Deep-Water Sands of the Brazilian Offshore Basins*

Emiliano Mutti[1] and Mario Carminatti[2]

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[1]University of Parma, Parma, Italy (mutti@unipr.it)
[2]Petrobras-Exploration, Rio de Janeiro, Brazil

Abstract

During the last three decades Petrobras continuously developed aggressive exploration and production activities in deep and ultra deep waters of the Brazilian Marginal basins. As a result, giant oil fields with original oil reserves of up to 2.7 Bn bbl were discovered (e.g. Marlim, Albacora and Roncador oil fields) leading to a very fast growth of Brazilian proved reserves.. Around 88% of these proved reserves and more than 80% of the 2 million boe daily production come from Cretaceous and Tertiary deep-water sandstones in Campos Basin, until recently interpreted as turbiditic depositional systems.

In this basin, a continuous search for the best geological model has been carried out in order to optimize the production systems which generated an impressive data base composed of 3D and 4D seismic surveys, well logs, cores and fluids samples. A study of these deep-water sands, based mainly on extensive core analysis, reveals their depositional complexity. Bottom currents played a major role since the late Cretaceous in reworking and redistributing turbidite fine sands derived from basin margins, thus generating mixed turbidite-contourite depositional systems. Fine-grained and current-laminated contourite sands form sizeable, high-quality and prolific reservoirs in many oil fields. As a consequence of this sedimentological constraint to manage reservoir uncertainties, most high-value economic decisions were systematically taken after monitoring extended well tests and/or pilot production projects. Contourite sandstone bodies can be seismically recognized and mapped at the limit of their vertical and lateral resolution to tie each of them to its corresponding source area. Through 3D-seismic amplitude maps it is possible to characterize depositional geometries, to infer facies and to determine bottom current directions and their relationship with the underlying topography. Clearly, this kind of depositional setting has no analogs in exposed ancient deep-water systems dominated by turbidity currents. External and internal geometry and facies distribution patterns of mixed turbidite-contourite systems will require a considerable research effort in future years because of their economic importance. The application of new production technologies to improve recovery factors and reduce the number of producing wells, by enhanced well productivities, is completely dependent on the physical and petrophysical characteristics of sedimentary facies.

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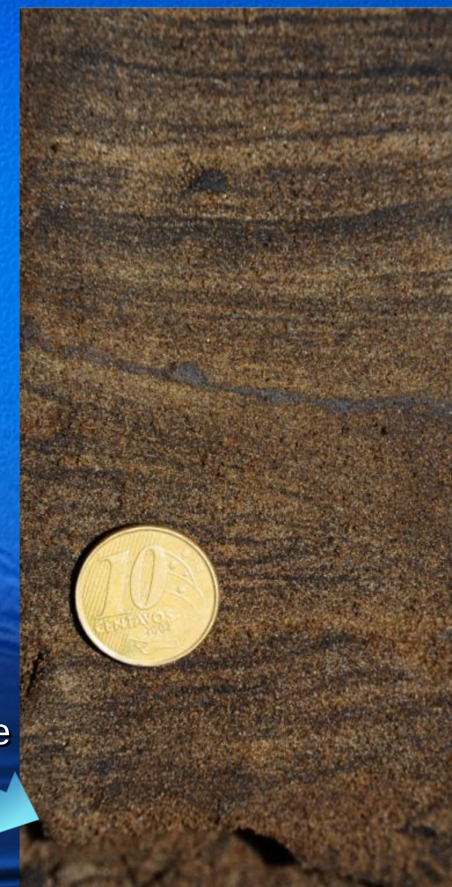
Deep-Water Sands in the Brazilian Offshore Basins

Emiliano Mutti
University of Parma, Italy

Mario Carminatti
Petrobras, Brazil

"Turbidites, reworked turbidites and contourites of the Brazilian offshore basins"

Turbidite pebbly sandstone



Contourite sandstone

Objectives

To show that a large proportion of the upper Cretaceous and Tertiary deep-water sands of the Brazilian offshore basins were mainly deposited under the control of bottom currents.

To show that the action of bottom currents was virtually ubiquitous.These currents can rework turbidites at various degrees of intensity (these deposits are herein referred to as ***reworked turbidite systems****) or build up laterally extensive bodies of fine-grained and well-sorted sand (herein referred to as* ***contourite systems s.s****.) which are excellent reservoirs.*

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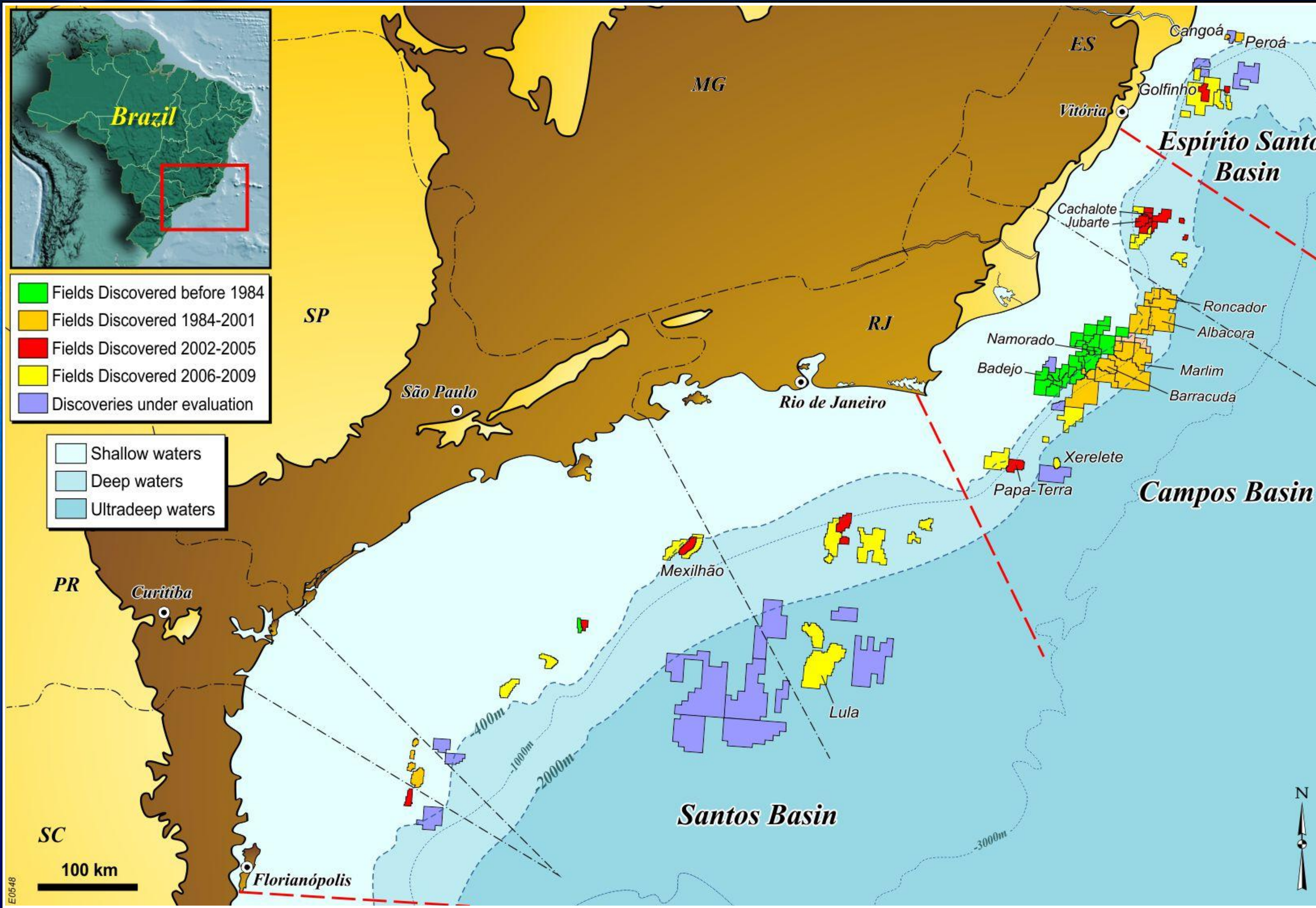
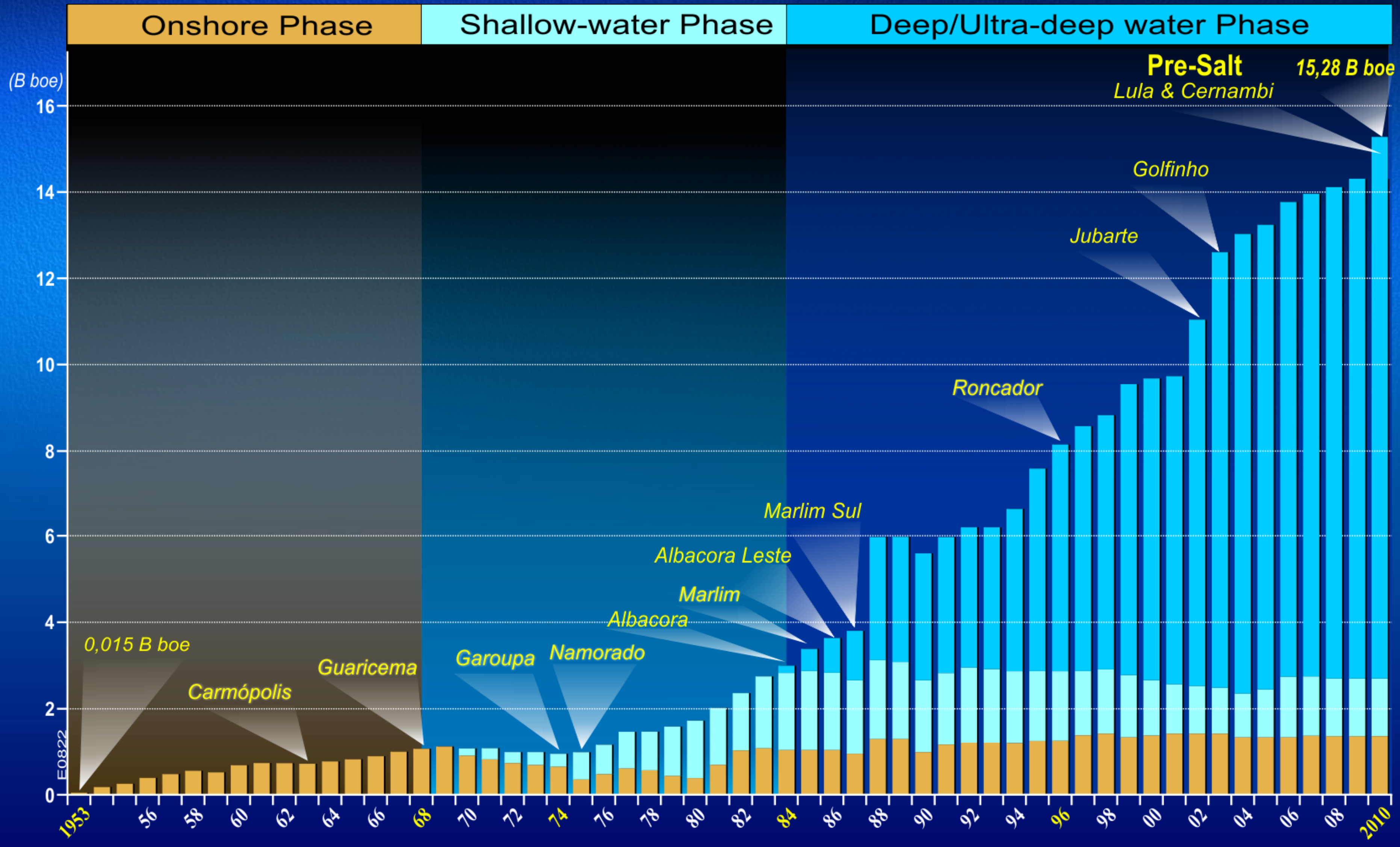
To preliminary show the great variety of depositional and erosional structures that can be observed in these sediments through a detailed core analysis.

