

Contourites and Turbidites of the Brazilian Marginal Basins*

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and Adriano R. Viana²**

Search and Discovery Article #51069 (2014)

Posted March 20, 2015

*Adapted from oral presentation at AAPG Annual Convention & Exhibition, Houston, USA, April 6-9, 2014

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Abstract

For the last three decades Petrobras has continuously developed aggressive exploration and production activity in deep and ultradeep waters of the Brazilian marginal basins. As a result, giant oil fields were discovered (e.g., Marlim, Albacora, and Roncador oil fields) leading to a very fast growth of the Brazilian proved reserves. The main daily production comes from Cretaceous and Tertiary deep-water sandstones in Campos Basin until recently interpreted as turbidite depositional systems. The search for the best geological model to optimize production systems has generated over time an impressive data base of 3D and 4D seismic surveys, well logs, cores, and fluid samples. Extensive core analysis of these sands, integrated with seismic data, reveals their depositional complexity.

The purpose of this article is to show that bottom currents played a fundamental role in reworking and redistributing turbidite sands. Marginally derived coarse-grained and thick-bedded turbidite sands were trapped in delta-fed slope channels, structurally controlled depressions (intraslope basins) and channel-terminus lobate features. Fine-grained sediment transported in suspension by turbidity currents was almost entirely removed by bottom currents during and immediately after deposition and transported northward, away from their turbidite feeder systems, to form spectacular fields of fine-grained and very well sorted contourite low-relief sand drifts, characterized by very distinctive facies in cores, which are highly prolific oil reservoirs (e.g., Barracuda, Marlim sul, Albacora leste). Bottom currents were flowing toward the northeast quadrant along the slope, following pathways locally controlled by bottom topography generated by salt mobility, growth faults, and basement block-faulting.

Amplitude maps show both erosional and depositional features associated with varying degrees of bottom-current current intensity in space and time, resulting in channels, sand ribbons, barchan dunes, and sandwaves. Clearly, this kind of depositional settings has no analogs in deep-water sedimentation dominated by turbidity currents, i.e., in classic deep-sea fan models with channels, levees, and lobe (frontal splay) elements.

External geometry and facies distribution patterns of sandy contourite systems will require a considerable research effort in future years due to the proven economic importance of these reservoirs. The application of new production technologies to improve recovery factors and reduce the number of producing wells by enhancing well productivity is completely dependent on the physical and petrophysical characteristics of sedimentary facies.

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PETROBRAS

CONTOURITES AND TURBIDITES OF THE BRAZILIAN MARGINAL BASINS

EMILIANO MUTTI¹, ROGÉRIO S. CUNHA², ÉLVIO M. BULHÕES², LUCI M. ARIENTI² AND ADRIANO R. VIANA²

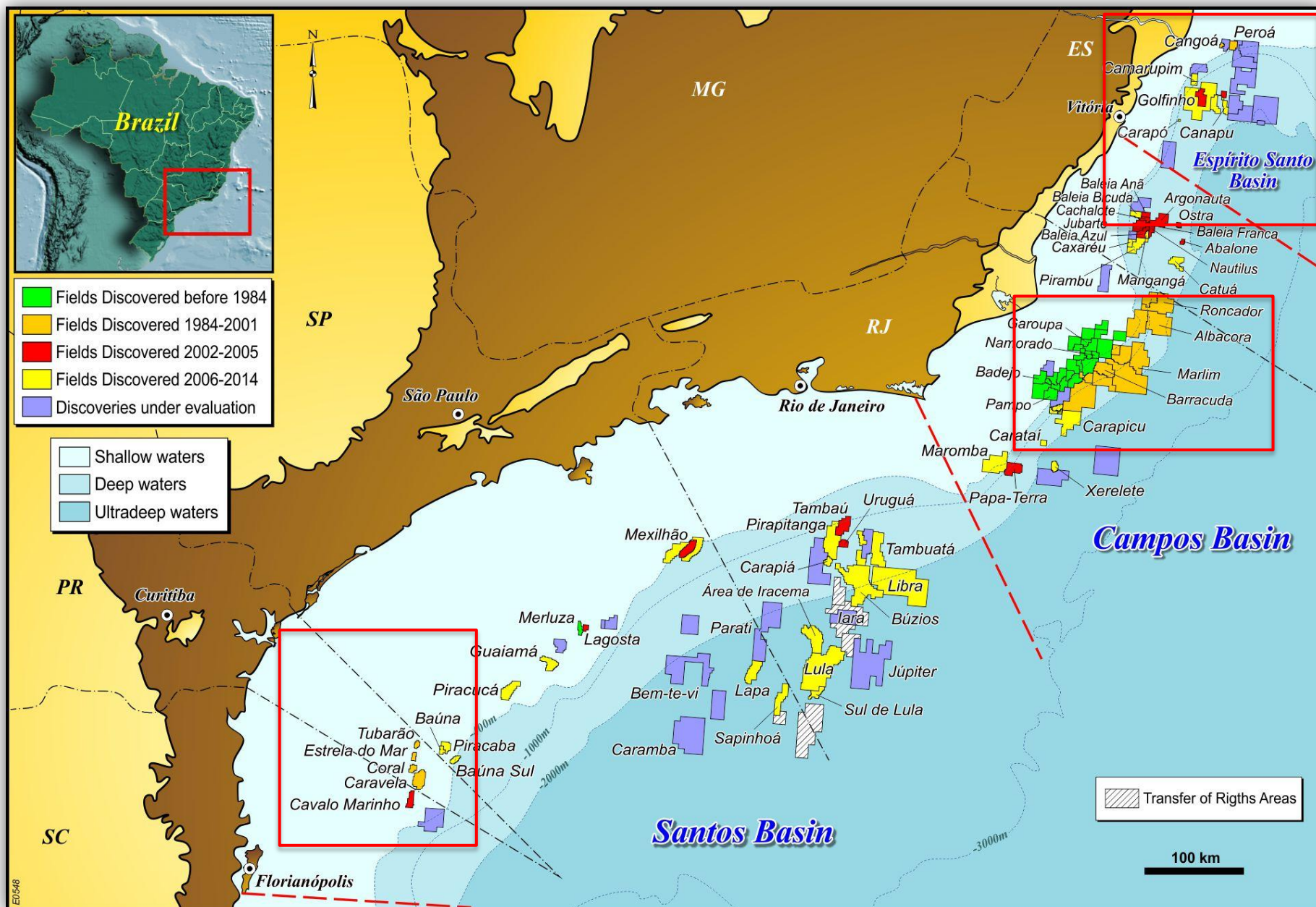
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2. PETROBRAS, BRAZIL

E&P – Exploration

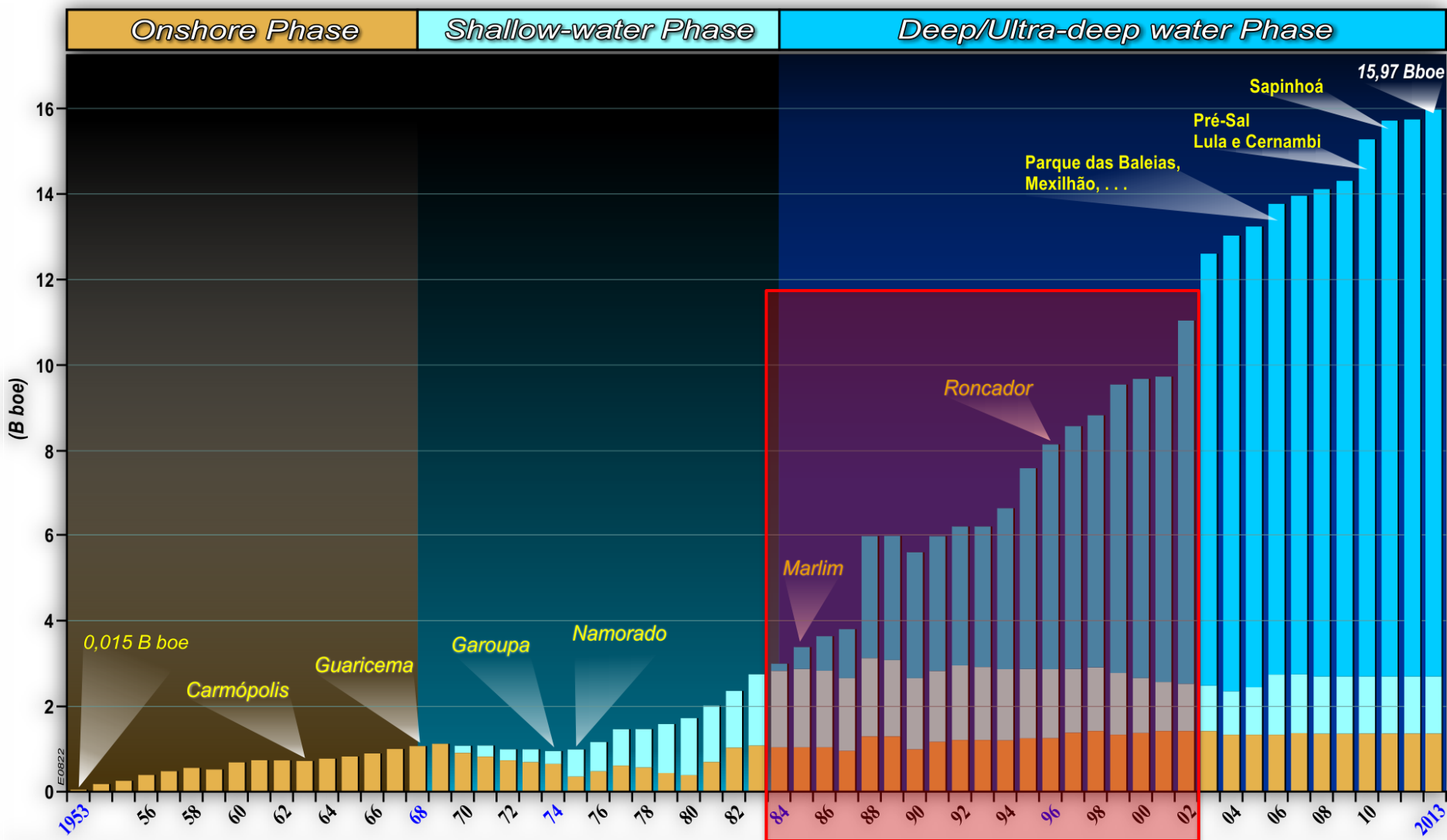
6 – 9 April, Houston - Texas

- TO HIGHLIGHT SOME EVIDENCE FROM CORES ANALYSIS AND SEISMIC DATA WHICH INDICATE THAT A SUBSTANTIAL PORTION OF THE UPPER CRETACEOUS AND TERTIARY SANDSTONES OF SANTOS, CAMPOS AND ESPÍRITO SANTO BASINS CONSISTS OF: **TURBIDITES REWORKED BY BOTTOM CURRENTS** AND **CONTOURITE** DEPOSITIONAL SYSTEMS;
- TO SHOW THAT BOTTOM-CURRENTS, WHATEVER THEIR ORIGIN, CERTAINLY PLAYED A FUNDAMENTAL ROLE IN CONTROLLING SAND DISTRIBUTION PATTERNS AND RESERVOIR CHARACTERISTICS IN THE BRAZILIAN OFFSHORE BASINS FROM LATE CRETACEOUS TO EARLY MIOCENE;
- TO SHOW THAT BOTTOM-CURRENT DEPOSITS ARE NOT ONLY AN IMPORTANT COMPONENT OF RECENT OCEANIC DEEP-WATER SEDIMENTATION, BUT ALSO ROCKS THAT HAVE A DISTINCT SIGNATURE IN CORES AND SEISMIC AND HAVE A GREAT ECONOMIC RELEVANCE.

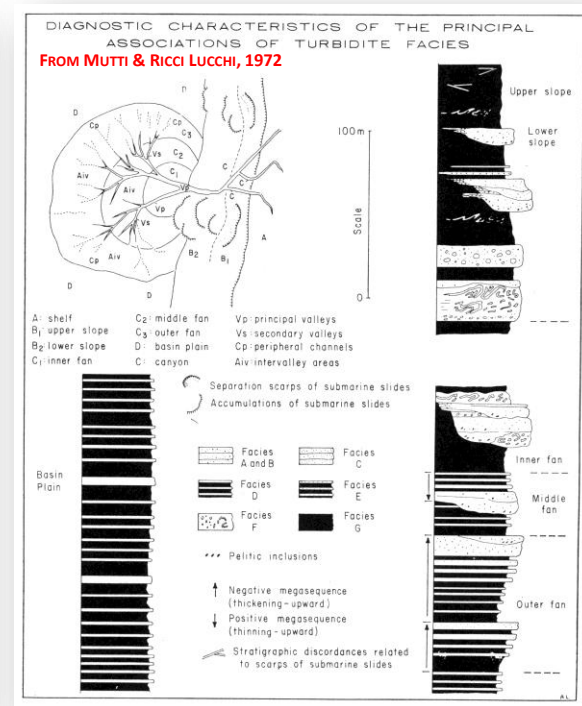
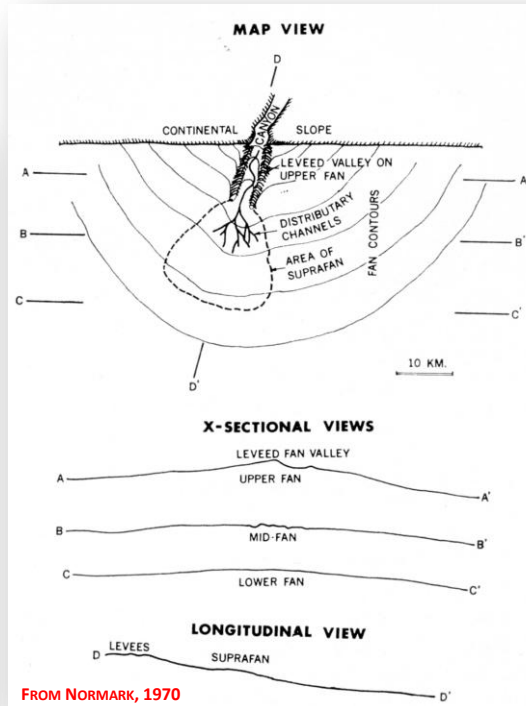
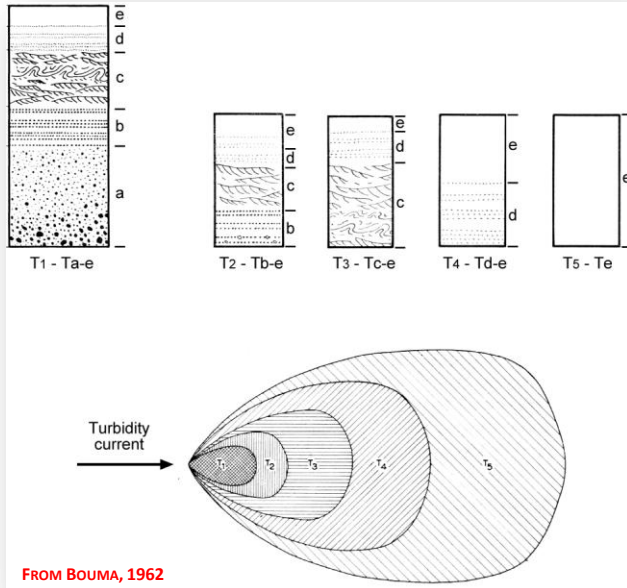




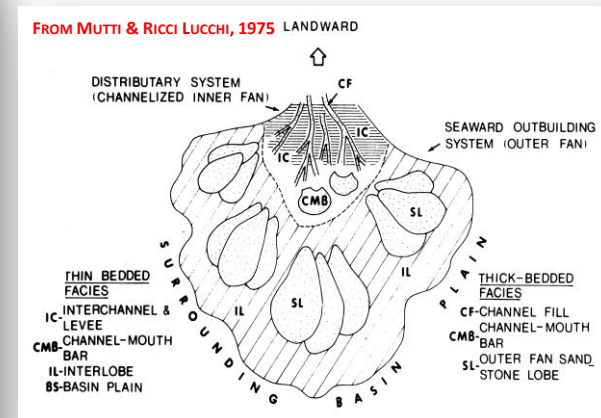
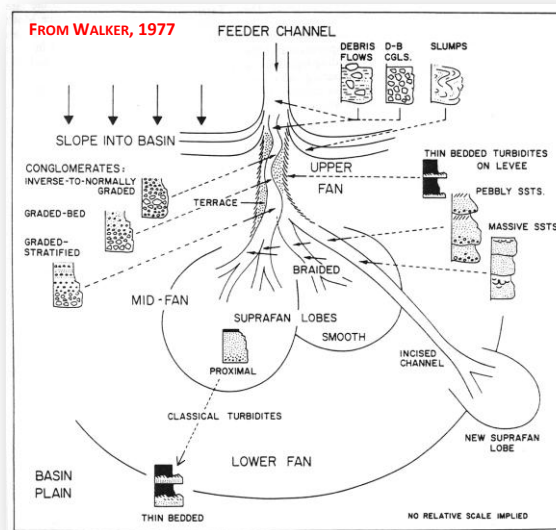
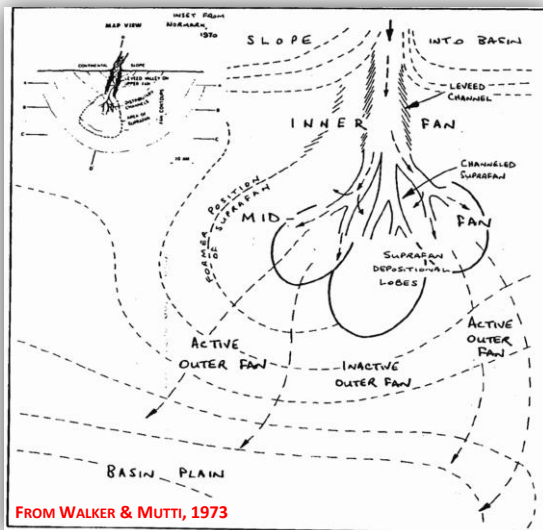
PROVED RESERVES IN BRAZIL (2013)



