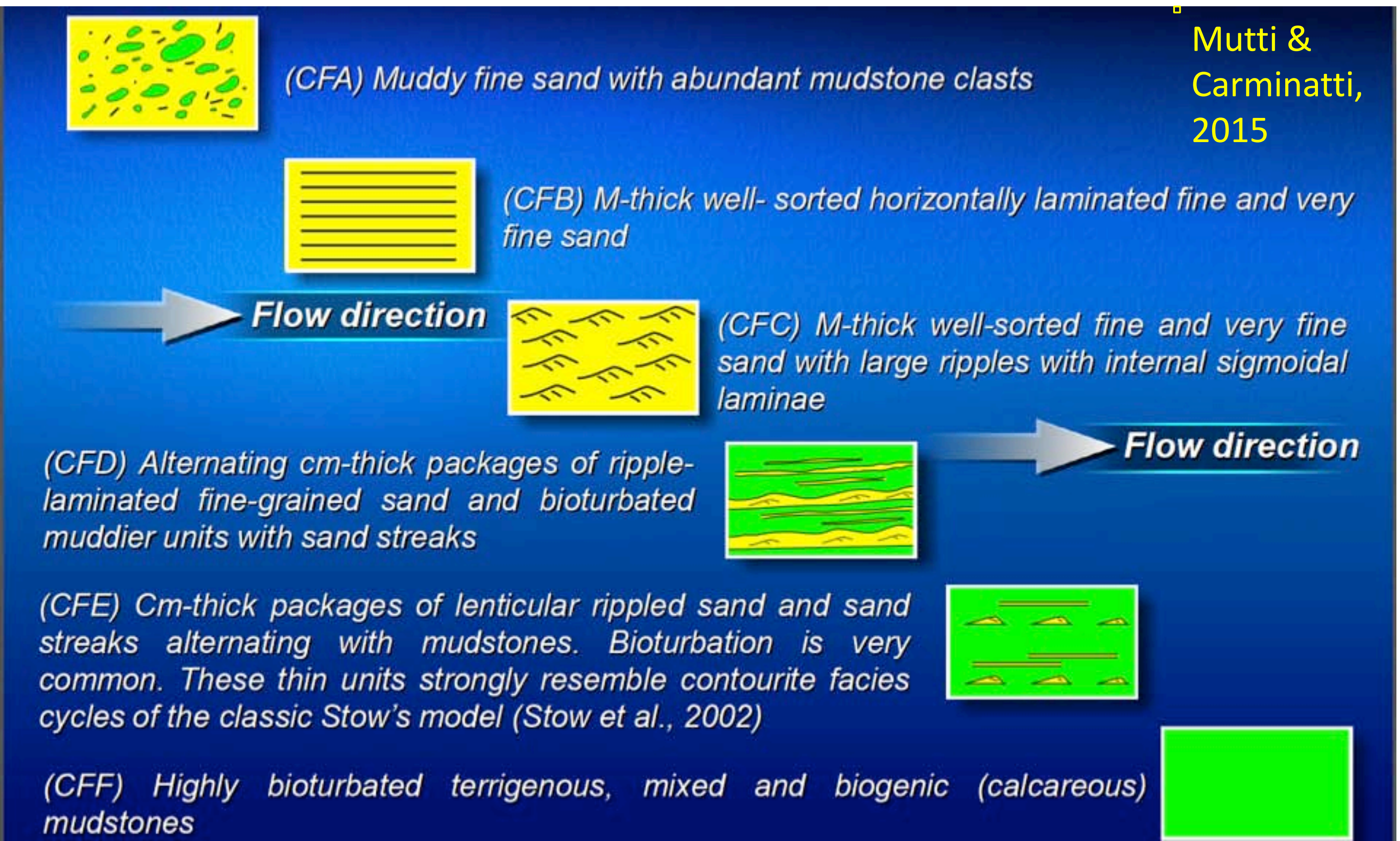
Most of the contacts between the classical contourite facies (mottled, fine sand, and coarse sand) are sharp rather than transitional.



Gravely contourite in the Gulf of Cádiz. Core log, X-ray, grain size, and indurated thin sections under natural light and fluorescence. (Mulder et al., 2013).

Preliminary contourite facies tract (?)

In the Campos Basin, bottom currents played a major role since late Cretaceous in reworking and redistributing turbidite fine sands derived from basin margins.