To show that currently available models for deep-water sedimentation of continental margins, still essentially based on sediment gravity flows and deep-sea fan models, are inadequate to describe and interpret the real world of continental margin sedimentation.

Location Map




Onshore Phase
Shallow-water Phase
Deep/Ultra-deep water Phase
(B boe)
16
14
12
10
8
6
4
2
0
Pre-Salt
Lula & Cernambi
15,28 B boe
Golfinho
Jubarte
Roncador
Marlim Sul
Albacora Leste
Marlim
Albacora
0,015 B boe
Guaricema
Garoupa
Namorado
Carmópolis
E0822
1953
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06
08
2010

CAMPOS BASIN

542 cored wells

19,230.61 meters of recovered cores

Fields with cores

ALBACORA
ALBACORA LESTE
ANEQUIM
AREA DO RJS-150
AREA DO RJS-485
AREA DO RJS-498
BADEJO
BAGRE
BALEIA AZUL
BALEIA FRANCA
BARRACUDA
BICUDO
BIJUPIRA
BONITO
CACHALOTE
CARAPEBA
CARAPICU
CARATAI
CARATINGA
CATUA
CAXAREU
CHERNE
CONGRO
CORVINA
ENCHOVA
ENCHOVA OESTE
ESPADARTE
FRADE
GAROUPA
GAROUPINHA
GUARAJUBA
JUBARTE
LINGUADO
MALHADO
MARIMBA
MARLIM
MARLIM LESTE
MARLIM SUL
MAROMBA
MOREIA
NAMORADO
NORDESTE DE NAMORADO
PAMPO
PAPA-TERRA
PARATI
PARGO
PIRAUNA
RONCADOR
SALEMA
TRILHA
VERMELHO
VIOLA
VOADOR
XERELETE

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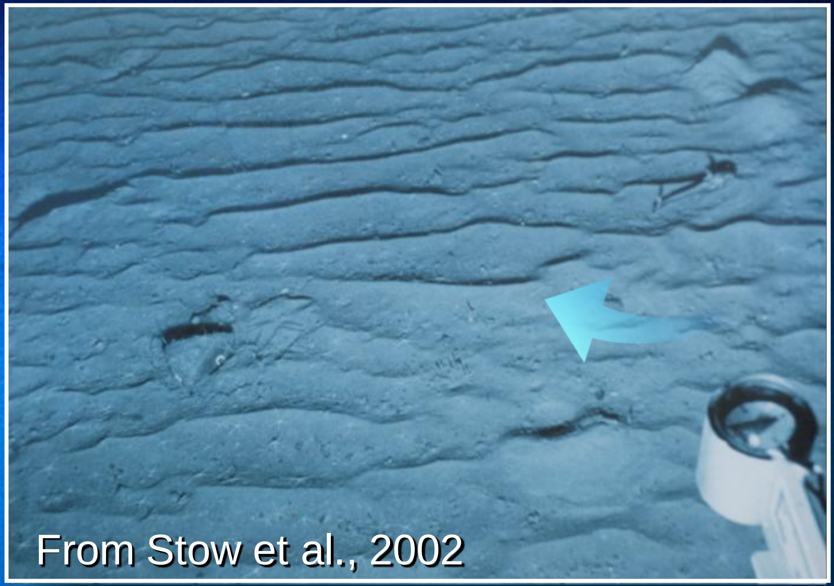
Seabed photograph showing ripples in a contourite sand



We concur with Stow and Lovell (1979) that the discovery of bottom currents and contourites in the North Atlantic (Hollister and Heezen, 1967) was potentially a breakthough contribution to sedimentary geology. However, the contribution had unfortunately, at that time, a modest impact on the sedimentary geology community because of the difficulties encountered in recognizing these sediments in ancient exposed successions. It seems that the same problem persists today.

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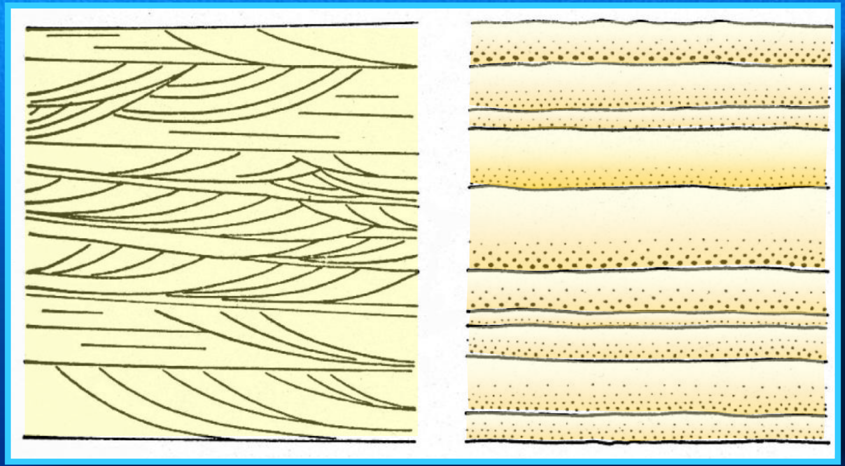
Conversely, the Kuenen and Migliorini's paper of 1950, introducing the revolutionary "turbidite" concept explaining deep-water graded sandstone beds, was nearly immediately and enthusiastically accepted by the scientific community and the concept could thus quickly spread out to promote extensive outcrop and oceanographic studies of turbidite sedimentation (see recent review of Mutti et al., 2009).



A **B**

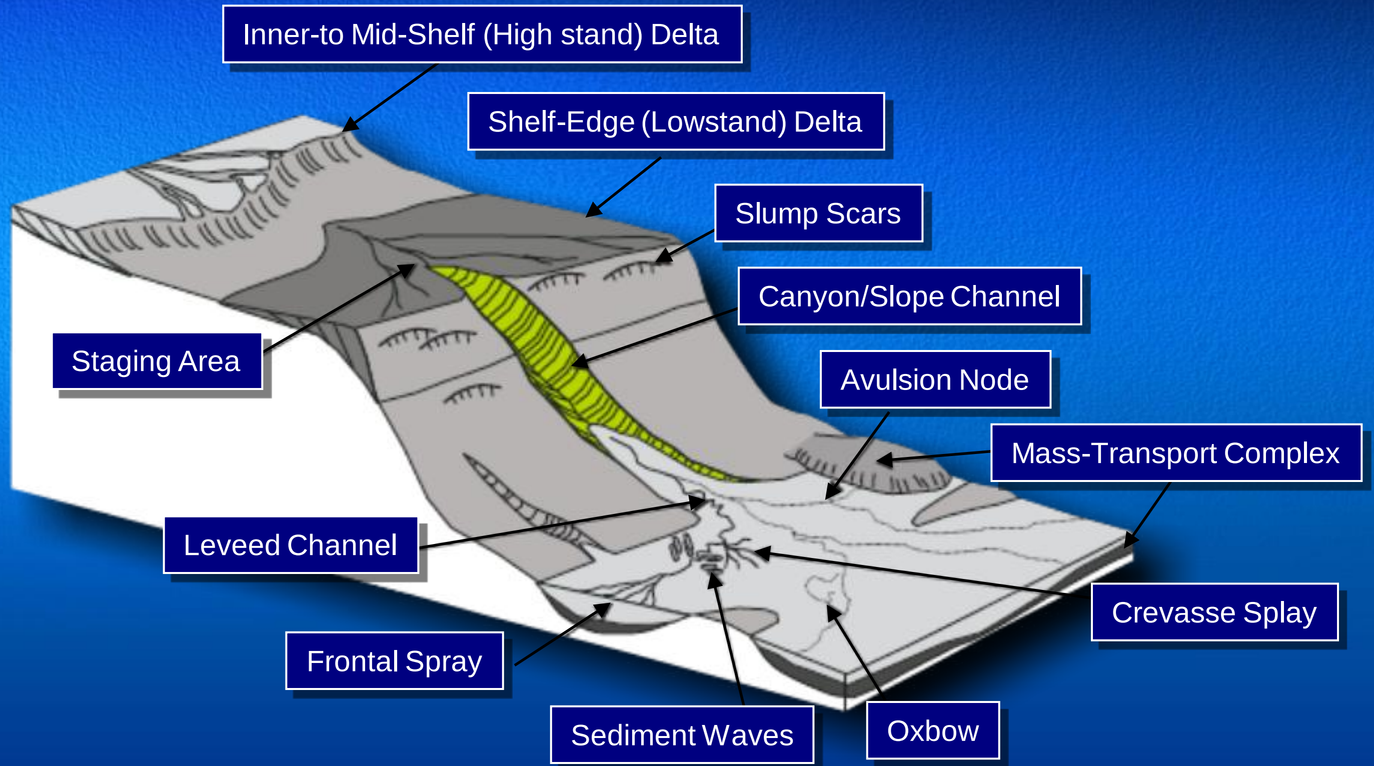
*Current bedding (**A**) and graded bedding (**B**) (from Bailey, 1936). Graded bedding remained enigmatic until the turbidite revolution of 1950.*

Deep-water sedimentation of continental margins dominated by turbidity currents and sediment gravity flows

As a consequence, deep-water sedimentation of continental margins has long been considered as the realm of turbidity currents and sediment gravity flows and its understanding has been mainly driven by sedimentological models derived from outcrop studies in such classic areas as the Apennines, Alps, and Pyrenees where these models were developed and progressively refined in the second half of the past century stemming from the papers by Bouma (1962) and Mutti and Ricci Lucchi (1972).