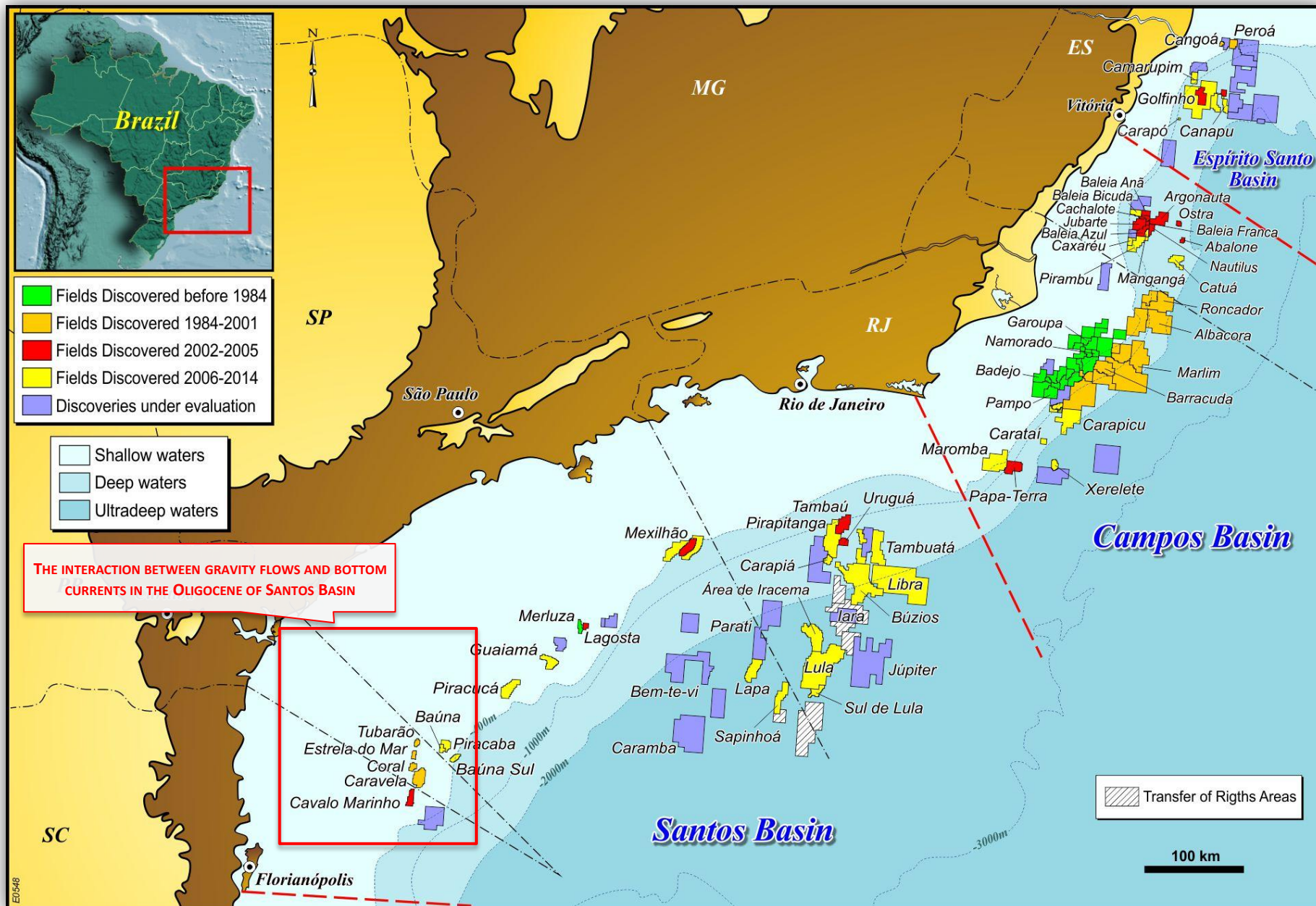
AN OVERVIEW OF PETROBRAS' HISTORICAL EVOLUTION...



MOST OF THESE MODELS REFER TO TURBIDITE BASINS IN WHICH DEEP OCEANIC CIRCULATION AND BOTTOM-CURRENT ACTIVITY WERE NEGLIGIBLE, IF ANY (MUTTI AND NORMARK, 1991)



THE DEEP WATER IS NOT ONLY THE REALM OF TURBIDITY CURRENTS !!! THERE IS SOMETHING ELSE...



MAIN DEPOSITIONAL ELEMENTS OBSERVED IN SOUTHERN SANTOS BASIN

TURBIDITES

- CANYONS
- CHANNELS
- INTRASLOPE CHANNELS
- DEPOSITIONAL LOBES

CONTOURITES

- LARGE SAND-DUNE FIELDS
- SAND WAVES
- BARCHAN DUNES
- SAND FURROWS
- SAND RIBBONS

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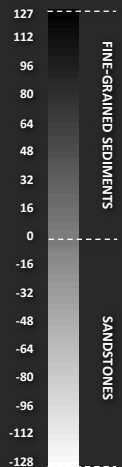
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WELL B

WELL C

WELL D

WELL A



13 km

TECVA AMPLITUDE MAP OF OLIGOCENE

MAIN DEPOSITIONAL ELEMENTS OBSERVED IN SOUTHERN SANTOS BASIN

TURBIDITES

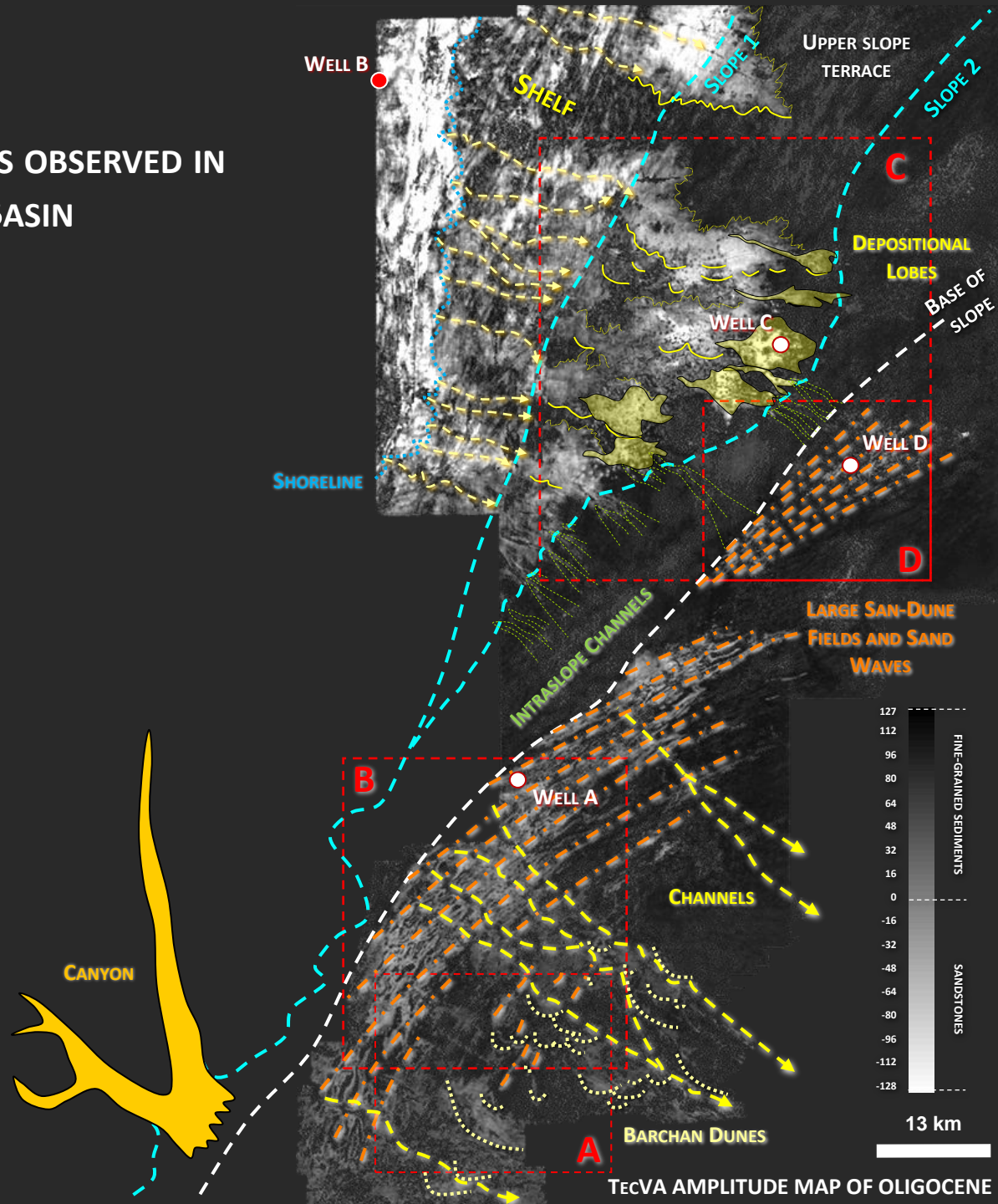
- CANYONS
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CONTOURITES

- LARGE SAND-DUNE FIELDS
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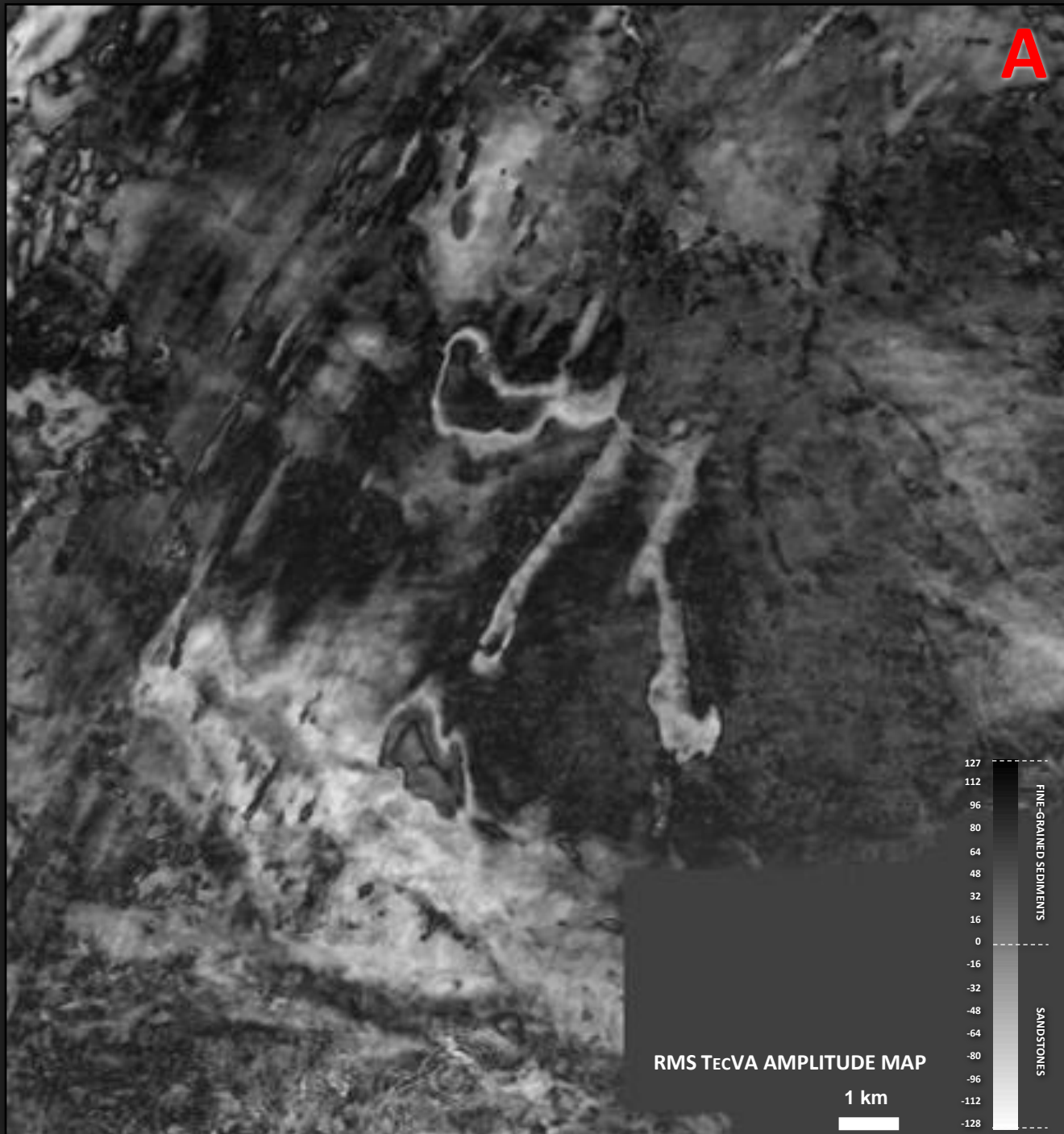
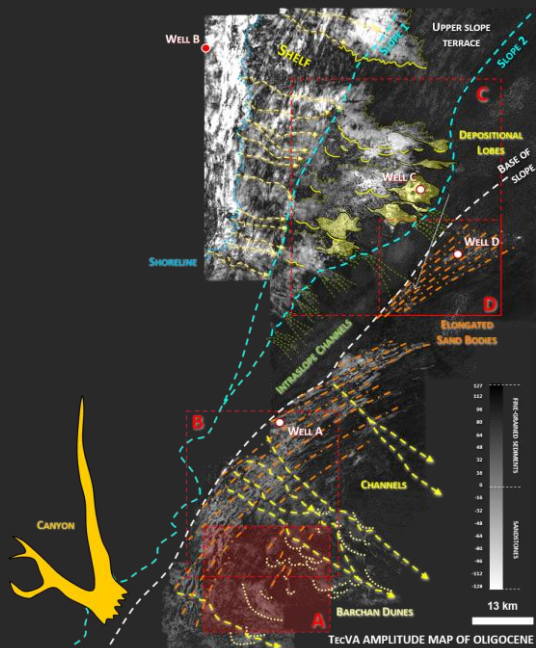


SANDY CONTOURITES

TYPES OF GEOMETRY

- LARGE SAND-DUNE FIELDS
- SAND WAVES
- BARCHAN DUNES
- SAND FURROWS
- SAND RIBBONS

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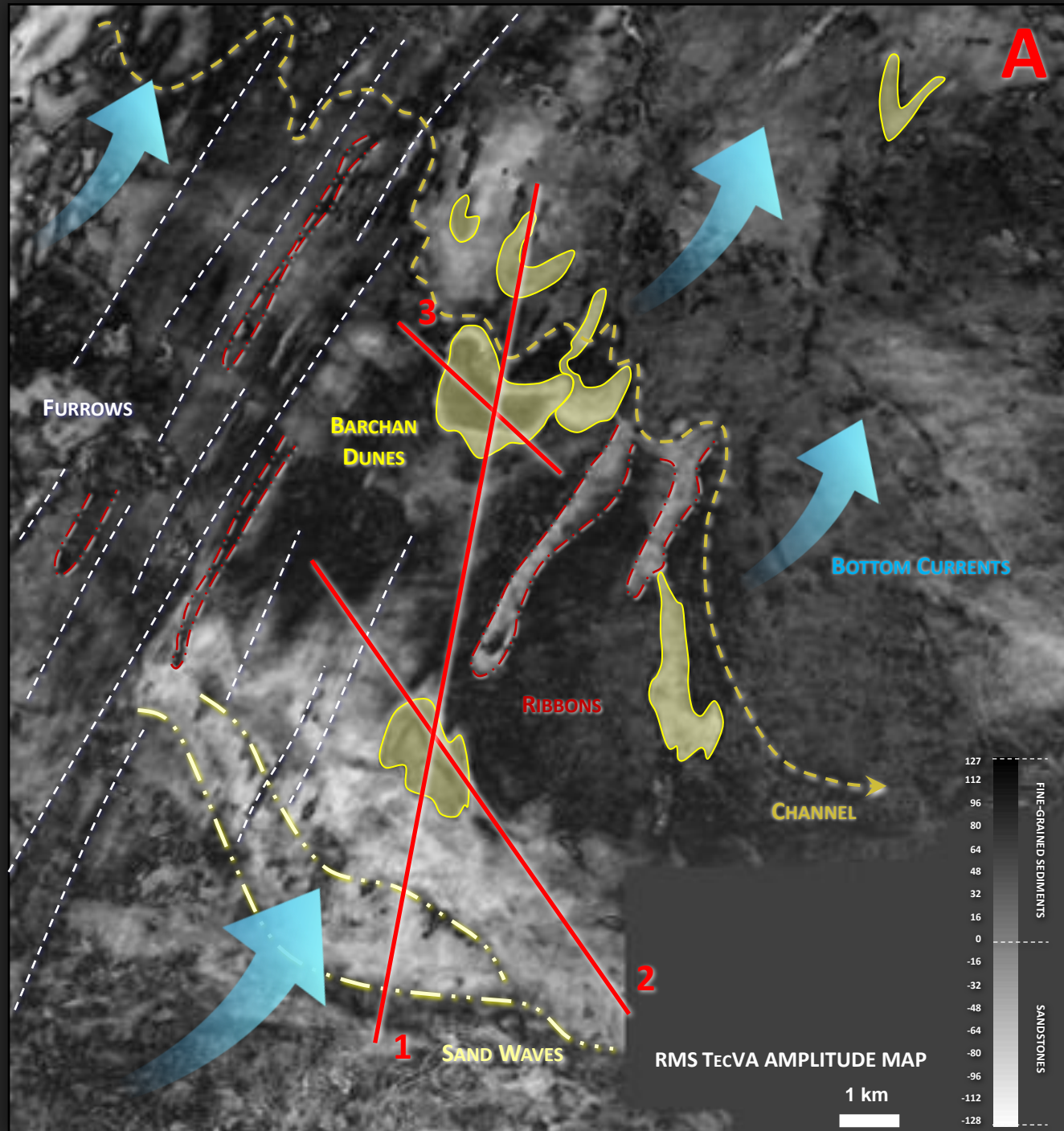
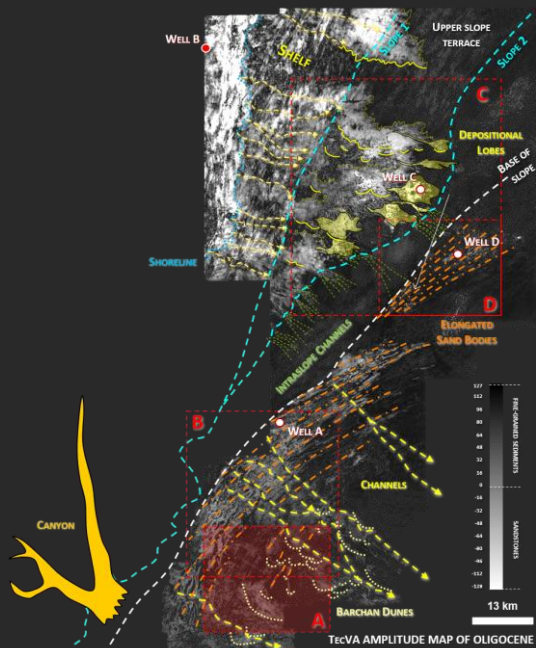