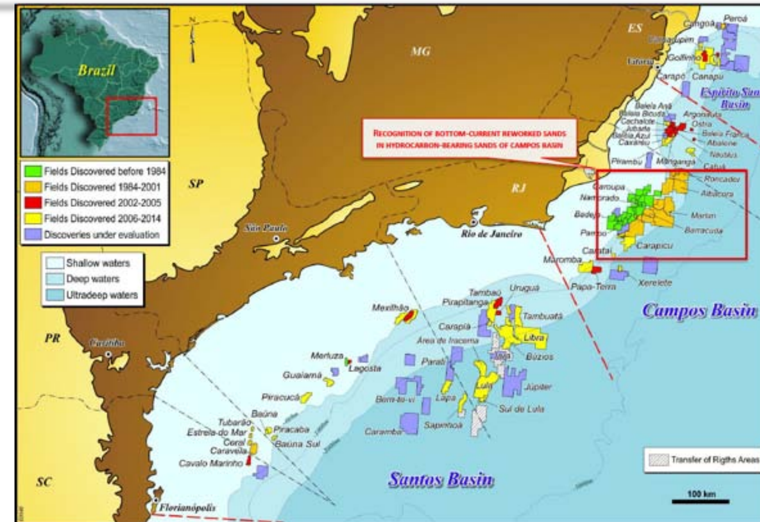


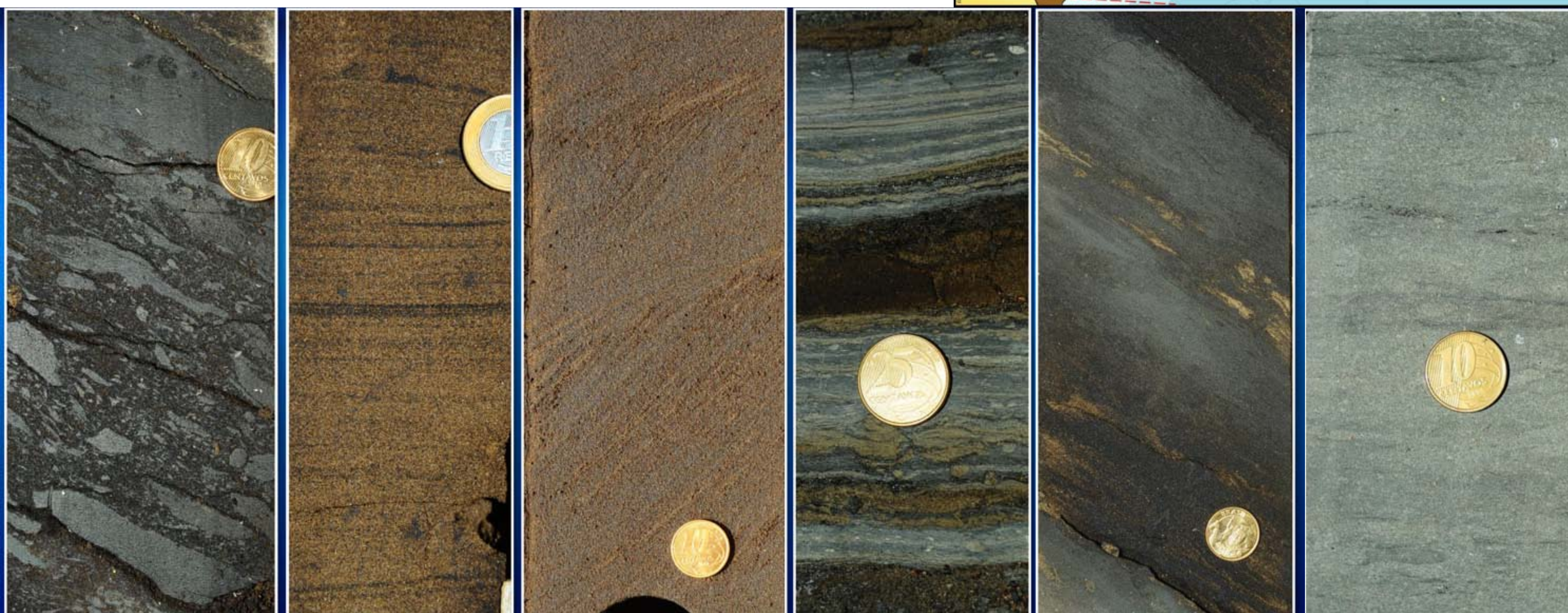
Mutti & Carminatti, 2015

Currently available models for deep-water sedimentation are inadequate to describe and interpret the complexity of depositional patterns developed by the interaction of bottom currents and sediment gravity flows.

Photos of Contourite Facies A-F in the Campos Basin

Mutti & Carminatti, 2015





CFA CFB CFC CFD CFE CFF

Most of the **future perspectives** in contourite research strongly depend on continuous technological advances.

Use of numerical or sand-box modelling, indurated thin sections, Ichnological Digital Analysis Images Package, CT scanning, HR 3D seismics, observations from AUV, seismic oceanography, fingerprinting of water masses using isotopic tools are steadily expanding techniques.

A more intensive collaboration between physical oceanographers and geologists!!!

Scale will be an especially important factor:

- high-resolution to elucidate the relationship currents and smaller contourite deposits;
- increased resolution to detail spatial and temporal variability within a single deposit;
- larger-scale perspective on CDS sharing the same basin, water masses and time scale.

The advances expected in contourite research should lead to the establishment of better diagnostic criteria for contourite identification.

CONCLUSIONS

Contourite processes are not as simple as initially thought.