The same turbidite-driven approach, though integrated with 3D seismic and marine geology data, has been recently followed also by Posamentier and Walker (2006) in discussing their facies model for "Turbidites and submarine fans".

Deep-water turbidites and submarine fans : the physiographic and depositional scheme offered by Posamentier and Walker (2006, their Fig. 1)



The shelf staging area is connected to the deep-water environment through slope cannels and/or canyons. Main depositional elements in the deep water include leveed channel, crevasse splays, sediment waves, and frontal splays or lobes. Note that no mention is made to bottom currents and their deposits.

Growing evidence for the importance of bottom currents and contourites

An increasing body of evidence is now casting serious doubts on the validity of the turbidite-driven model as the only available approach to understand deep-water sedimentation of continental margins. Modern contourite sedimentation dominates in most oceans and marginal seas and seismic data indicate its importance also in many continental margins since late Cenozoic. Most of the available information on this kind of sedimentation and related problems is amply discussed in recent special volumes (Stow et al.,eds., 2002; Viana and Rebesco, eds., 2007; Rebesco and Camerlenghi, eds., 2008).

This wealth of information cannot be overlooked any longer in the exploration of continental margins because of its obvious economic implications. The deep water is not only the realm of turbidity currents !

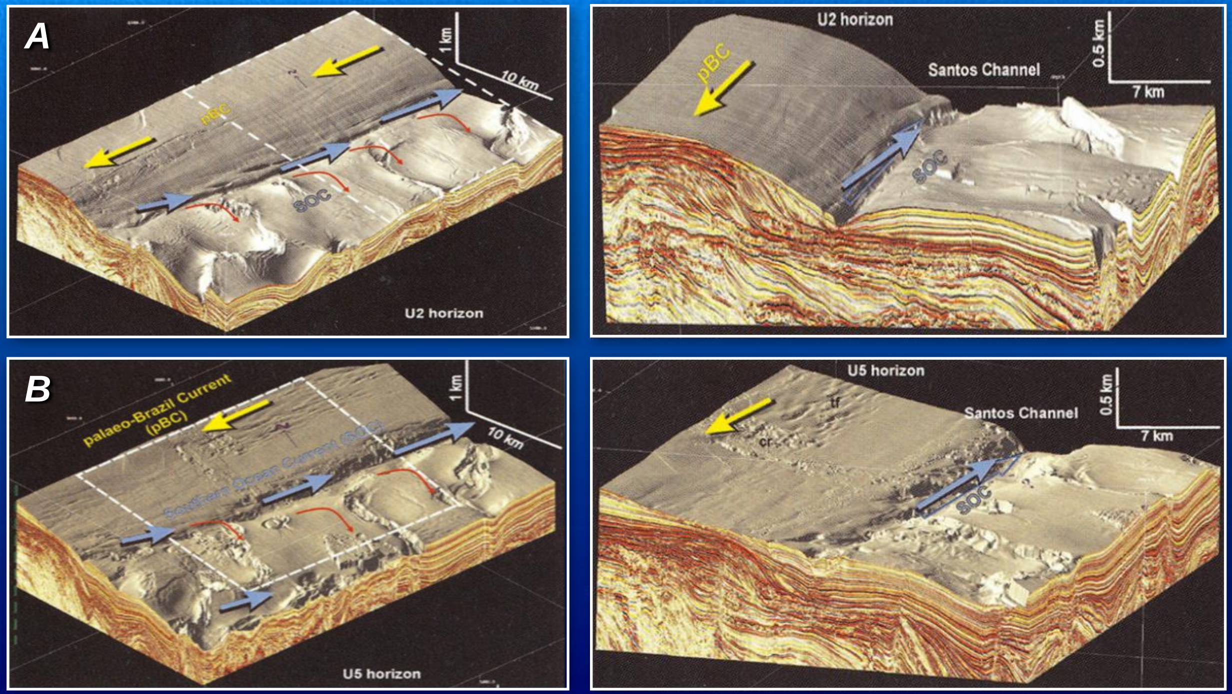
What do we know about modern contourites?

Fine-Grained Contourites: Sediment Drifts

The great majority of the contourite deposits reported from the study of continental margins are fine-grained (muddy contourites) forming a great variety of depositional features generally known as drifts. Most large drifts have impressive size and form very distinctive seismic units reported in many papers.

The example below shows a seismic diagram of the Santos contourite drift as reconstructed by Duarte and Viana (2007) for late Cenozoic circulation in the SW Atlantic Ocean

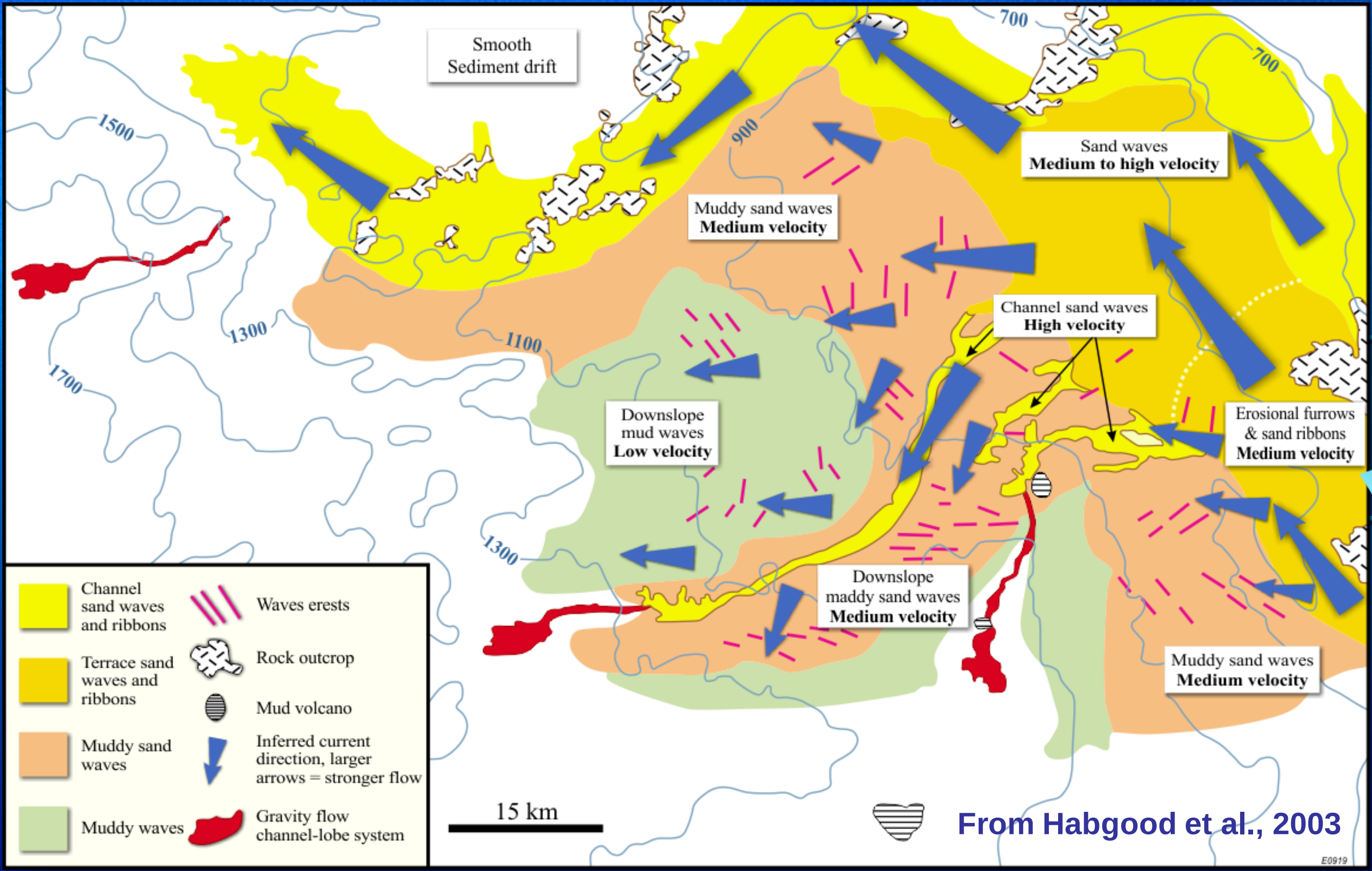
SANTOS DRIFT



DUARTE AND VIANA, 2007

Sandy Contourites : Modern Examples

Sandy contourites are well documented in the north Atlantic west of the Faeroe Bank Channel and especially in the Gulf of Cadiz where the Mediterranean Outflow Water (MOW) forms well-studied contourite systems (see summary for both examples in Akhmetzhanov et al., 2007).



Slope terrace with geostrophic circulation

The example above shows the major bedform zones, sediment transport paths and inferred current strength from the Gulf of Cadiz. Currents are stronger and geostrophic in the slope terrace becoming weaker and ageostrophic descending the slope, forming channels and terminal turbidite sand lobes.