SANDY CONTOURITES

TYPES OF GEOMETRY

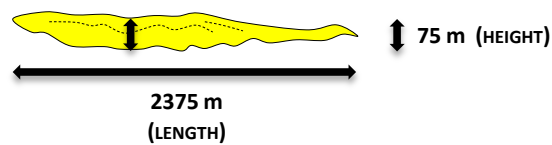
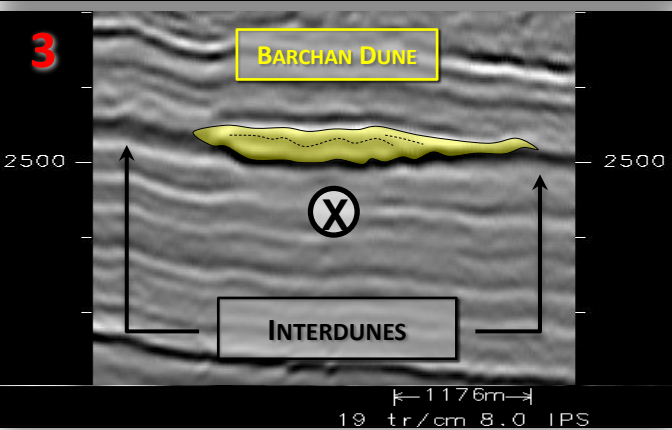
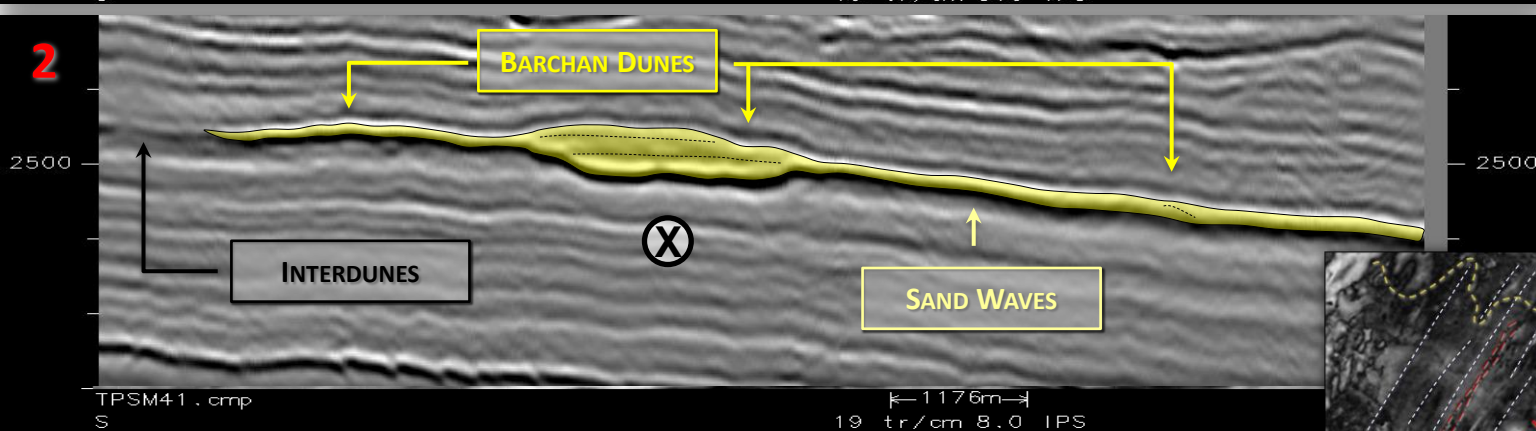
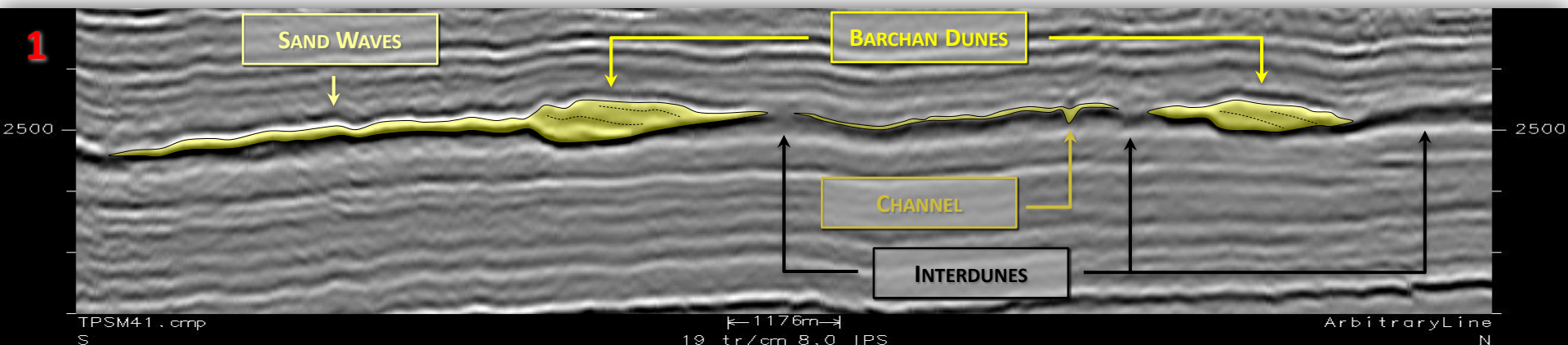
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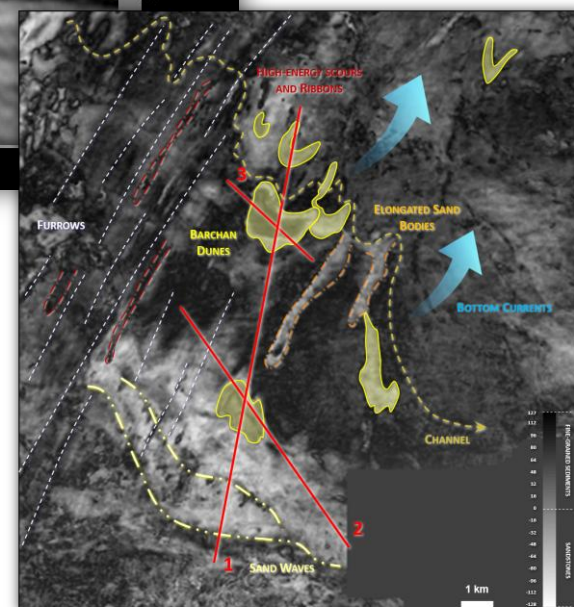


SANDY CONTOURITES

SEISMIC EXPRESSIONS (SANTOS BASIN)



GEOMETRY OF BARCHAN DUNE

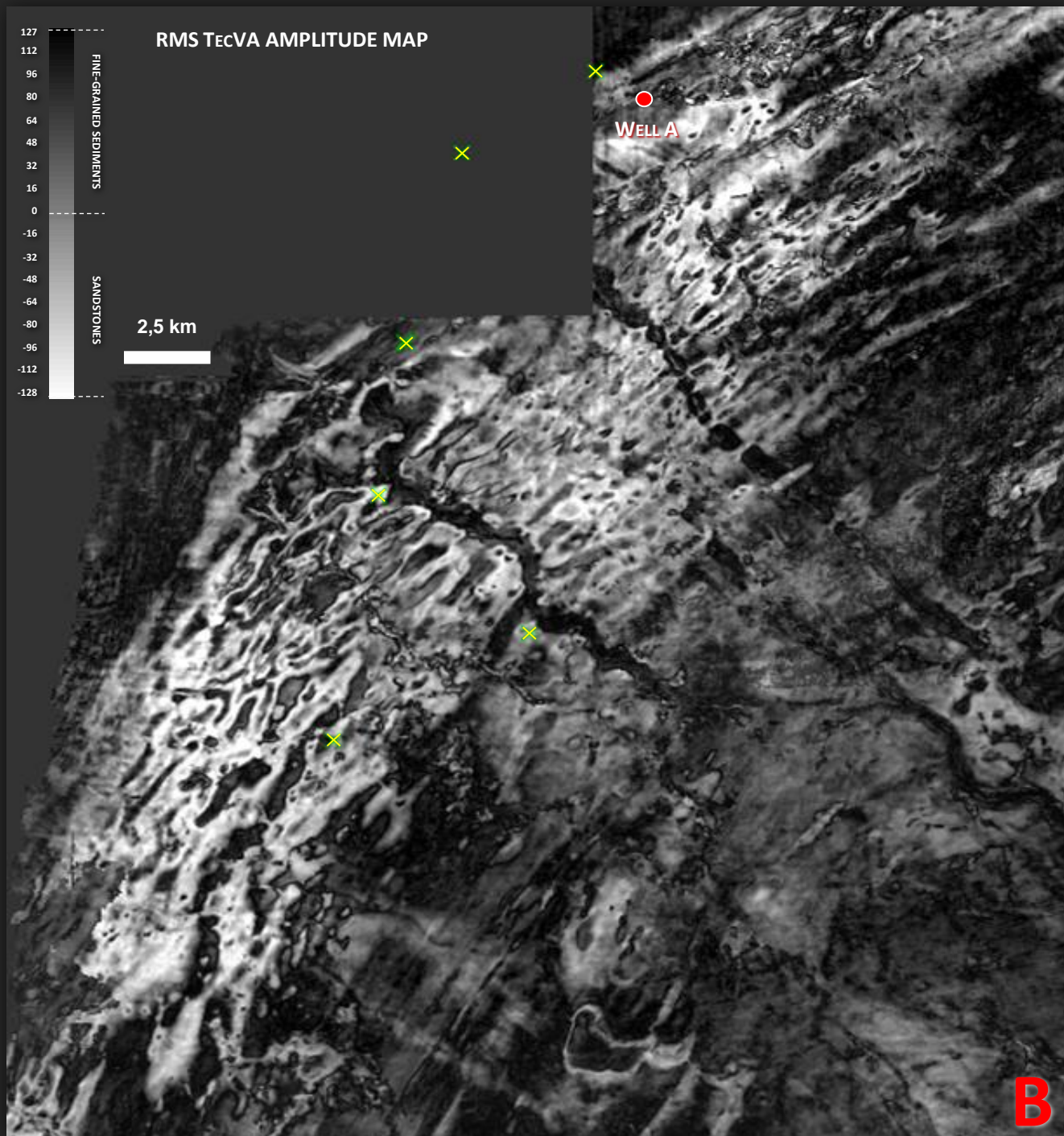
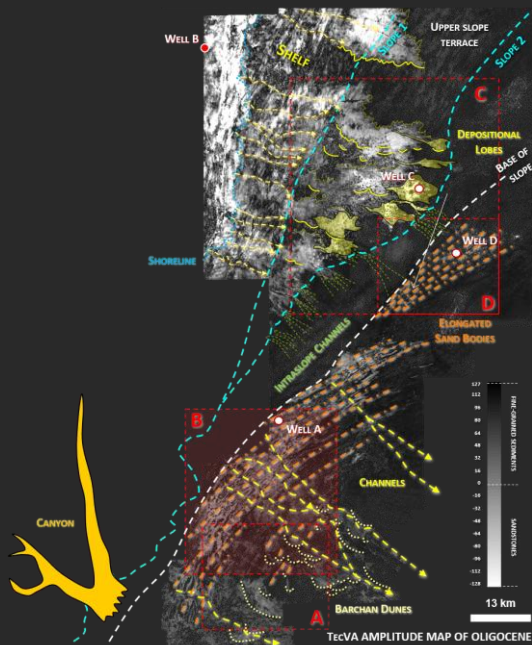


SANDY CONTOURITES

TYPES OF GEOMETRY

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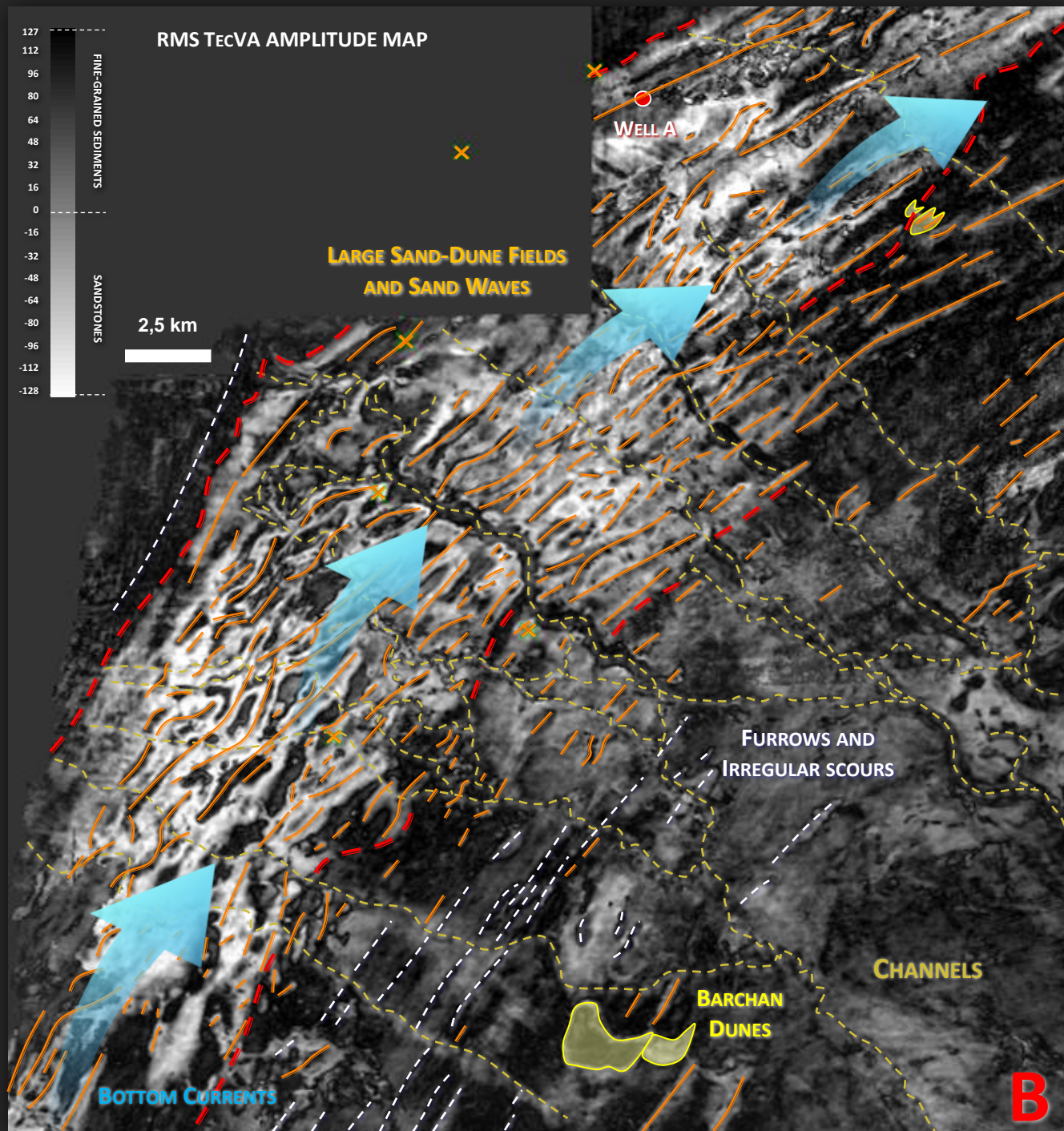
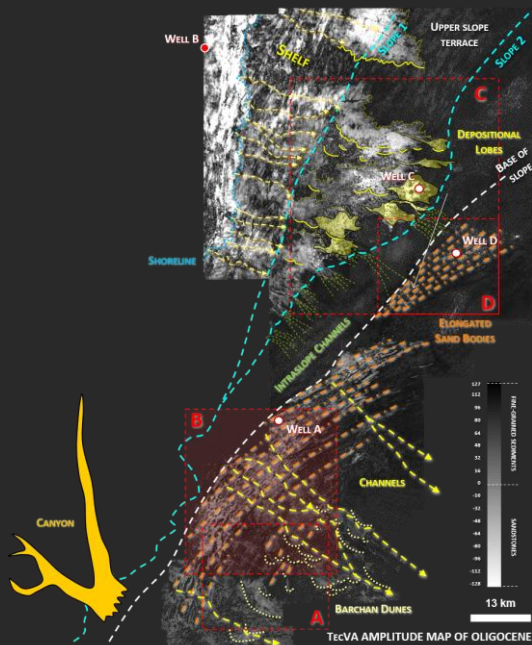