Contourite nomenclature might need to be reconsidered.

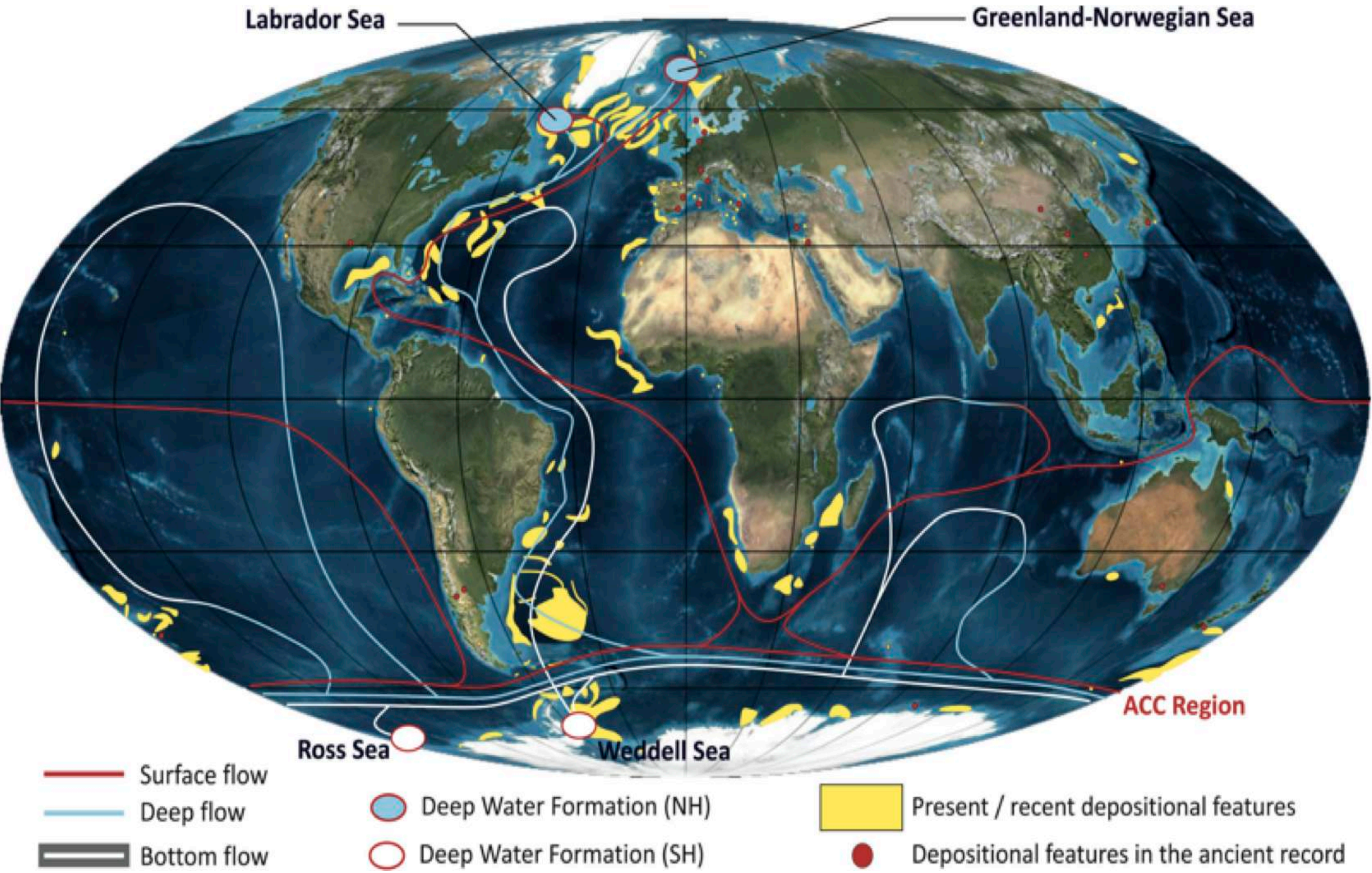
New facies models must be established.

More work is needed to understand sandy contourites.

Integrated studies will be essential for an holistic perspective.

Pervasiveness of bottom-water circulation to be reconsidered.

Future discoveries?



Take home message

Bottom currents,’persistent’ water current near the sea-floor, are influenced by a series of factors and pervasively affect the seafloor sediments.

Contourites, sediments deposited or significantly affected by bottom current, begin to be perceived as a fundamental component of deep sea depositional systems.

Contourite drifts generally composed of fine sediments, are large sedimentary accumulations produced by bottom currents, which can allow us to reconstruct their evolution and paloceaonography.

The **sedimentary facies** are manifold and the diagnostic sedimentary characteristics are still under discussion.

Bottom currents and contourites are of **great importance** for paleoclimatic reconstructions, investigations on continental slopes and their stability, the exploration of hydrocarbons and polymetallic nodules, definition of the “extended continental shelf”, ecological health of deepwater ecosystems, accumulation of microplastics and contaminants .