Sandy contourites : bedforms and facies models

What do we know about sandy contourite facies?
Exiting a gateway, bedforms show a clear downcurrent evolution indicating the transition from erosional features (with velocities up to 3m/sec) to depositional bedfoms that for decreasing flow velocities include gravel waves,gravel and sand ribbons, barchan dunes and sandwaves (with wavelengths up to 320m and amplitudes of 5-10m), and ripples (e.g., Habgood et al.,2003; Stow et al., 2008).

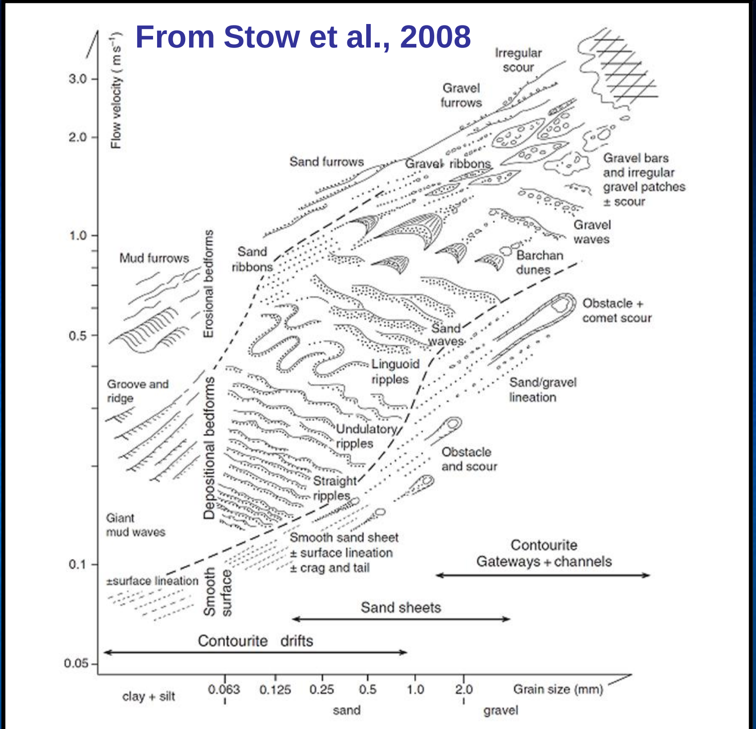


Figure 9.3 Bedform-velocity matrix: a schematic distribution of bedform types with respect to flow velocity and grain size (from Stow et al., in press; with permission from the Geological Society of America).

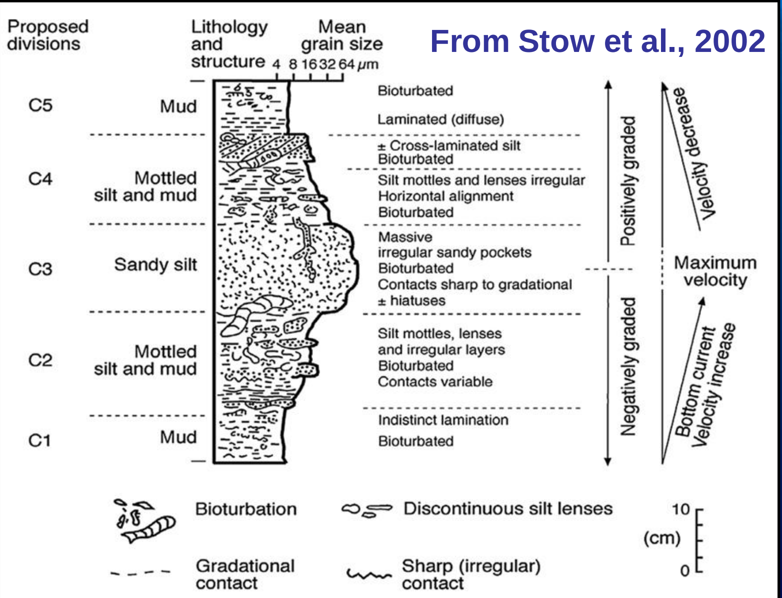
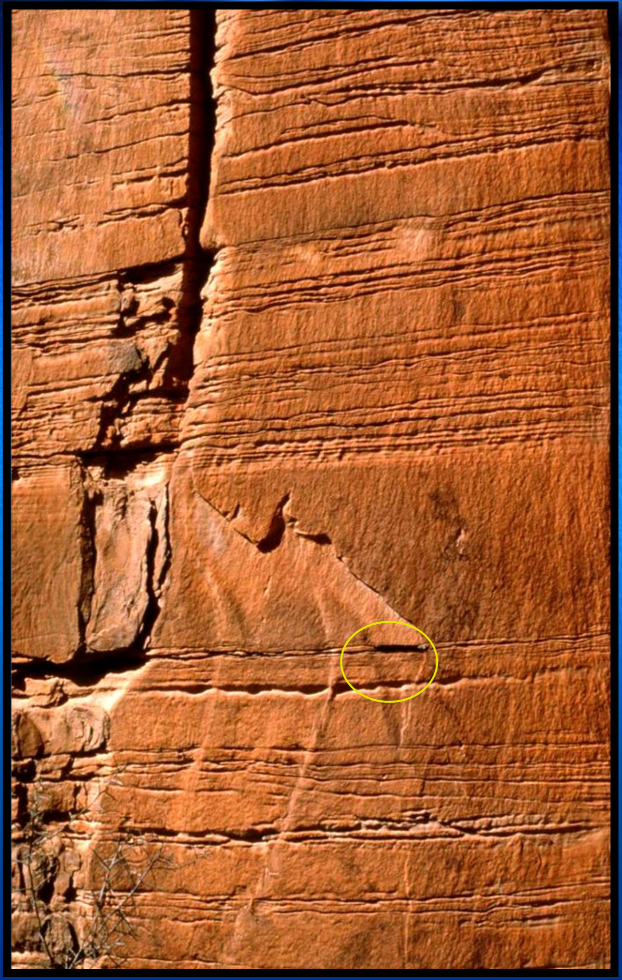


Figure 13.9 Composite contourite facies model showing grain-size variation through the standard mud–silt–sand contourite sequence, linked to variation in contour-current velocity (from Stow et al., 2002b; Stow, 2005; with permission from The Geological Society, London).

Nonetheless, classic facies models of modern sandy contourites emphasize bioturbation and essentially their occurrence as thin sandy units The problem is largely due to the fact that bottom-current deposits are essentially unknown from exposed thrust-and-fold basin fills.

AN EXPOSED EXAMPLE OF BOTTOM-CURRENT DEPOSITS:



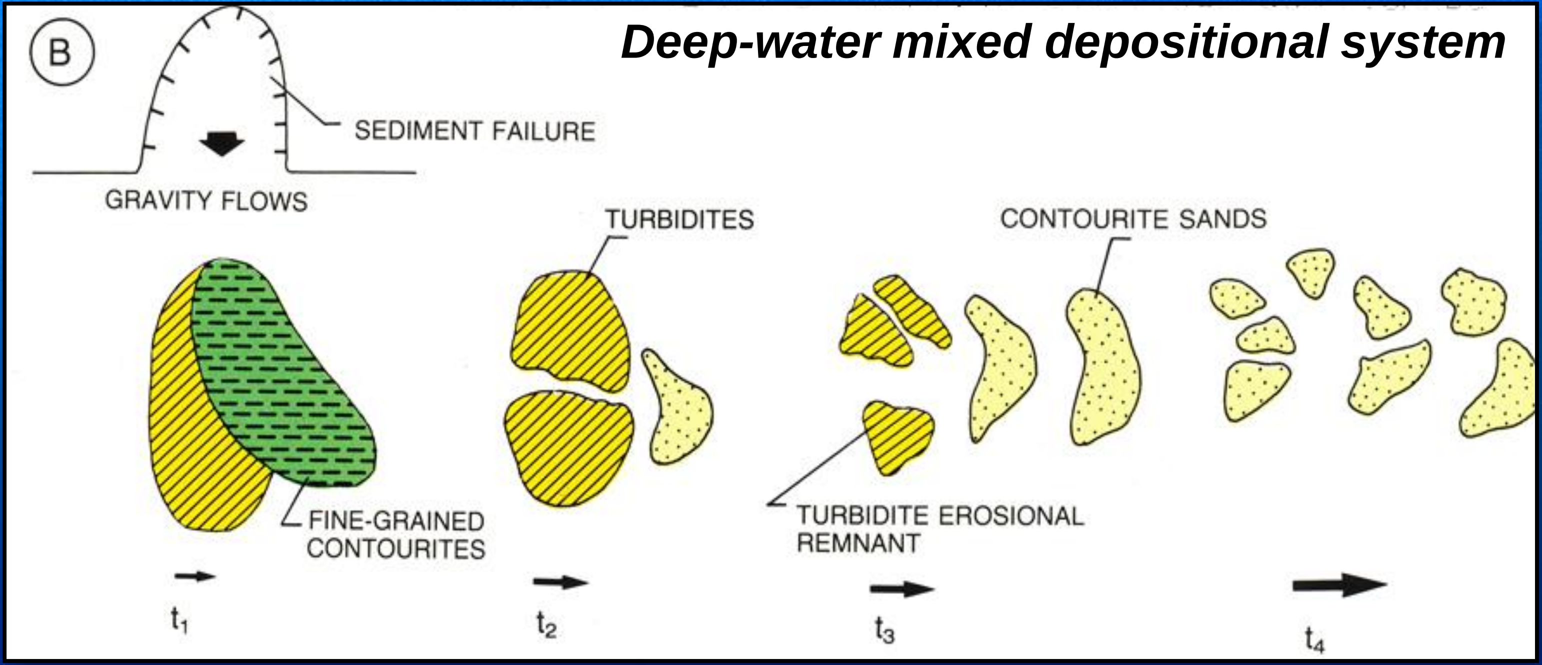
THE BRUSHY CANYON MEMBER, PERMIAN DELAWARE BASIN, WEST TEXAS (FROM MUTTI,1992)

The Brushy Canyon Member (Permian Delaware Basin, West Texas) is a well-known example of turbidite deposition with channels, lobes and their transitional zones (e.g., Gardner et al.,2003), though some of its depositional elements have long been recognized as possible bottom-current deposit (e.g., Jacka et al, 1969; Harms, 1974). Whatever their local origin, bottom currents appear as the only plausible process for transport and deposition of these fine-grained and current-laminated sand bodies that are conspicuous for the lack of turbidite features (Mutti, 1990, 1992).