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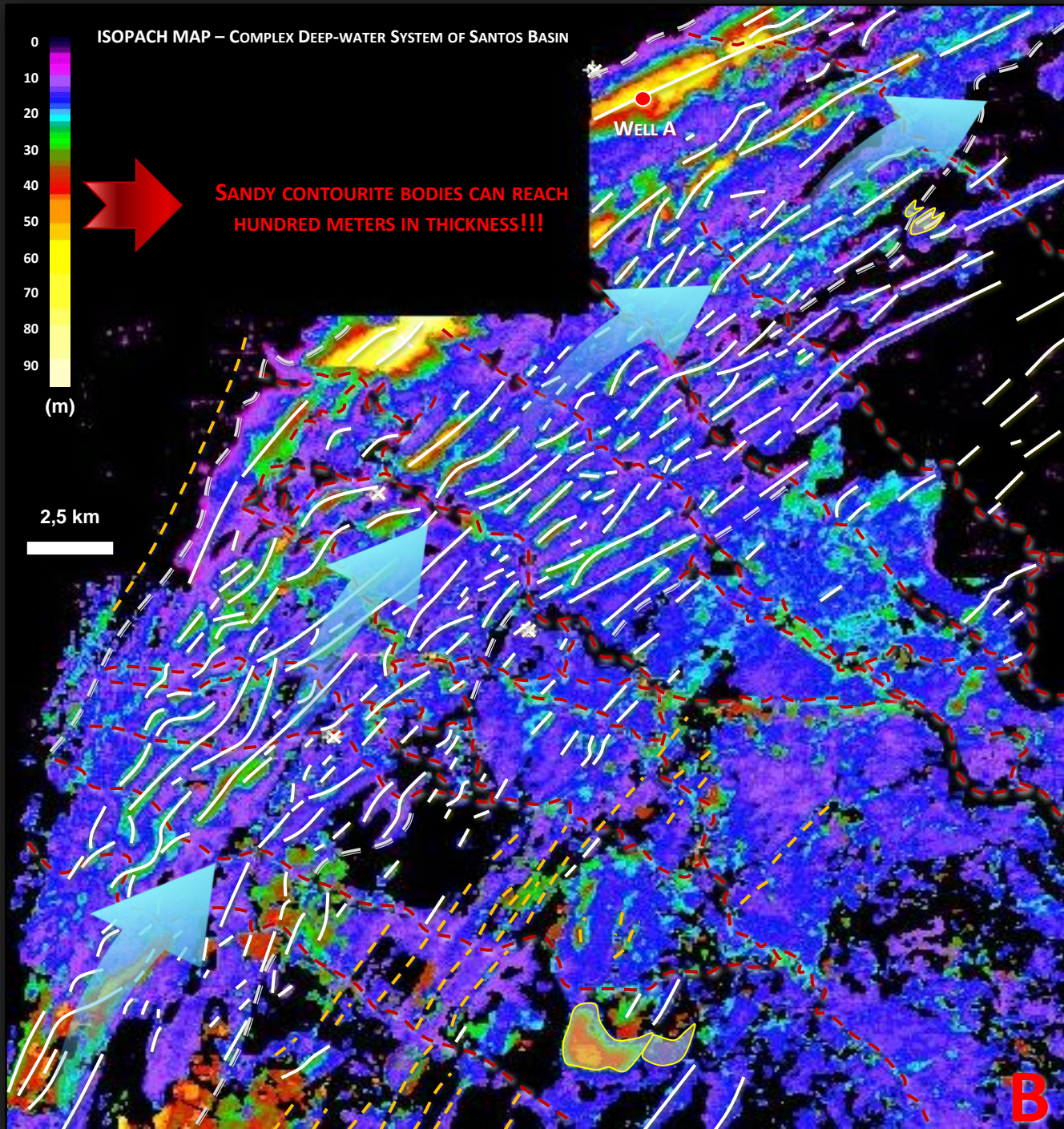
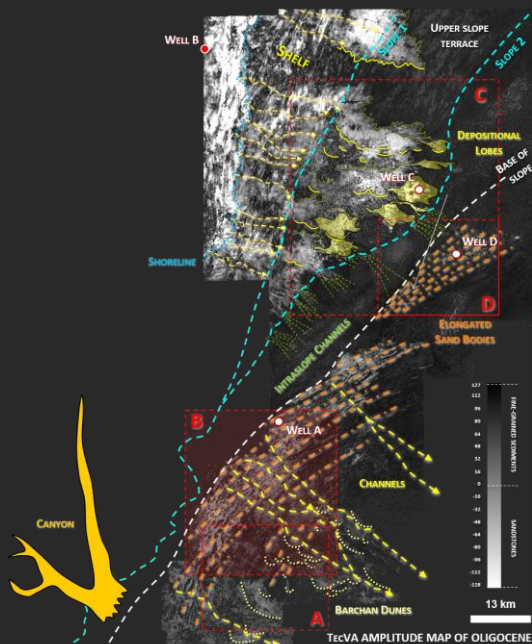


SANDY CONTOURITES

TYPES OF GEOMETRY

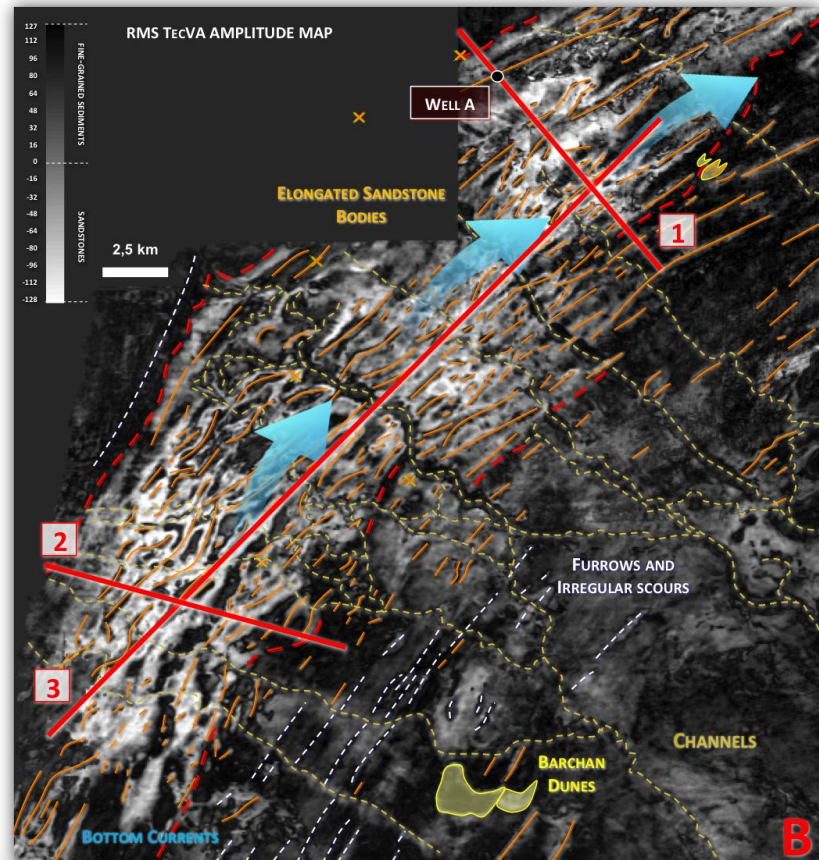
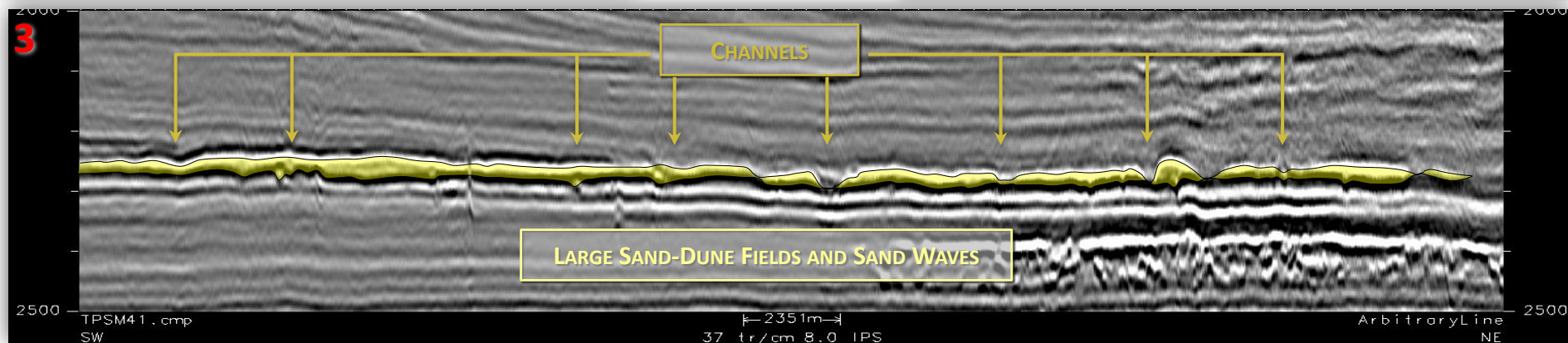
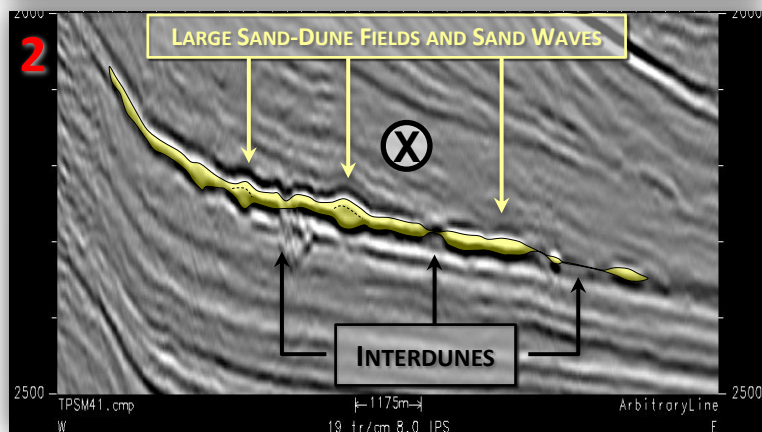
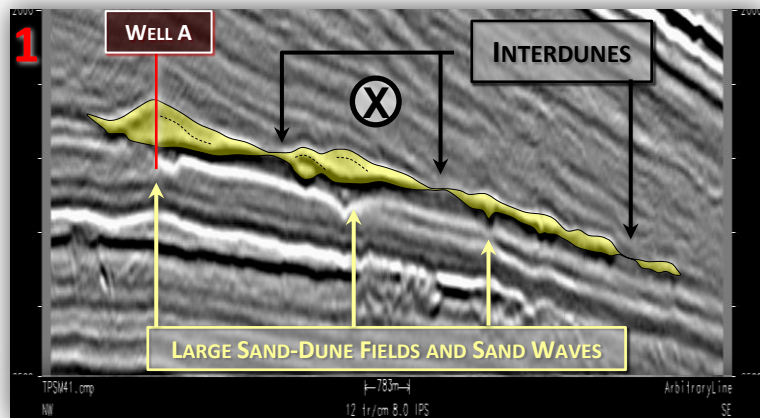
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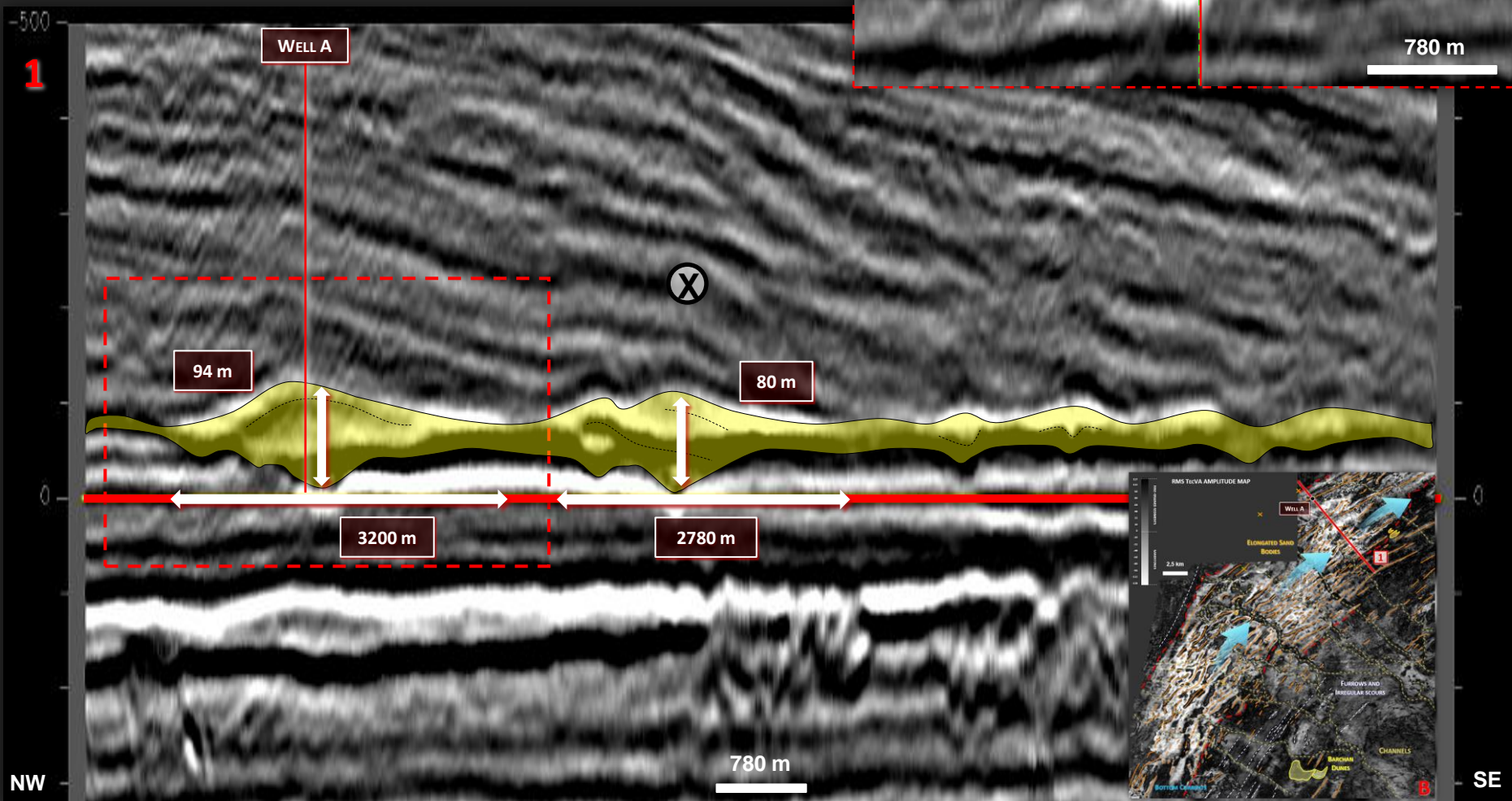
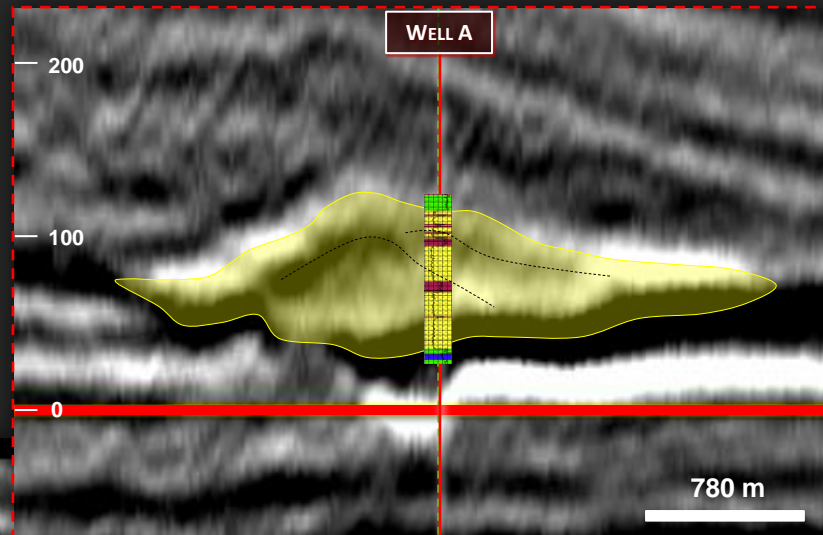


SANDY CONTOURITES

SEISMIC EXPRESSIONS (SANTOS BASIN)

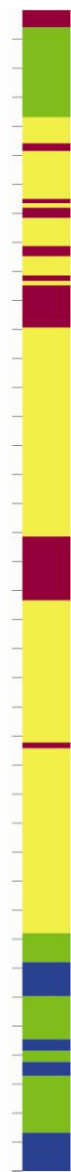


THE SEISMIC EXPRESSION OF THESE SEDIMENTS SUGGESTS THAT THEY FORMED PRIMARILY AS FEATURES WITH CROSS-SECTIONAL AND PLAN-VIEW GEOMETRY THAT INDICATES THE MIGRATION OF LARGE BEDFORMS (SANDWAVES, BARCHAN DUNES, SAND RIBBONS) OVER AN ESSENTIALLY FLAT SEA-BOTTOM. AMPLITUDE MAPS SHOW THAT THESE DEPOSITIONAL FEATURES ARE CLOSELY ASSOCIATED WITH LINEAR EROSIONAL FEATURES (SAND AND/OR GRAVEL FURROWS AND MORE GENERALLY LINEAR SCOURS) PRODUCED BY HIGHER VELOCITY CURRENTS



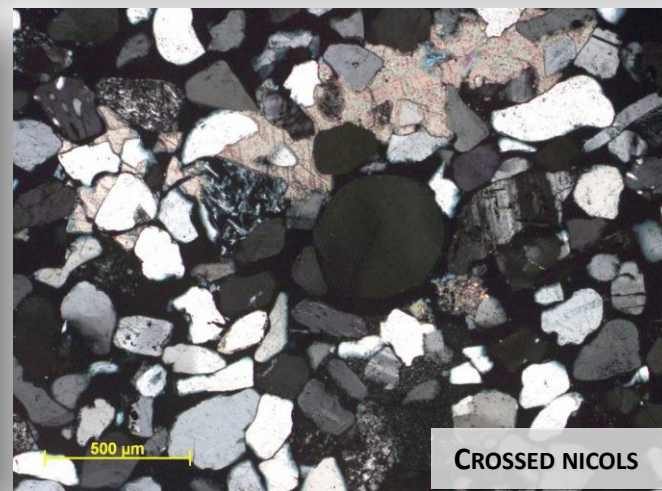
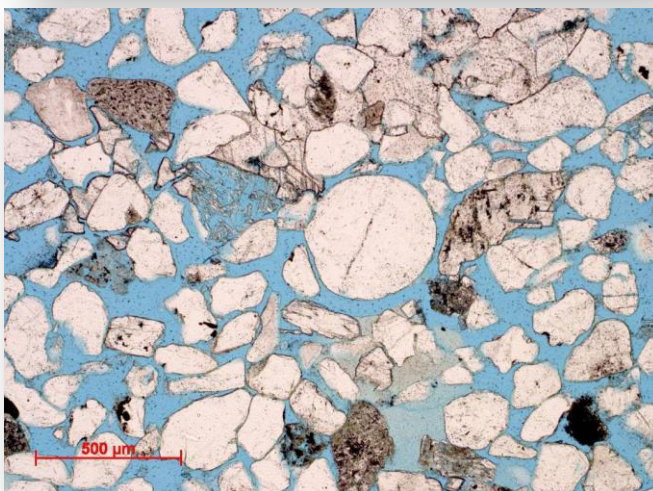
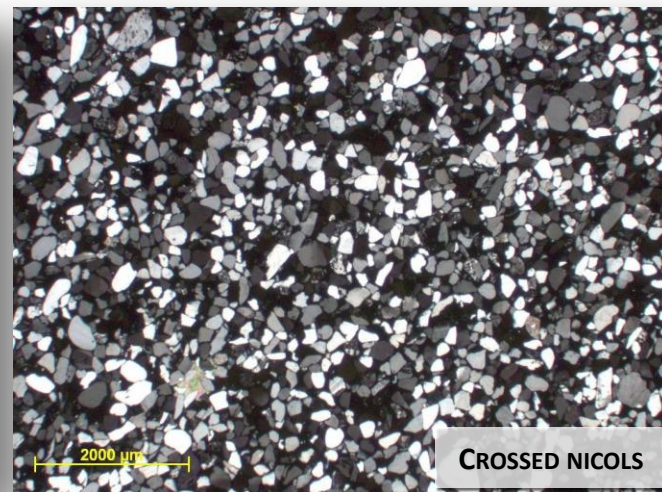
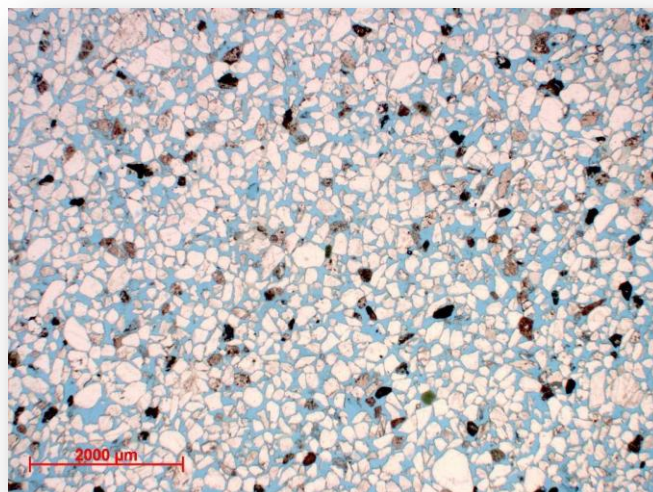
WELL A

GR



BLOCKY LOG PATTERN

94 m OF SAND THICKNESS

 $\Phi > 35\%$ 

VERY WELL SORTED AND LOW DEPOSITIONAL MATRIX FINE-GRAINED SANDSTONE

AS POINTED OUT BY SHANMUNGAM *ET AL.* (1993), BOTTOM CURRENTS CAN RESULT IN WELL SORTED SAND WITH GOOD POROSITY AND PERMEABILITY BECAUSE OF REWORKING AND WINNOWING AWAY OF MUD. PRIMARY POROSITY IS WELL DEVELOPED.

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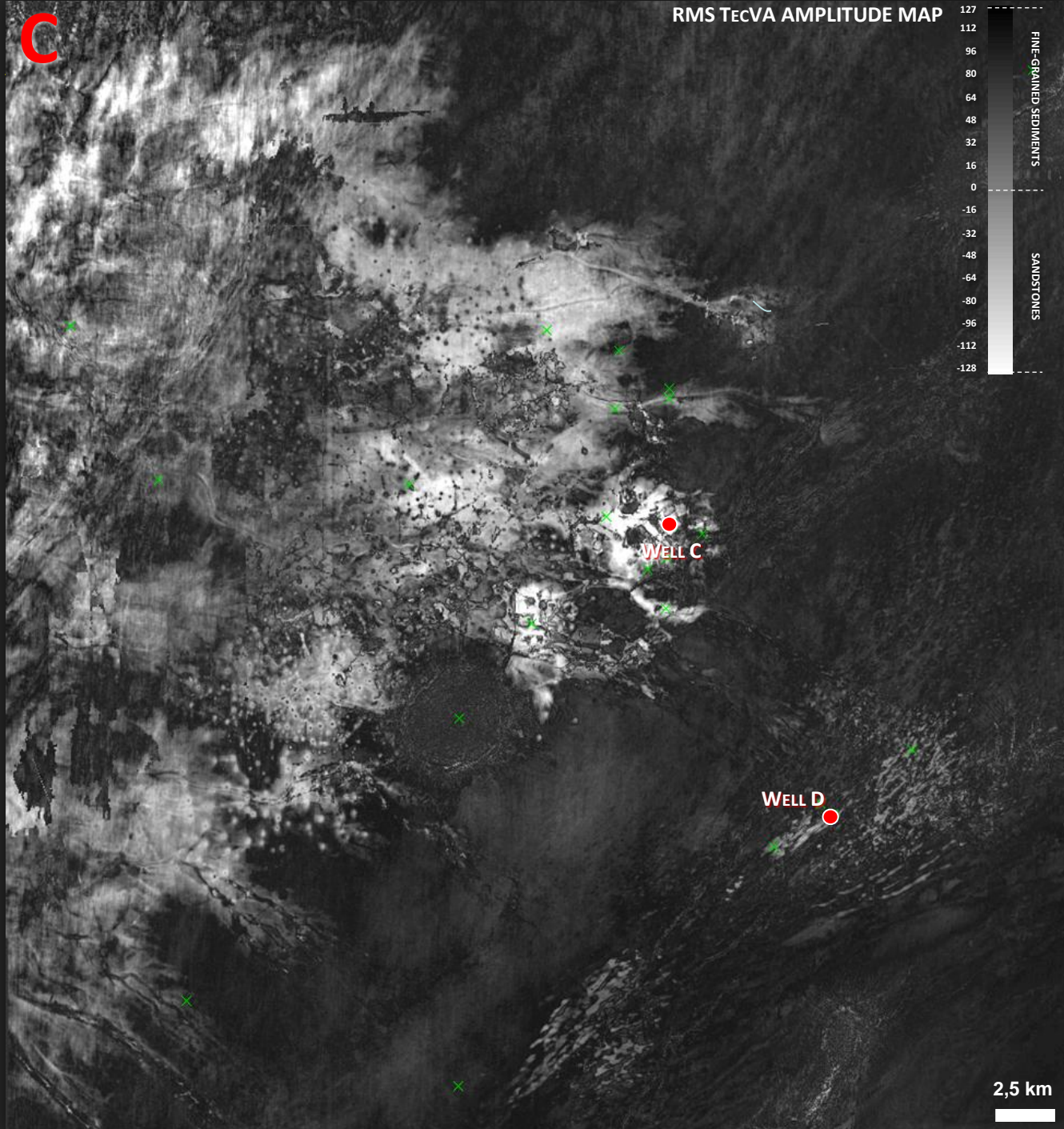
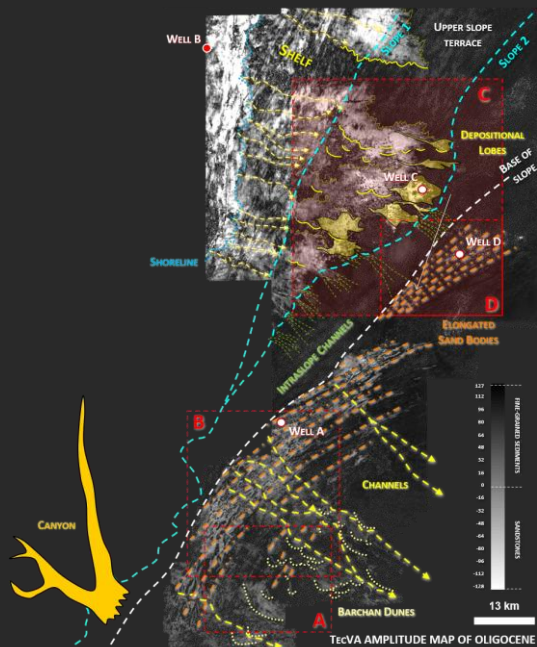
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SANDY CONTOURITES TYPES OF GEOMETRY

- LARGE SAND-DUNE FIELDS
- SAND WAVES
- BARCHAN DUNES
- SAND FURROWS
- SAND RIBBONS

TURBIDITES DEPOSITIONAL ELEMENTS

- CHANNELS
- DEPOSITIONAL LOBES





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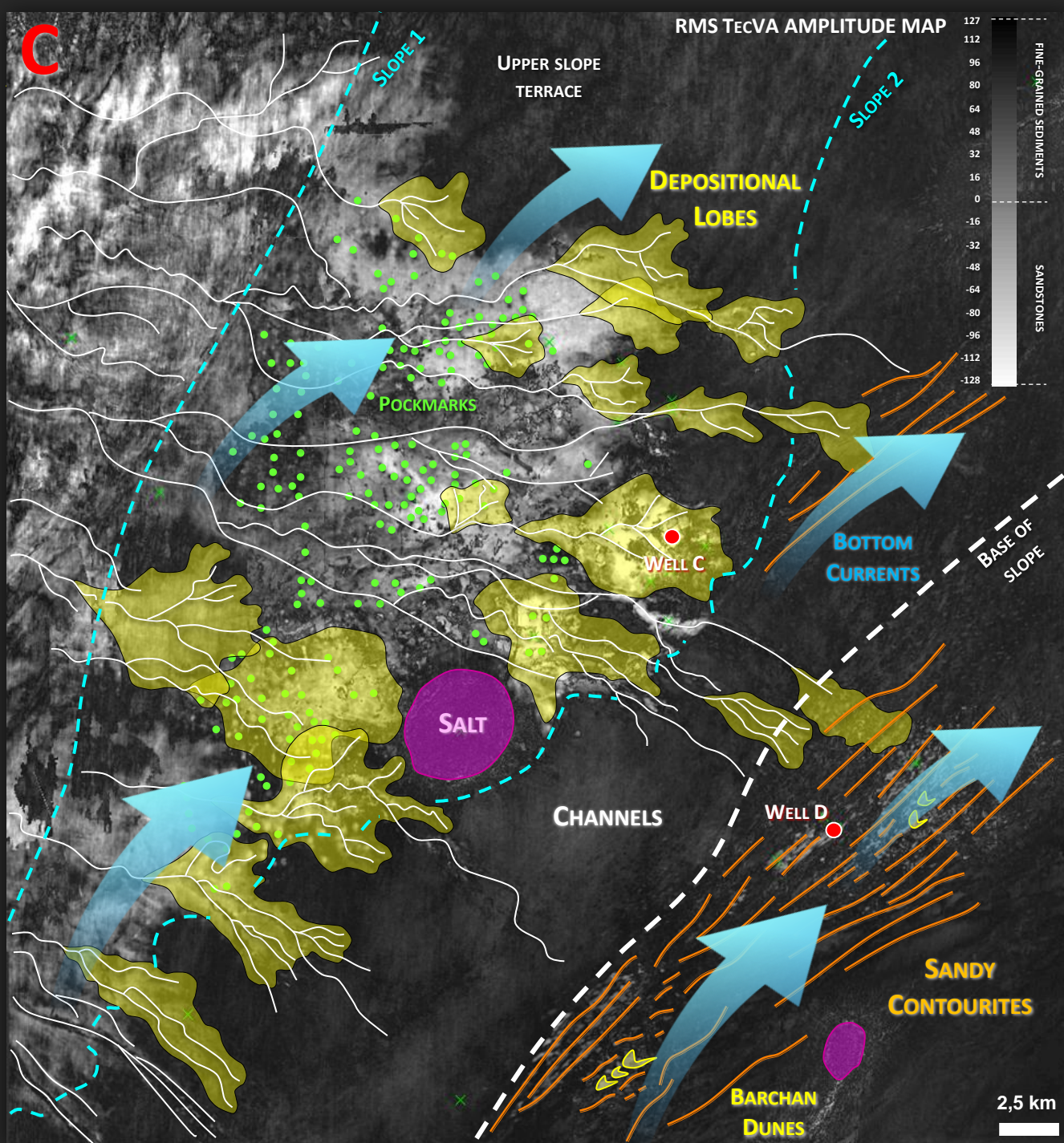
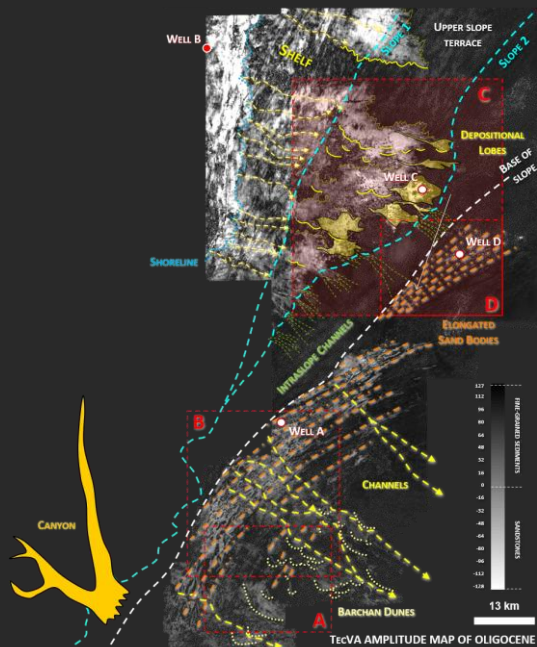
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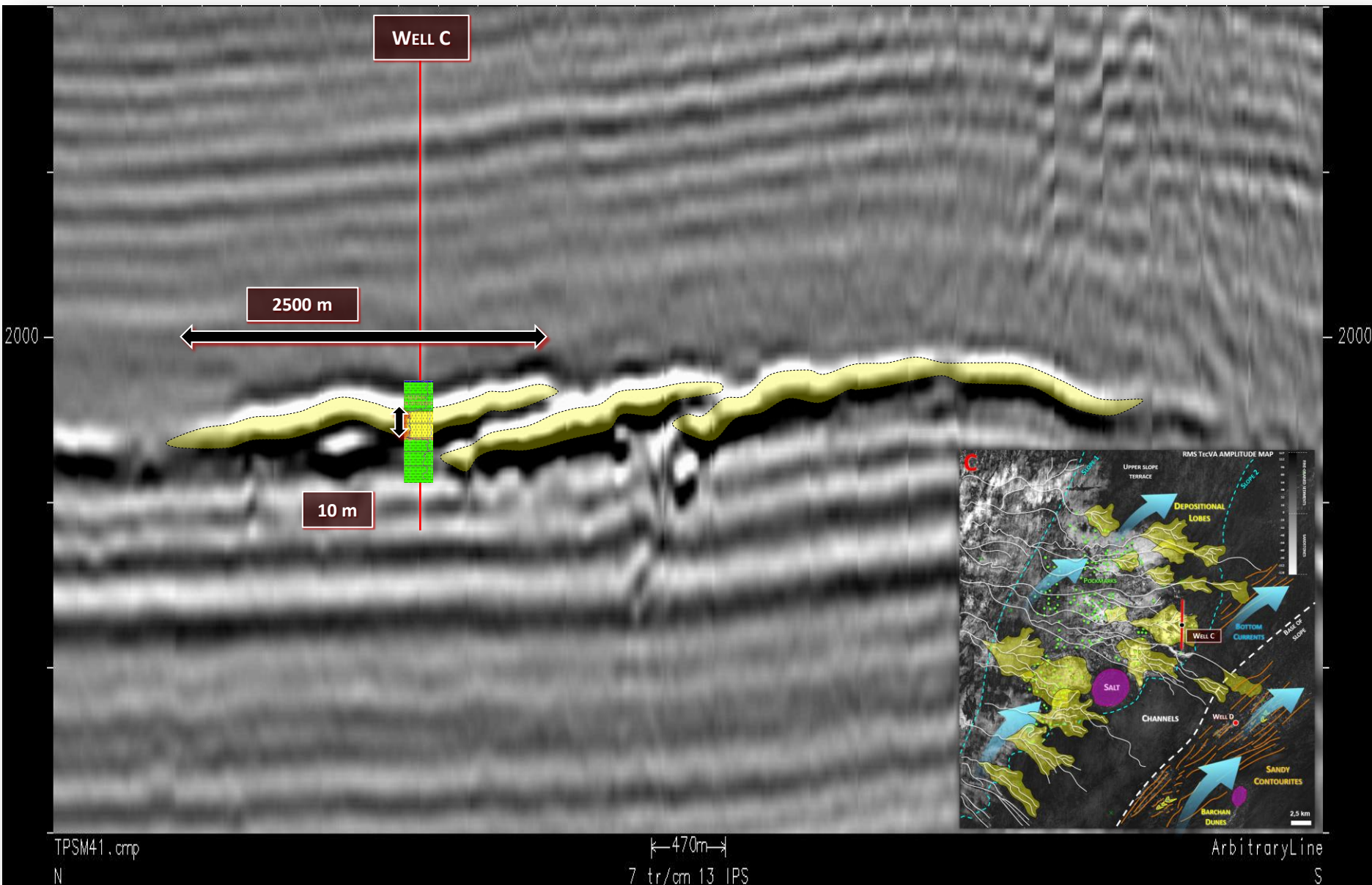
TURBIDITES DEPOSITIONAL ELEMENTS