These sediments are a quite unique yet overlooked example of bottom-current deposits consisting of fine-grained sandstone displaying ripple, horizontal and low-angle cross lamination (pencil for scale). These facies closely resemble the sandy contourites observed in cores of the Campos Basin (see later).

Main Results of our Work

The late Cretaceous and Tertiary deep-water sands of the Brazilian offshore basins consist of mixed depositional systems (as defined by Mutti, 1992) where turbidite and bottom-current deposits give way to hybrid facies associations and sand-body geometries which are difficult to explain with currently turbidite-dominated models for deep-water sedimentation.



Hybrid facies association : The vertical and lateral association of facies produced by genetically distinct processes (turbidity currents and bottom currents)

Turbidite Systems

A. *They are mainly confined to the fill of structural/erosional depressions and erosional fan remnants where they consist of thick-bedded and coarse-grained facies.*

B. *Delta-slope (and very subordinately channel-levee deposits) consisting of thin-bedded and fine-grained turbidites are also common*

Weak to moderate bottom-current action may be common in both cases

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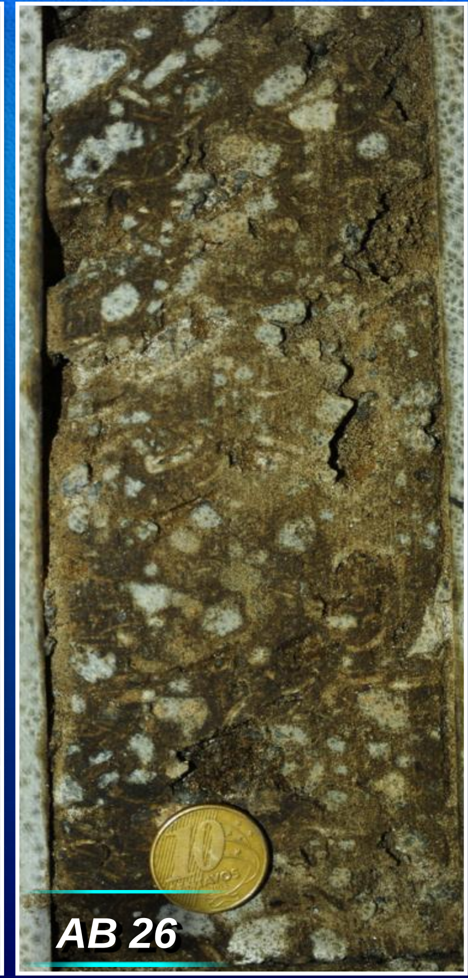
A - Examples of turbidite coarse-grained sandstones, pebbly sandstones and matrix (sandy)- supported pebbly and cobbly conglomerates devoid of internal structures. Grading may or may not be present. In some beds, abundant shell fragments can be observed



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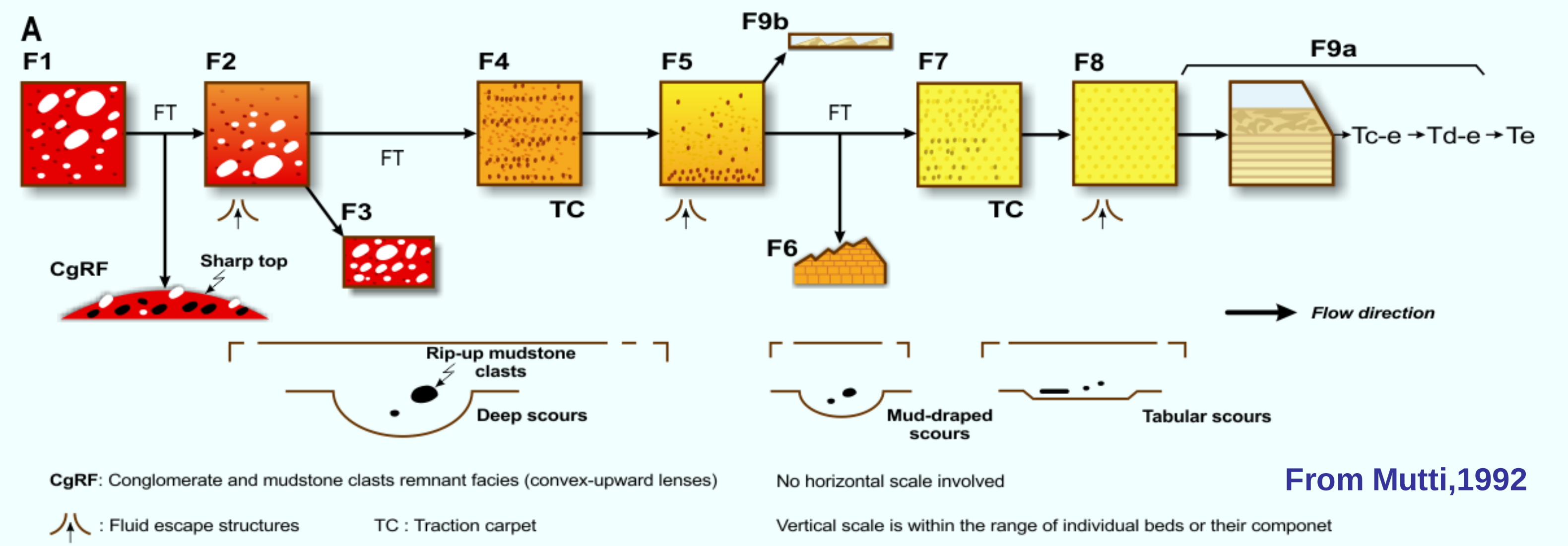
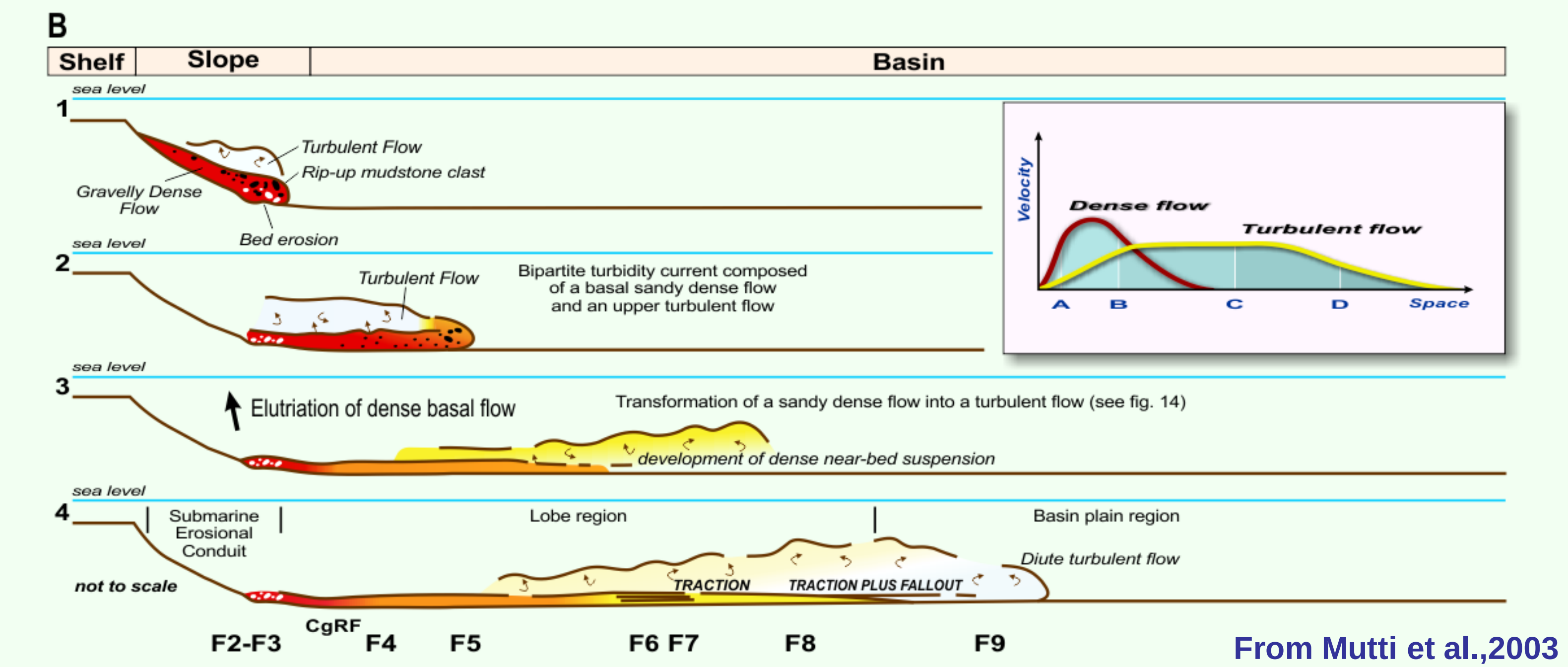
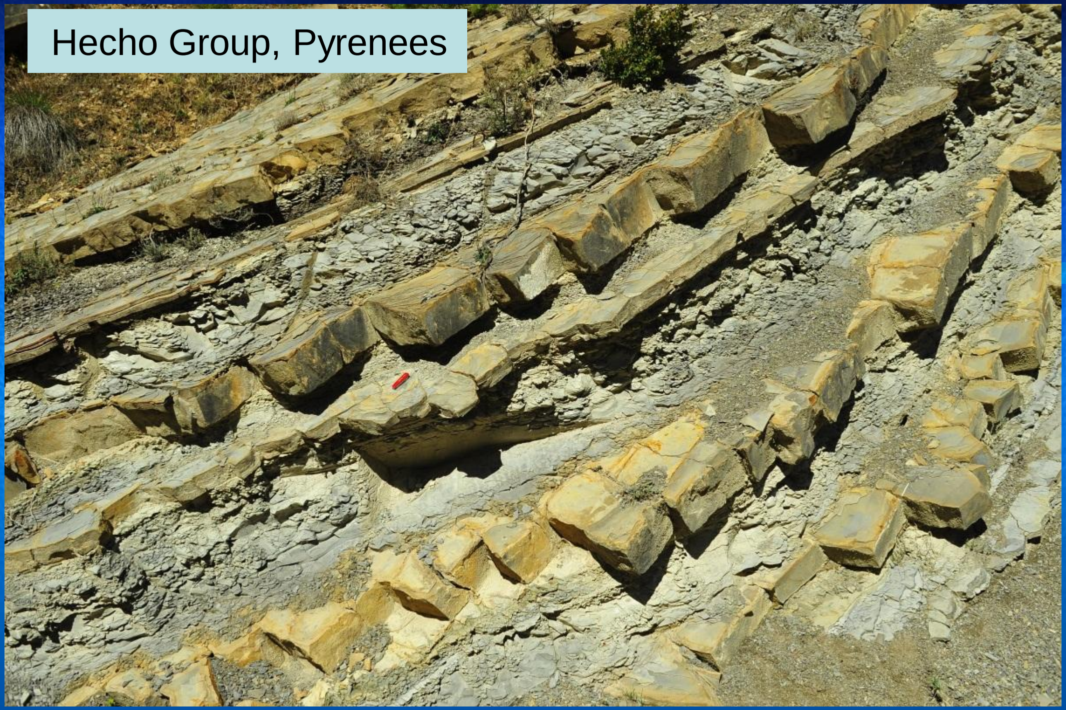