- CHANNELS
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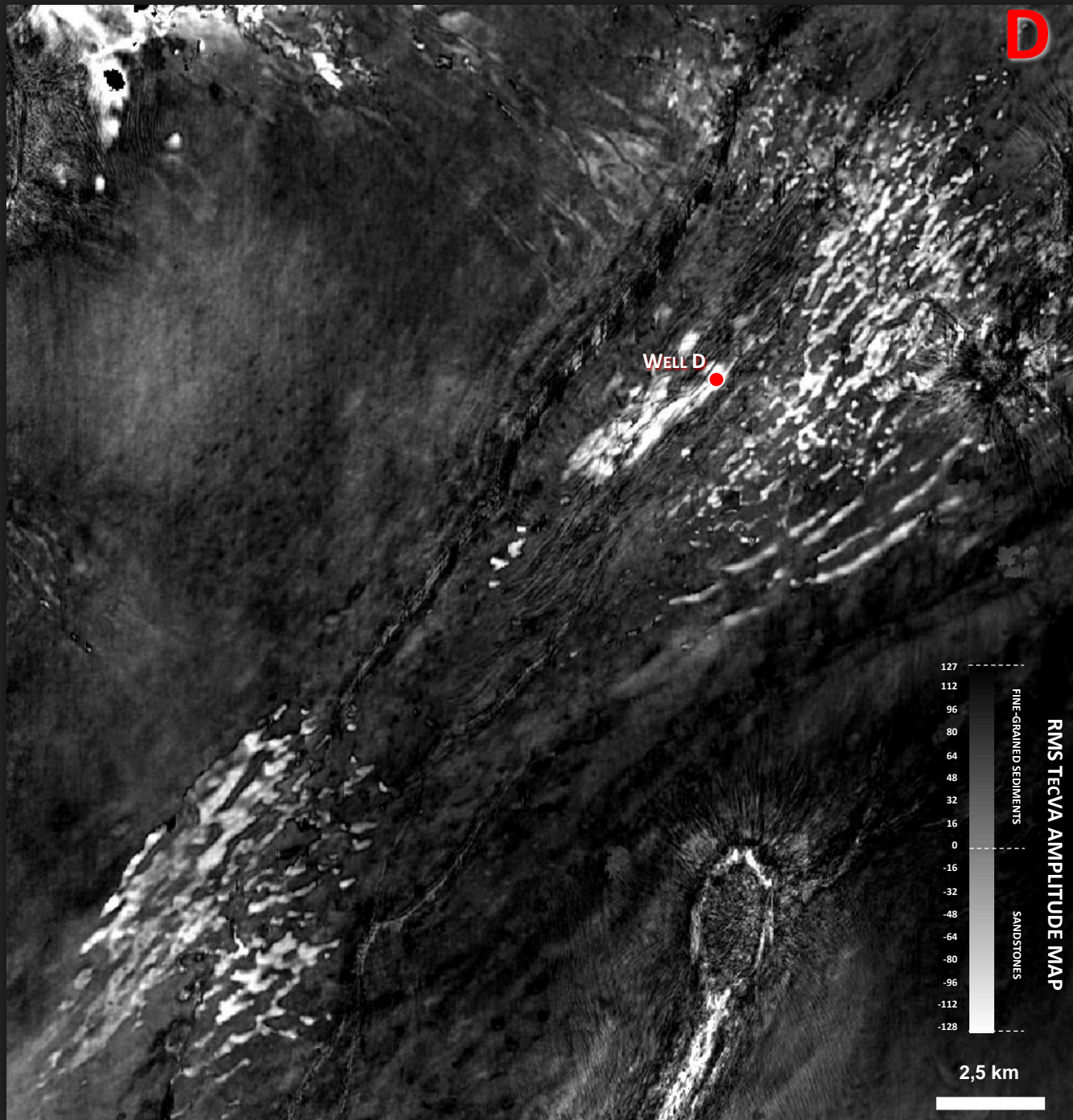
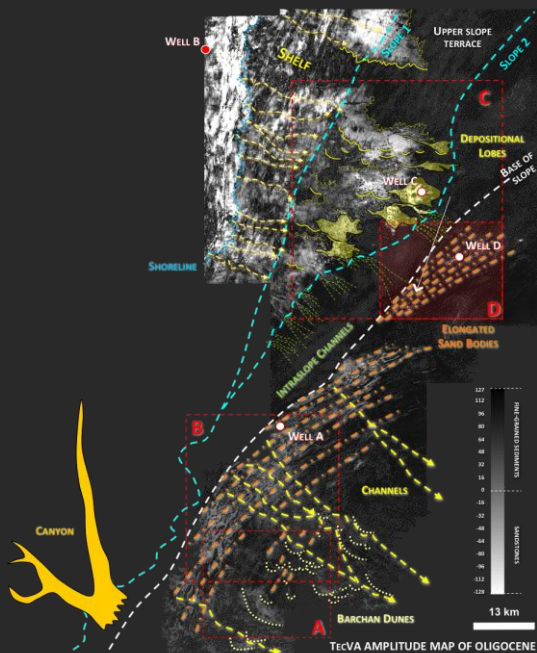


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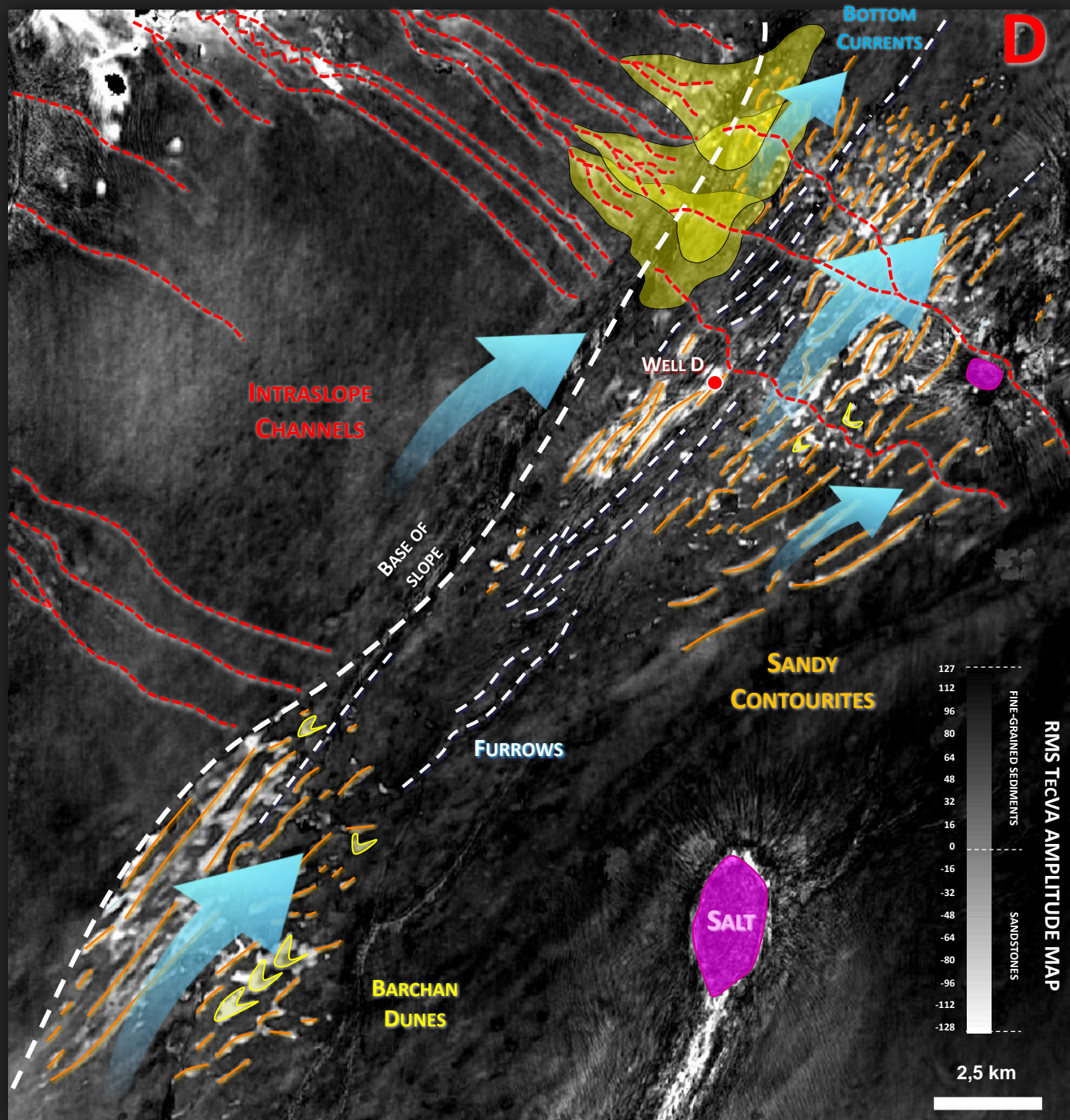
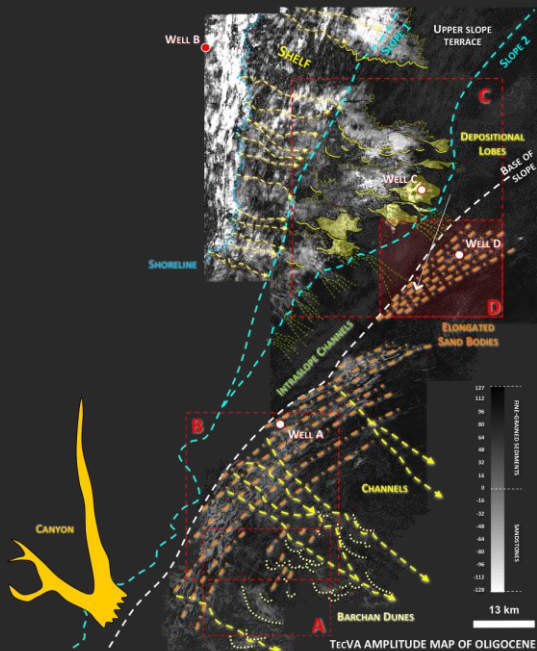


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- SAND RIBBONS

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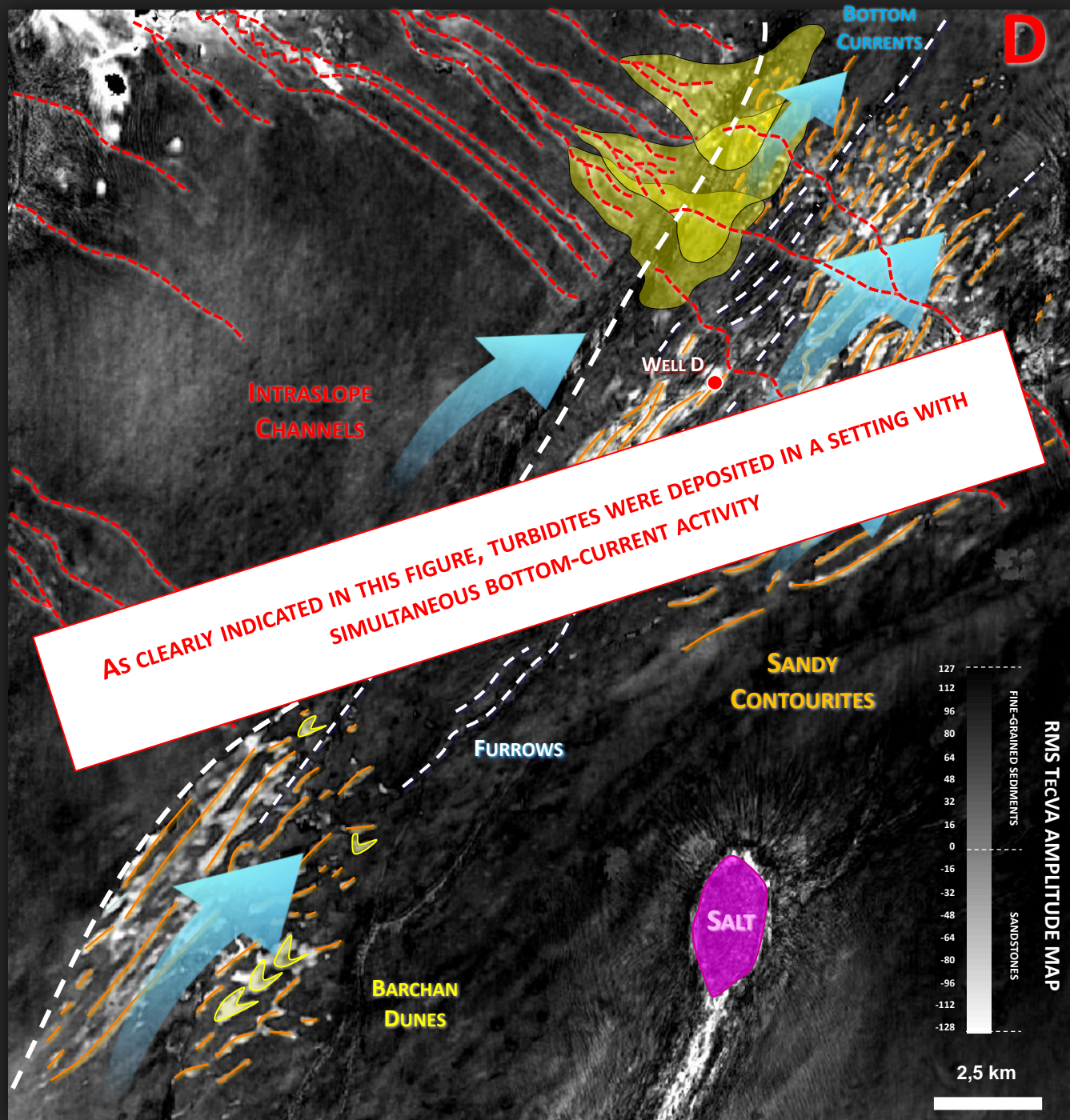
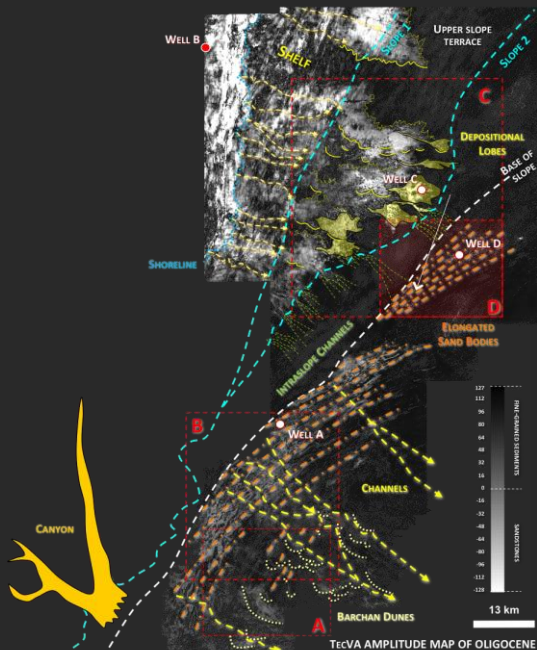


SANDY CONTOURITES

TYPES OF GEOMETRY

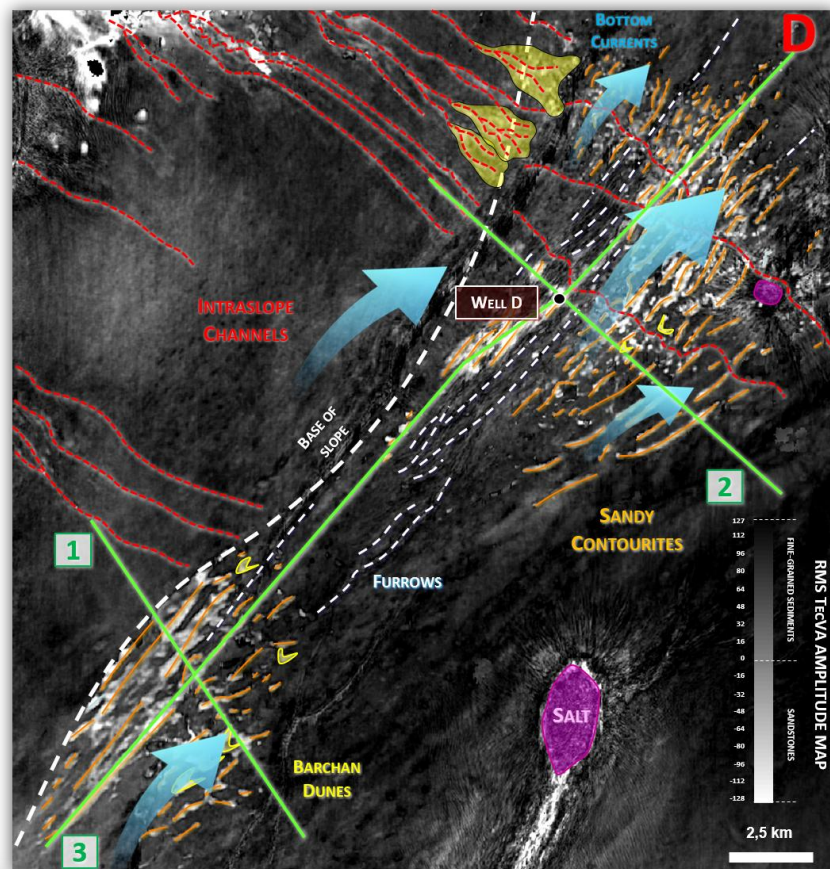
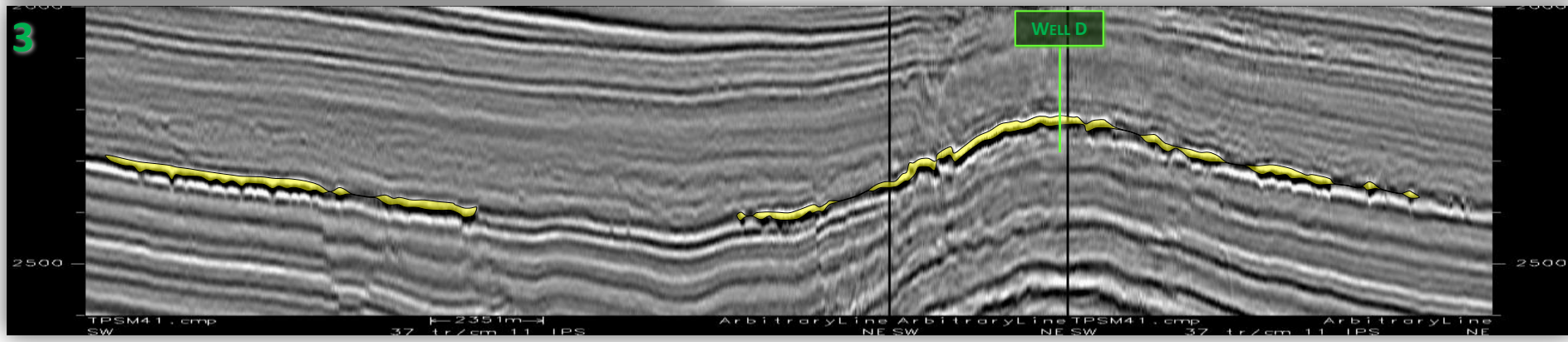
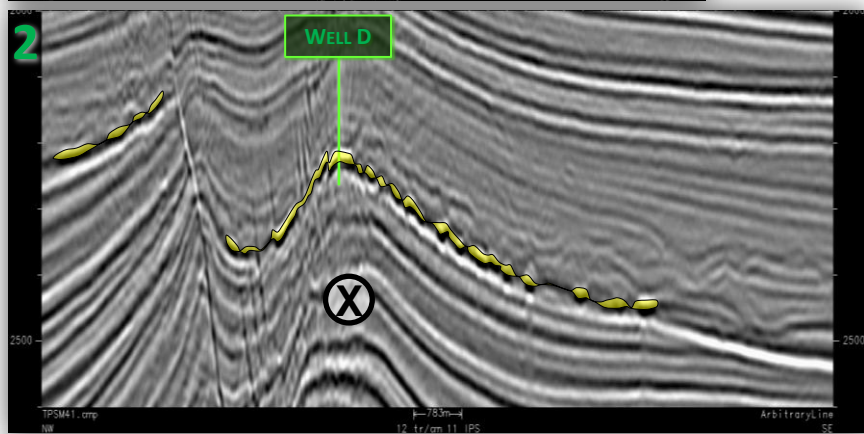
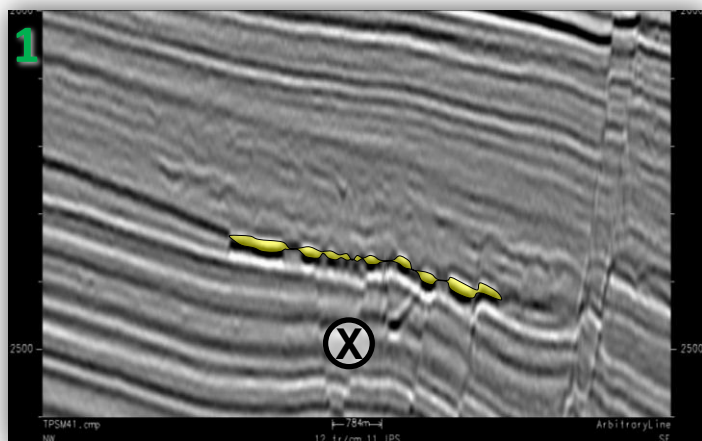
- LARGE SAND-DUNE FIELDS
- SAND WAVES
- BARCHAN DUNES
- SAND FURROWS
- SAND RIBBONS

MODIFIED FROM BULHOES *ET AL.*, 2012

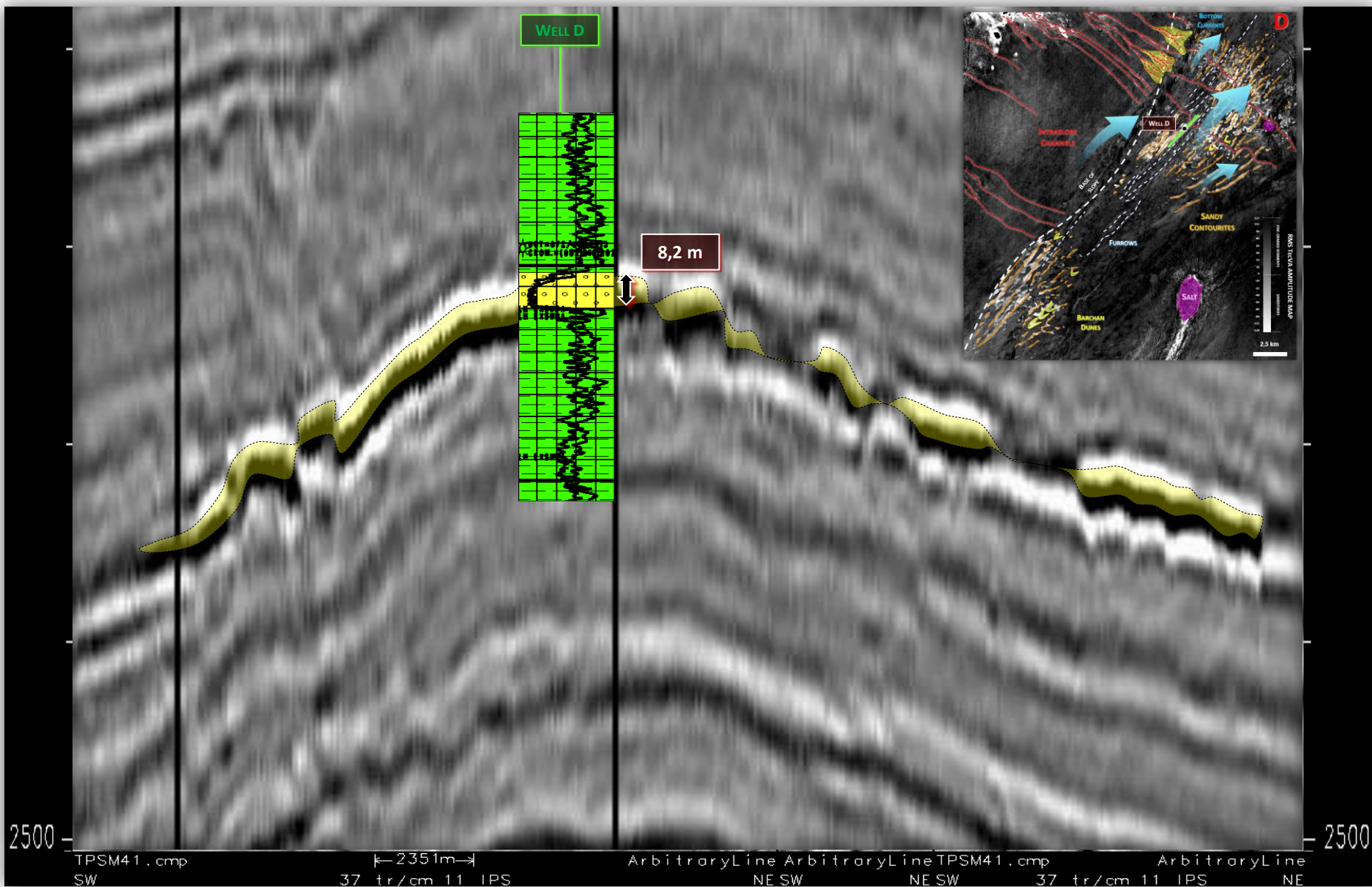


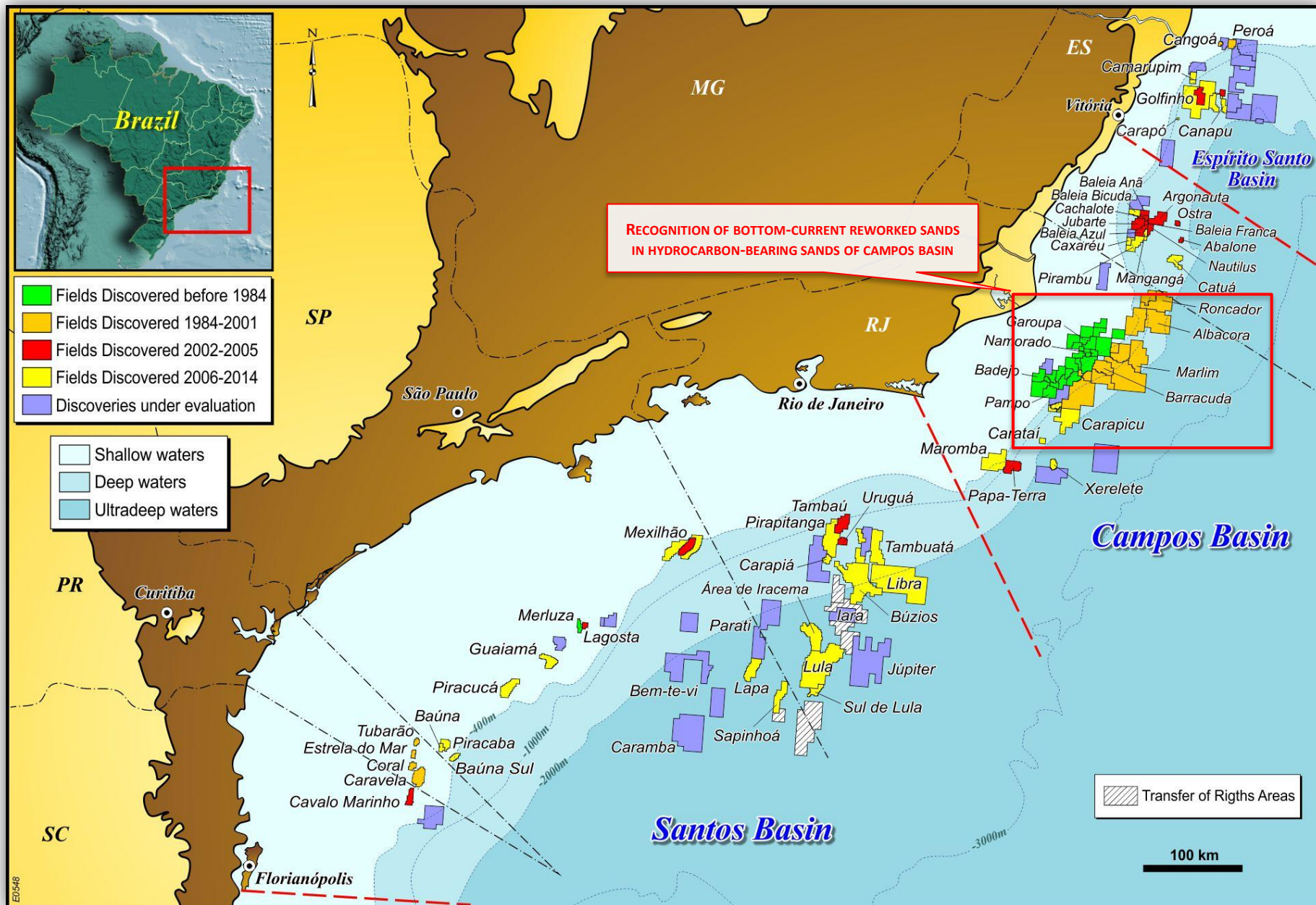
SANDY CONTOURITES

SEISMIC EXPRESSIONS (SANTOS BASIN)



MODIFIED FROM BULHOES ET AL., 2012







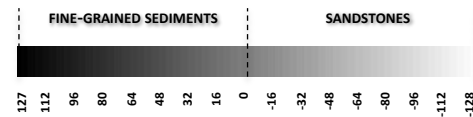
PETRÓLEO BRASILEIRO S.A.
PETROBRAS

TURBIDITES VS. CONTOURITES

SEISMIC EXPRESSIONS (CAMPOS BASIN)

5 km

LOWER OLIGOCENE RMS TecVA
AMPLITUDE MAP

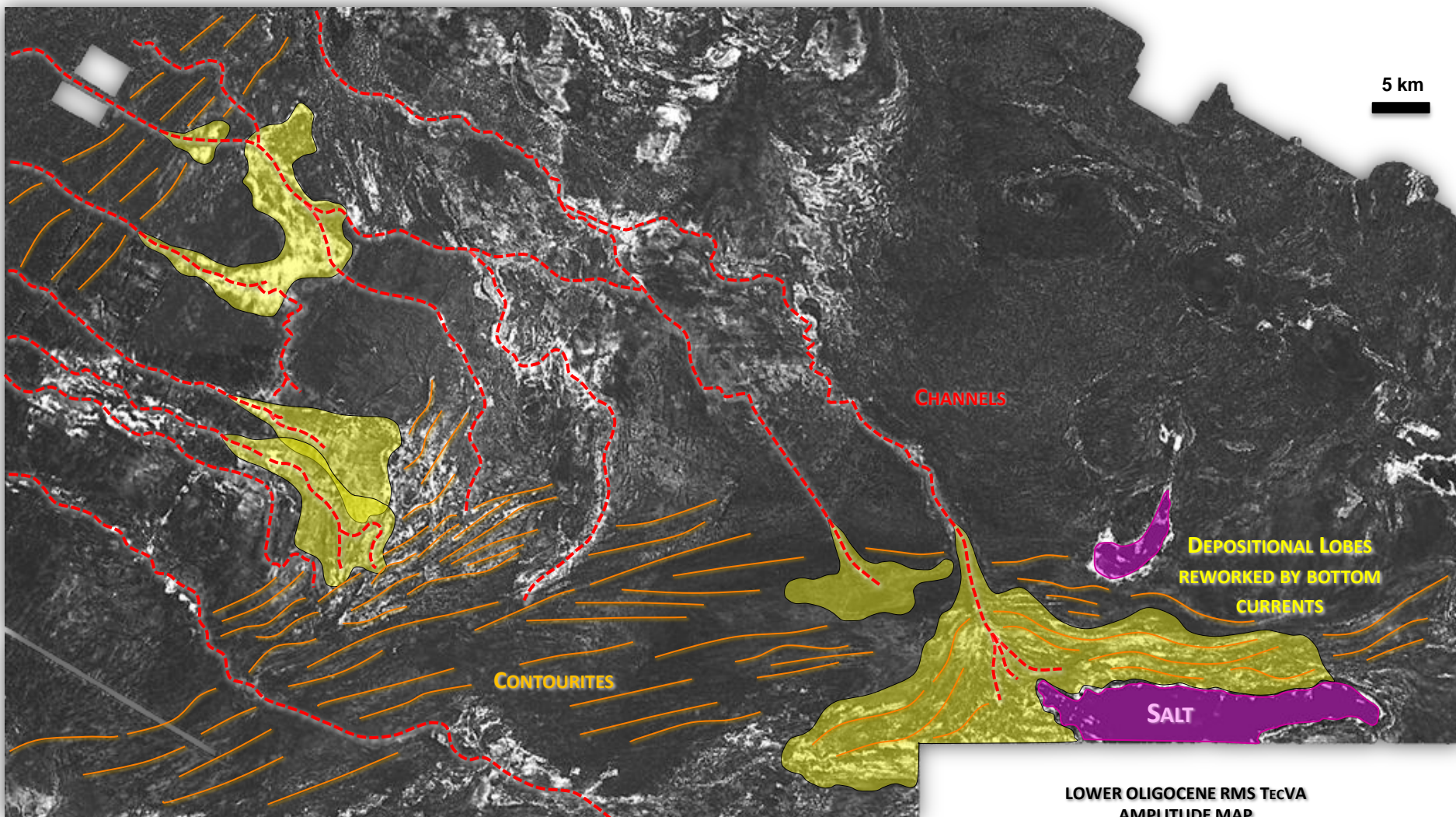




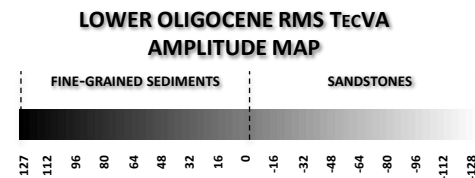
PETRÓLEO BRASILEIRO S.A.
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TURBIDITES VS. CONTOURITES

SEISMIC EXPRESSIONS (CAMPOS BASIN)



SAND-LADEN TURBIDITY CURRENTS ENTERING DEEP WATERS VIA DELTA-SLOPE CHANNELS AND STRUCTURALLY CONTROLLED PATHWAYS. BOTTOM CURRENTS MOVING TOWARD THE NORTHEASTERN QUADRANT ALONG THE SLOPE