From Mutti,1992



From Mutti et al.,2003

The Missing Turbidite Facies !!!!!



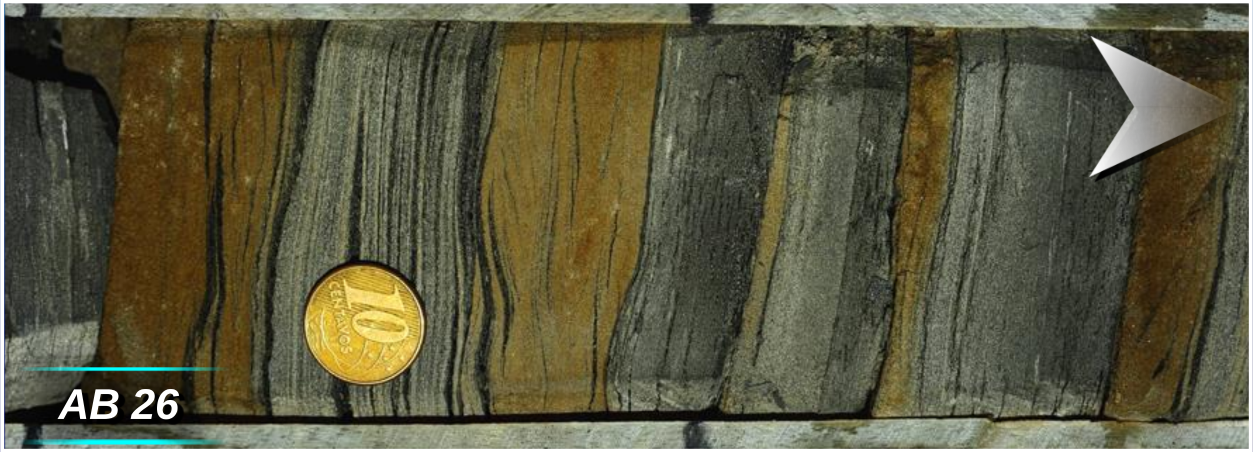
Examples of current-laminated fine-grained turbidite facies with associated thick mudstone divisions

With few exceptions, thick-bedded and coarse-grained turbidites are conspicuous for the lack of vertically and laterally associated fine-grained facies deposited by the dilute and turbulent part of turbidity currents (F8 and F9). Where preserved, these facies show strong evidence of transport and deposition affected by the interaction of turbidite turbulent flow and bottom-current motion.

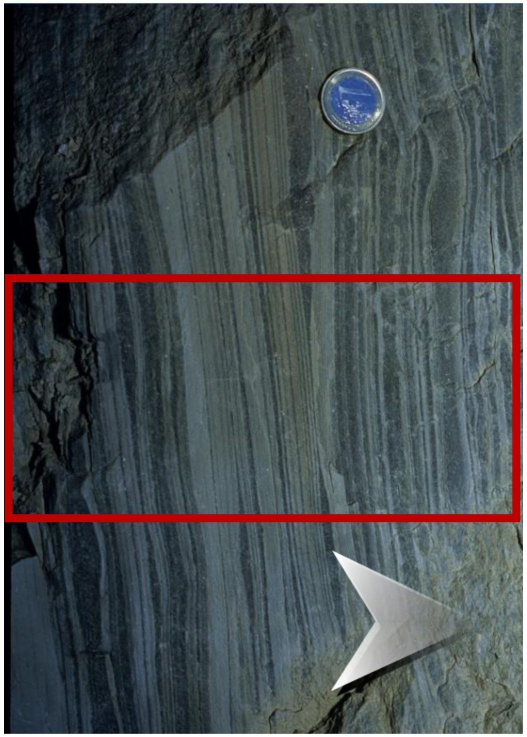
More generally, this fine-grained sediment was entirely incorporated by bottom currents during transport and sedimentation.

B - Delta-Slope Turbidites

Examples of thin-bedded and fine-grained delta-slope turbidites (MRL 66 and AB 26) thought to be deposited by dilute hyperpycnal flows (ripples) and buoyant river plumes(silty-mud couplets). As clearly shown by seismic-reflection profiles,these sediments typically downlap onto deeper water sandy turbidites or contourites.



Outcrop example from the Eocene of Southern Pyrenees (Castisent Group)

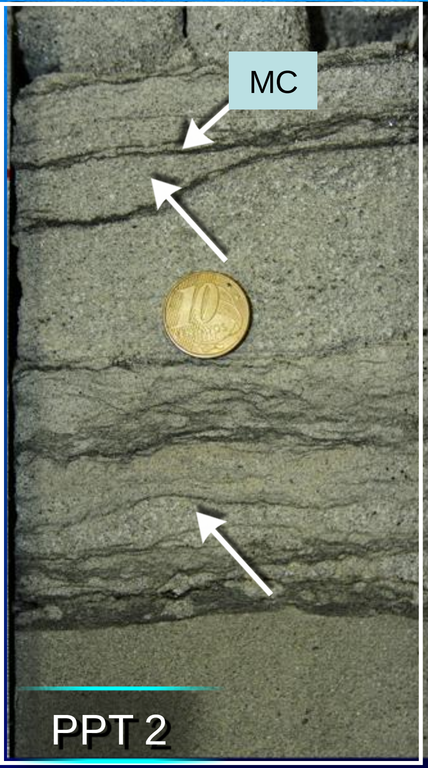


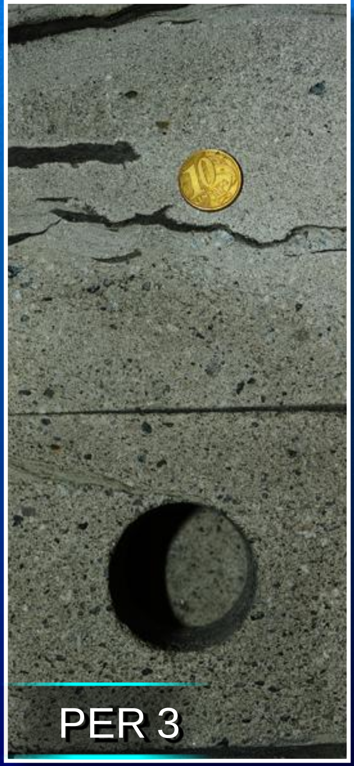
Reworked Turbidite Systems
(turbidite systems reworked by tidal bottom currents)

For practical purposes of basin analysis, we denote with this term original turbidite sediments reworked at various degrees of intensity by bottom currents. Remnants of turbidite beds are always recognizeable and associated with facies showing evidence of strong action of ***bottom tidal currents****.*
As already noted by Shanmugam (1993, 2003), reworked turbidite systems are typically found in canyons where, in modern settings, bottom tidal currents may attain velocities of 25-50 cm/sec at depths varying between 50-4200 m.

A - Coarse-grained turbidites in situ reworked by tidal bottom currents (hybrid facies association)

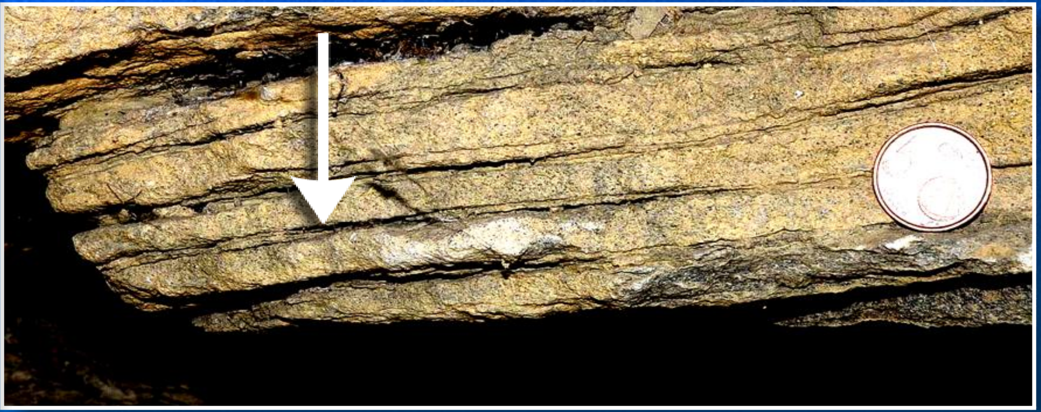
Coarse-grained turbidite beds reworked by tidal bottom currents. Thinner and lenticular coarse-grained units (arrows) were locally retransported by bottom currents. Note mudstone partings, mud couplets (MC) and small angular mudstone clasts. Bioturbation is present in bottom-current deposits. Reworking of coarse sand suggests considerable bottom current velocities.





Reworked Thin-Bedded Slope Turbidites (left)

MUD COUPLETS IN THE EOCENE FIGOLS GROUP, SOUTHERN PYRENEES



Mud couplets (arrows) form when tidal cycles show a marked time-velocity asimmetry whereby the subordinate flow is recorded by a thin sandstone layer bounded above and below by slack water mudstones. Thicker sand beds are deposited by the dominant flow.

Ideally, in a semidiurnal cycle a thick sand unit and an overlying mud couplet containing the thin sand unit of the subordinate flow are the record of about 12 hours.

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Contourites

We denote with this term a broad facies association thought to have been entirely transported and deposited by bottom currents forming contourite depositional systems primarily recording the migration of sand waves and related bedforms. These sediments, here reported for the first time from ancient successions, are interpreted as ***contourites s.s.****,i.e. the deposits of thermohaline bottom currents flowing parallel to contours in open slope regions.*

The main facies types include:

A. Horizontally- and ripple-laminated fine-grained and well-sorted sandstones (*thick-bedded sandy contourites*)

B. Thin-bedded ripple-laminated sandstones (*thin-bedded sandy contourites*)

C. Calcareous silty mudstones (*muddy contourites*)

B - Thick-Bedded Sandy Contourites

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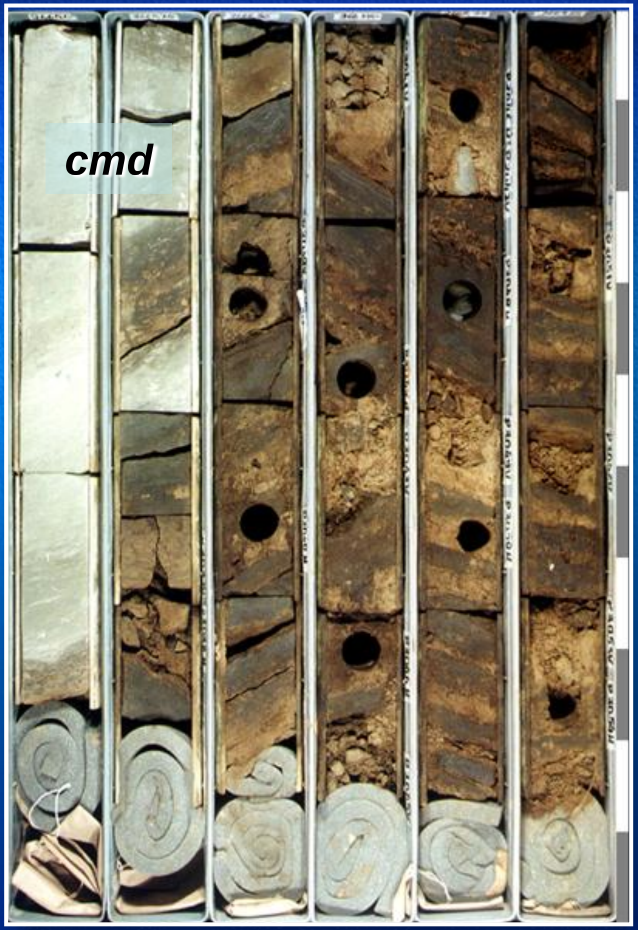

CX-01 CX-02 CX-03 CX-04 CX-05 CX-06/11

Fine-grained horizontally and ripple laminated sandstone in units up to 30 m (most commonly between 2-8 m) thick typically alternating with highly bioturbated silty calcareous mudstones (cmd) with foramifera

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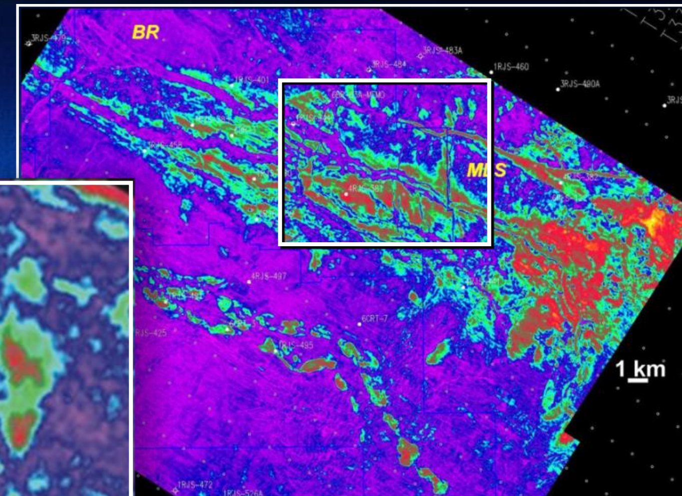
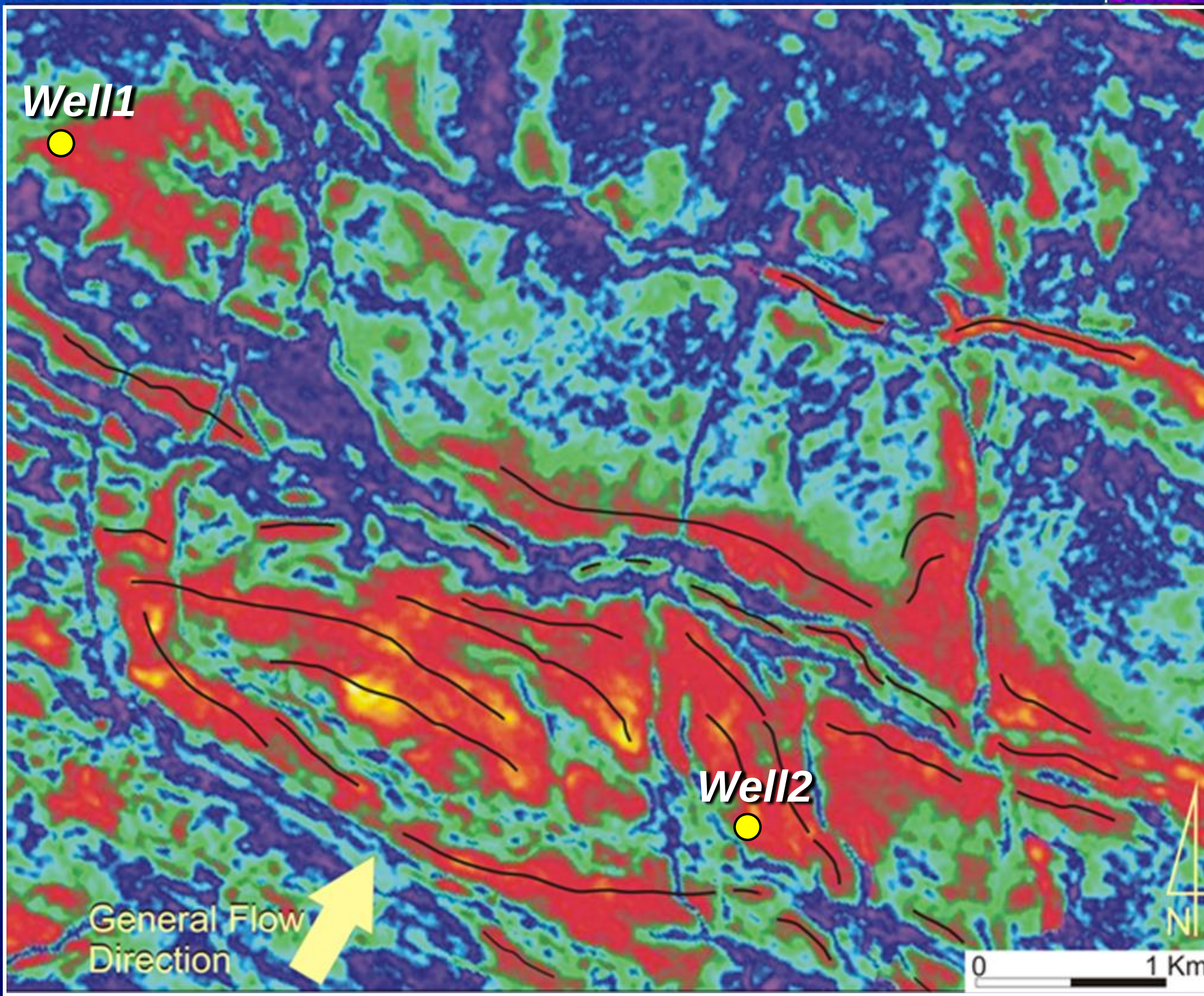
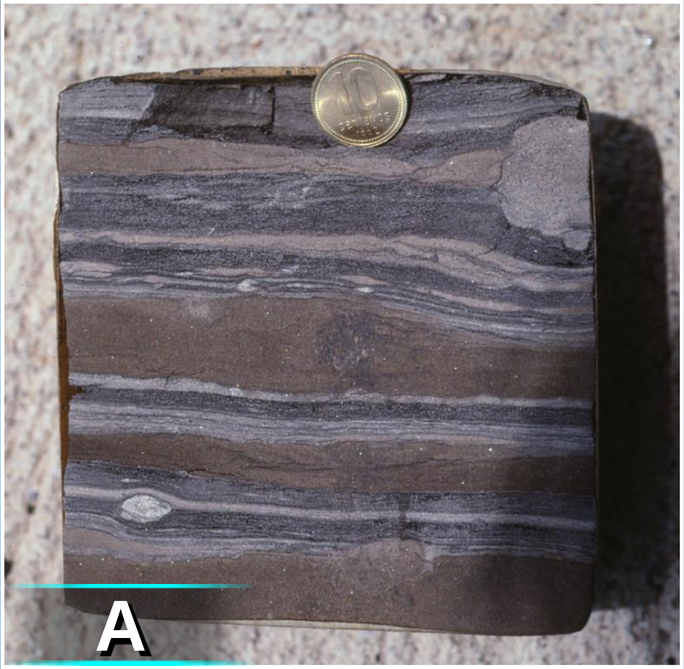
Amplitude Map

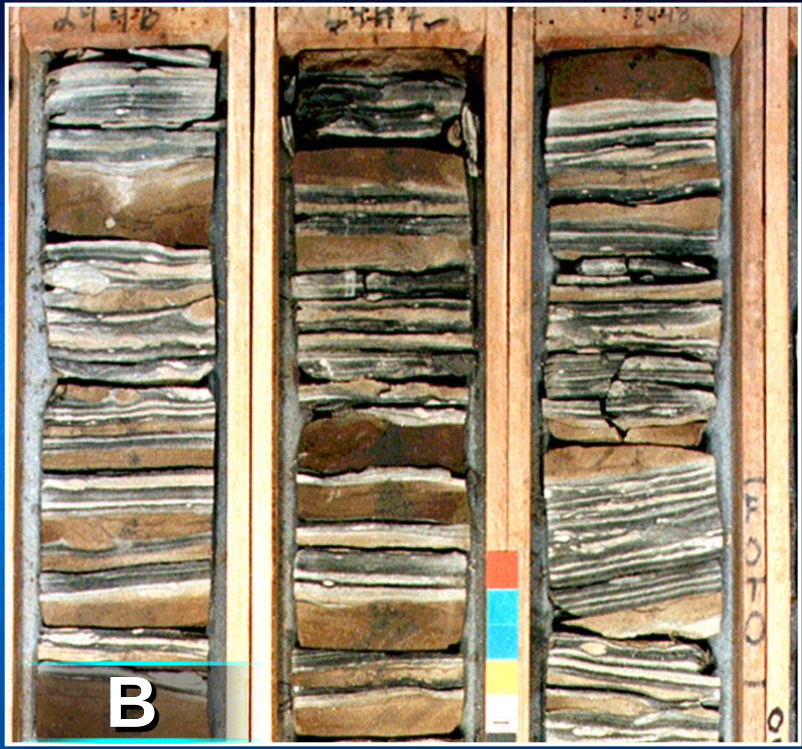
SEISMIC EXPRESSION OF CONTOURITE SAND WAVES

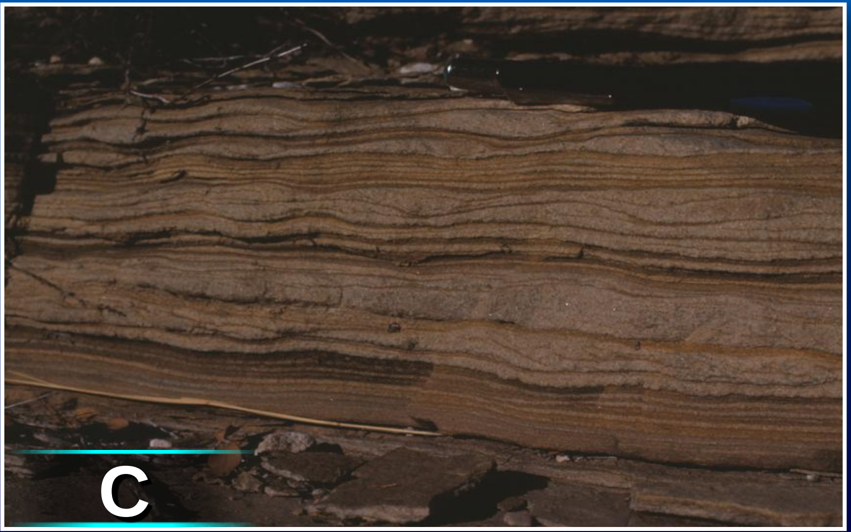




C - Thin-Bedded Contourites

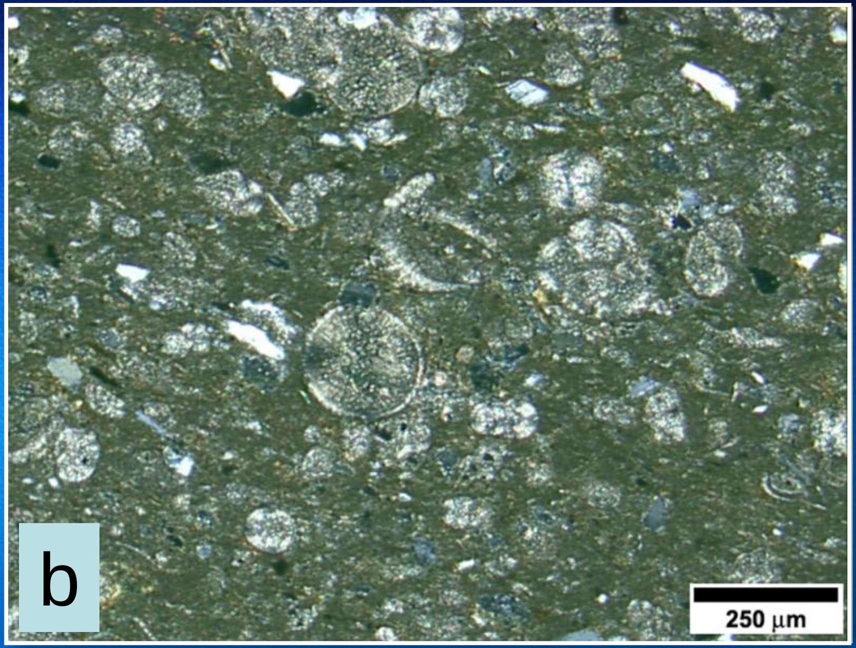






Examples of cyclically stacked thin-bedded contourites from the Moreia field (A and B). Compare with similar thin-bedded facies from the Permian Delaware Basin(C).Relatively strong and weak currents alternate with time in both cases.

D - Muddy Contourites



Sediment drifts produced by weak bottom currents and mainly consisting of biogenic and terrigenous mud

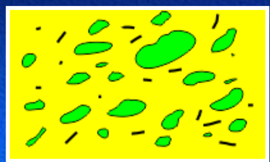
Calcareous silty mudstones with abundant microfossils.

a) General aspect in core (note faint lamination and extensive bioturbation)

b) Microscopic facies

c) Slightly erosive contact on an underlying sandy contourite bed

Preliminary Contourite Facies Tract Inferred from Core Observations



(CFA) Muddy fine sand with abundant mudstone clasts

(CFB) M-thick well- sorted horizontally laminated fine and very fine sand

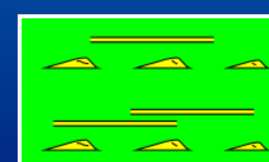
Flow direction

(CFC) M-thick well-sorted fine and very fine sand with large ripples with internal sigmoidal laminae

(CFD) Alternating cm-thick packages of ripple-laminated fine-grained sand and bioturbated muddier units with sand streaks

Flow direction

(CFE) Cm-thick packages of lenticular rippled sand and sand streaks alternating with mudstones. Bioturbation is very common. These thin units strongly resemble contourite facies cycles of the classic Stow's model (Stow et al., 2002)

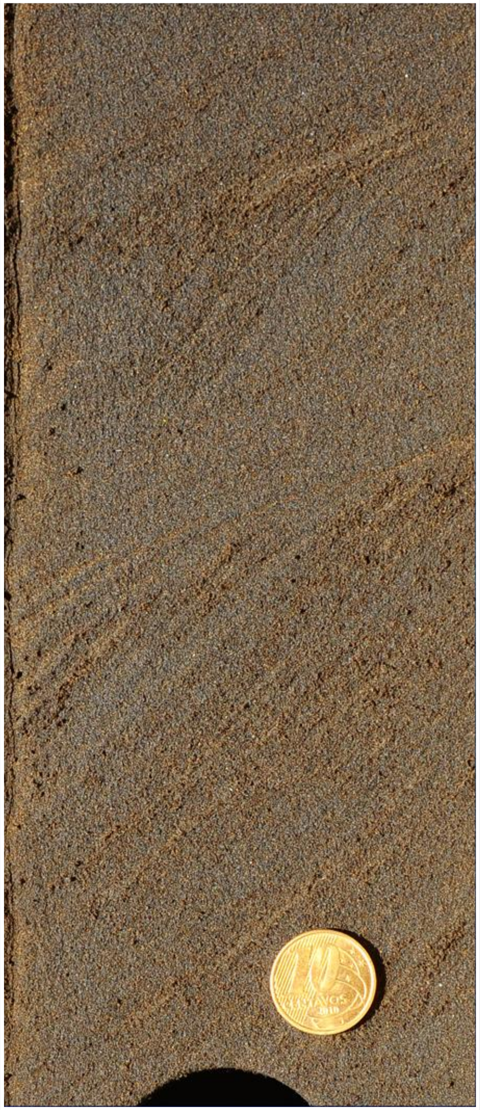


(CFF) Highly bioturbated terrigenous, mixed and biogenic (calcareous) mudstones

Contourite Facies Tract

CFA

CFB



CFC

CFD

Contourite Facies Tract

CFD

CFE

CFF

CONCLUSIONS

- ***In the Campos Basin, bottom currents played a major role since late Cretaceous in reworking and redistributing turbidite fine sands derived from basin margins.These sands form excellent reservoirs in many oil fields.***

- ***Deep tidal currents reworked with varying degrees of intensity turbidite sand accumulations in confined conduits and their terminuses particularly after rates of turbidite deposition decreased and turbidite systems gradually became inactive.The setting seems similar to that of incised-valley fills where fluvial sediments are overlain by transgressive tide-dominated estuarine facies.***

- ***In open slope settings geostrophic thermohaline currents established permanent or quasi-permanent flow patterns controlled by local and regional topography that moved large amounts of fine sand through migrating large-scale sand waves and smaller bedforms.***

- ***These sediments are herein interpreted as genuine sandy contourites that can be easily recognized in cores and 3D seismics.***

- ***Seismic, well-log and core data suggest that bottom-current intensity reaches its peak during lowstand and early transgressive times and decreases with relative sea-level rising Bottom-current sandy facies are thus overlain by transgressive and high stand fine-grained contourite drifts or progradational delta-slope wedges***

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- ***Clearly, 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.***

- ***Careful analysis of facies and facies associations without preconceived ideas (models and analogs) still remains a basic and unexpensive tool for a better understanding of deep-water sedimentation, thus lowering risks in exploration and production.***

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