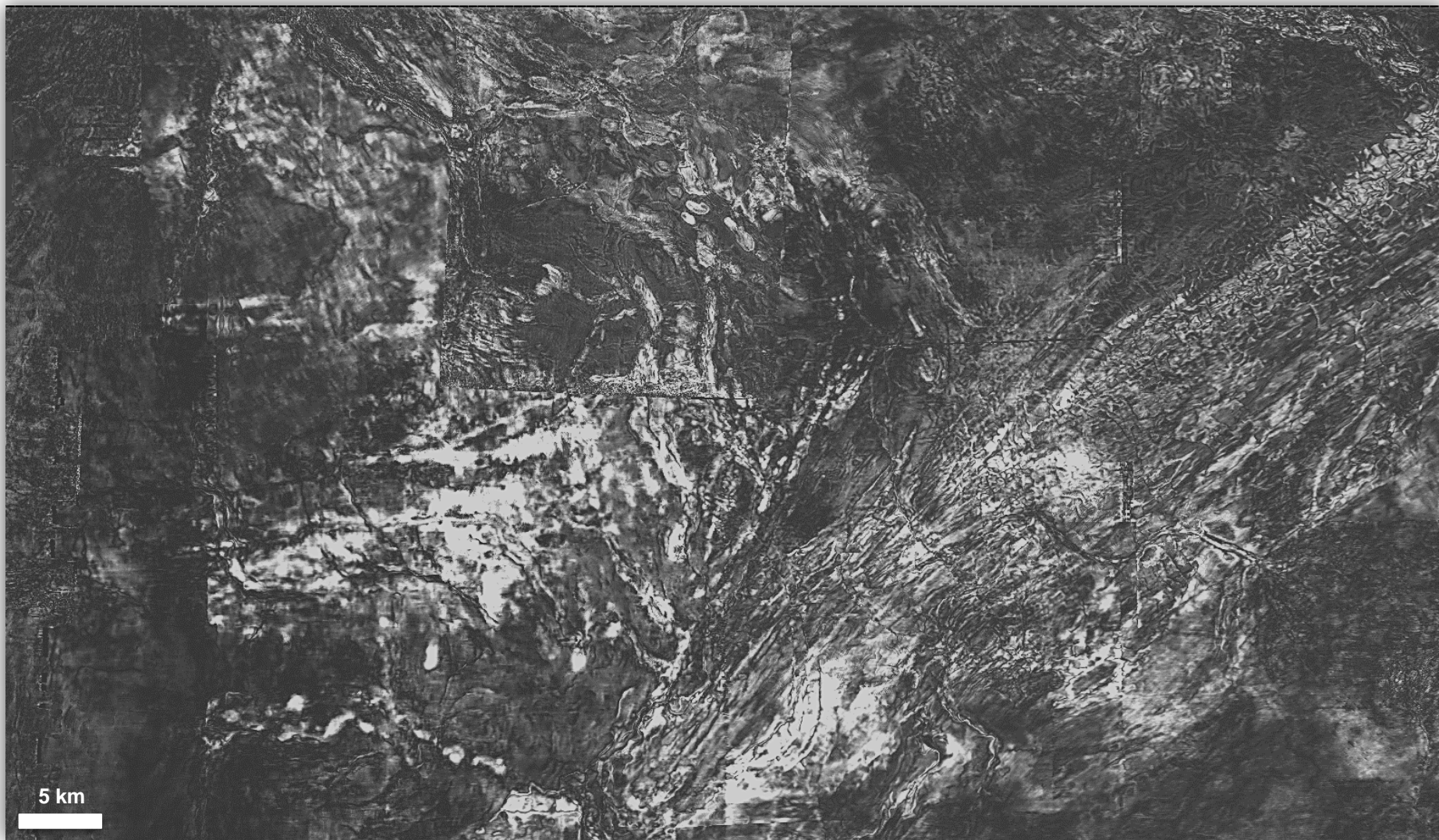




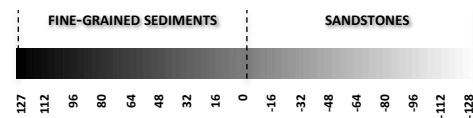
PETRÓLEO BRASILEIRO S.A.
PETROBRAS

TURBIDITES VS. CONTOURITES

SEISMIC EXPRESSIONS (CAMPOS BASIN)



RMS TecVA AMPLITUDE MAP

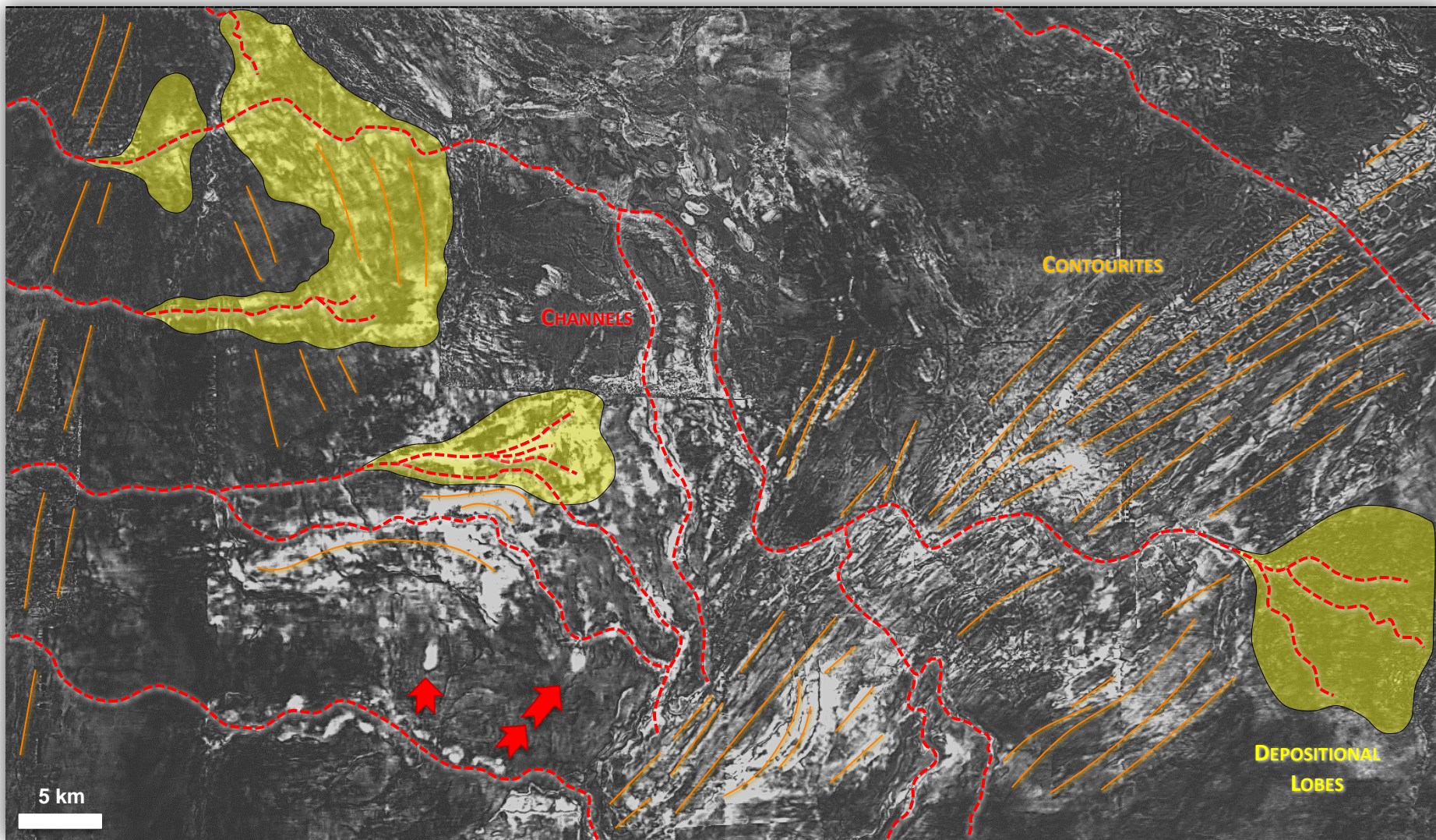




PETRÓLEO BRASILEIRO S.A.
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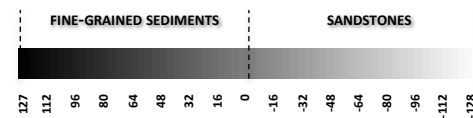
TURBIDITES VS. CONTOURITES

SEISMIC EXPRESSIONS (CAMPOS BASIN)



TURBIDITES WERE DEPOSITED IN A SETTING WHERE LARGE PORTIONS OF THE BASIN WERE UNDERGOING BOTTOM-CURRENT ACTIVITY AT THE SAME TIME. AS A RESULT, MOST TURBIDITES SUFFERED VARIOUS KIND AND DEGREES OF REWORKING DURING AND AFTER DEPOSITION.

RMS TecVA AMPLITUDE MAP

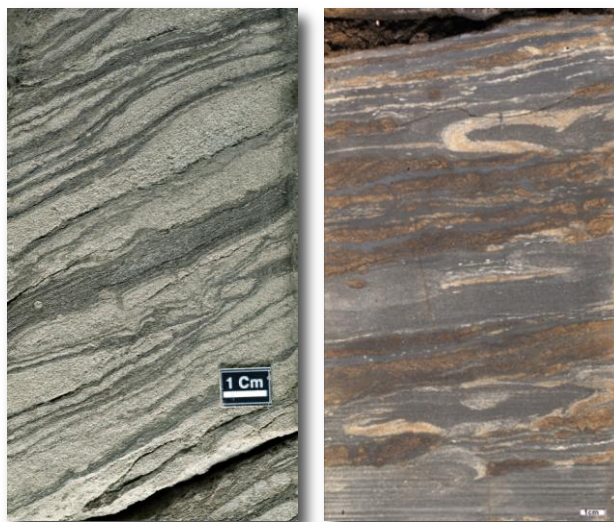


BASED ON CAMPOS BASIN DATA, CONTOURITES OCCUR PRIMARILY IN THREE SETTINGS:

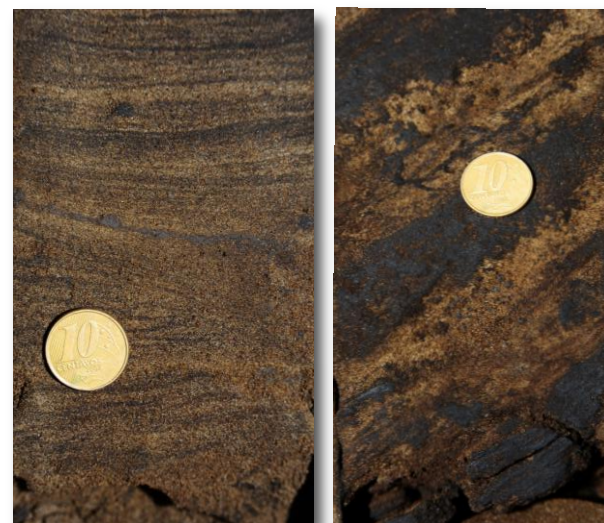
- **WITHIN CHANNELS OR IN TURBIDITE FAN REMNANTS;**
- **WITHIN CHANNELS WHERE BOTTOM CURRENTS APPARENTLY MOVED UP AND DOWN BEING ENHANCED BY A TIDAL COMPONENT;**
- **IN OPEN SLOPE SETTINGS, WHERE GEOSTROPHIC THERMOHALINE CURRENTS ESTABLISHED PERMANENT OR QUASI-PERMANENT FLOW PATTERNS CONTROLLED BY LOCAL AND REGIONAL TOPOGRAPHY THAT MOVED LARGE AMOUNTS OF FINE SAND THROUGH MIGRATING LARGE-SCALE SAND-DUNE FIELDS AND SAND WAVES, AND SMALLER BEDFORMS.**



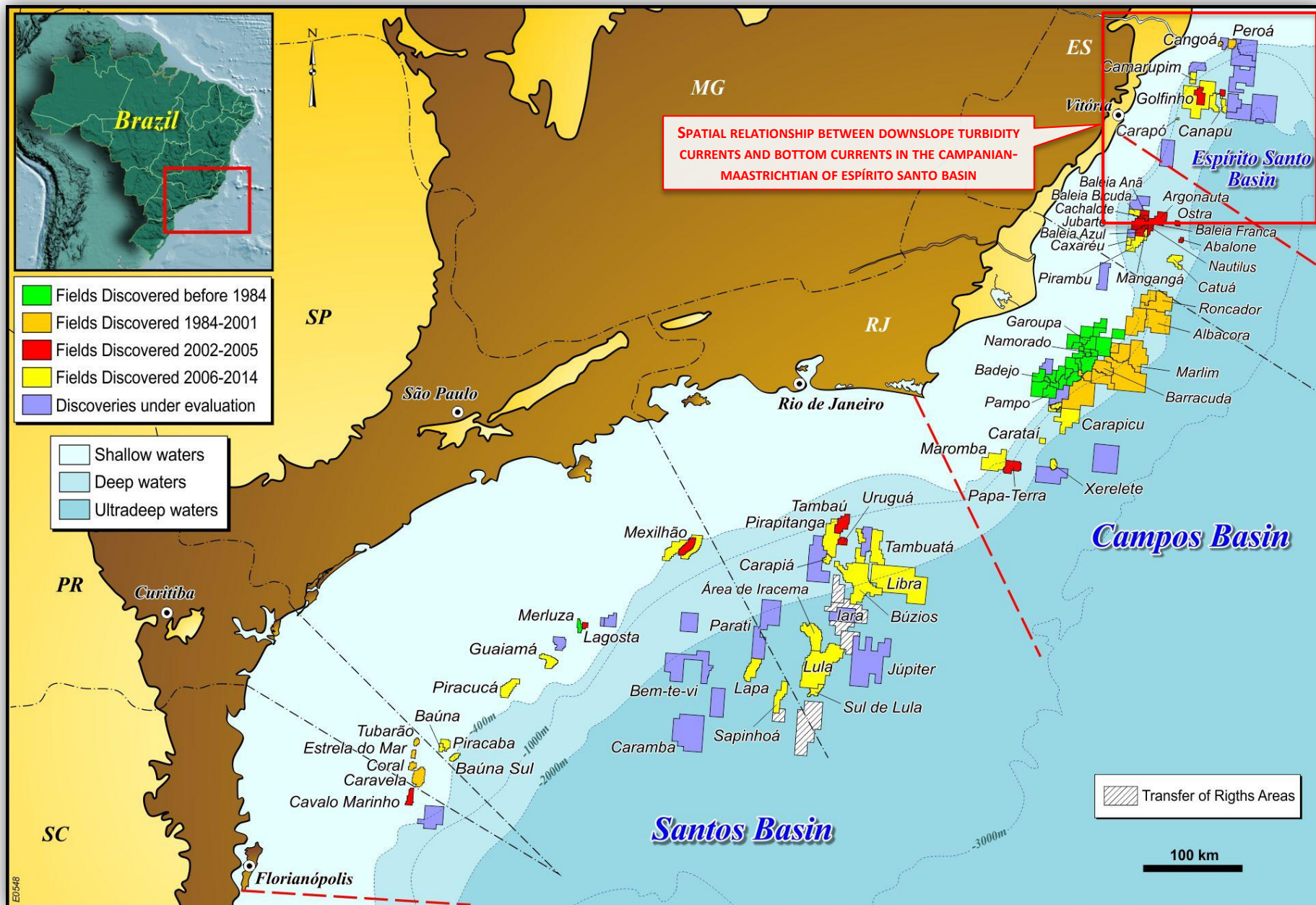
**COARSE-GRAINED TURBIDITE BEDS REWORKED BY TIDAL
BOTTOM CURRENTS (HYBRID FACIES ASSOCIATION)**



CYCLICALLY STACKED THIN-BEDDED CONTOURITES



CURRENT-LAMINATED SANDY CONTOURITES

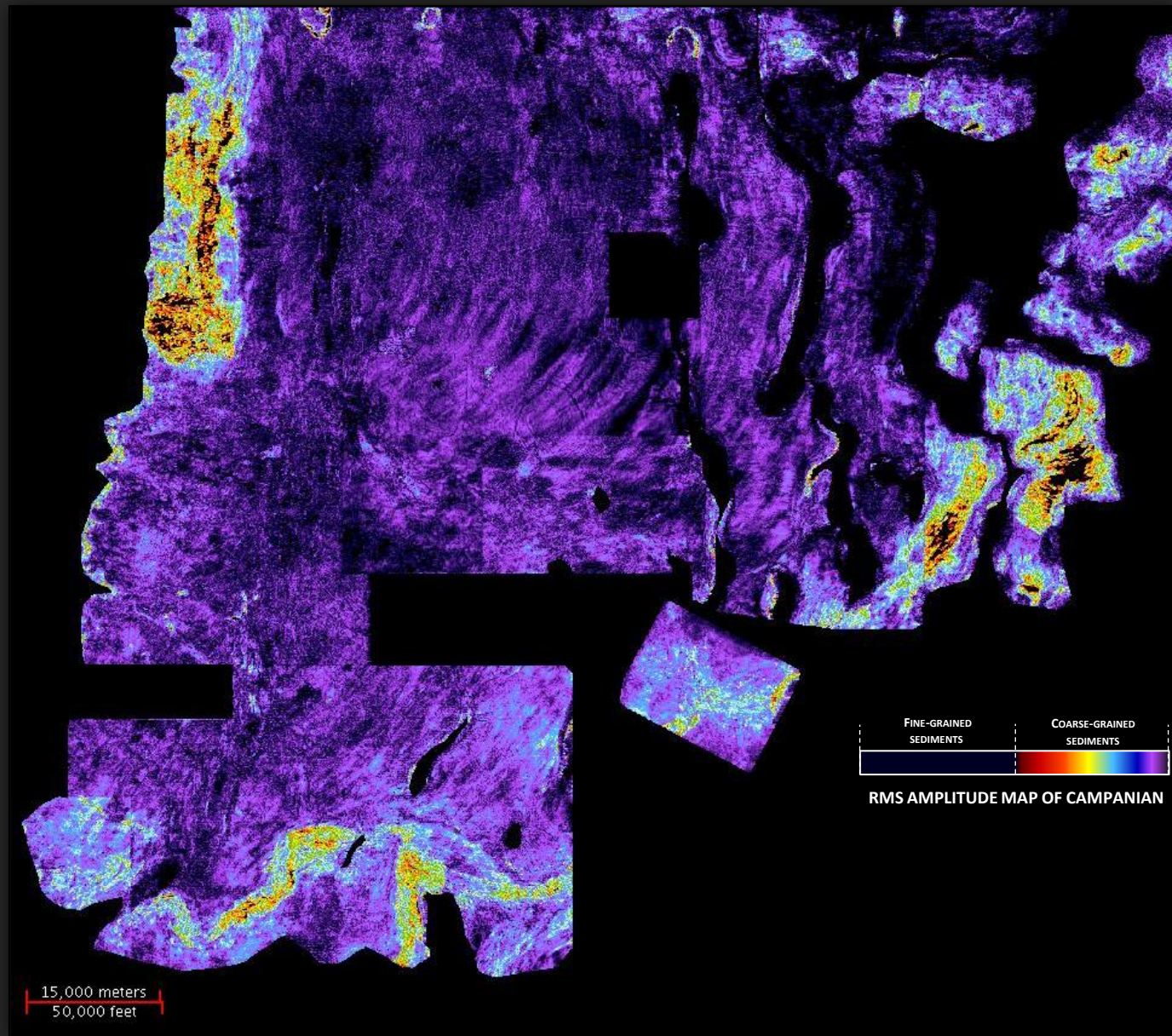


SANDY CONTOURITES TYPES OF GEOMETRY

- ELONGATED SANDSTONE BODIES
- SAND FURROWS
- SAND RIBBONS
- CONTOURITE DRIFTS

TURBIDITES DEPOSITIONAL ELEMENTS

- SINUOUS DEEP-WATER CHANNELS
- DEPOSITIONAL LOBES



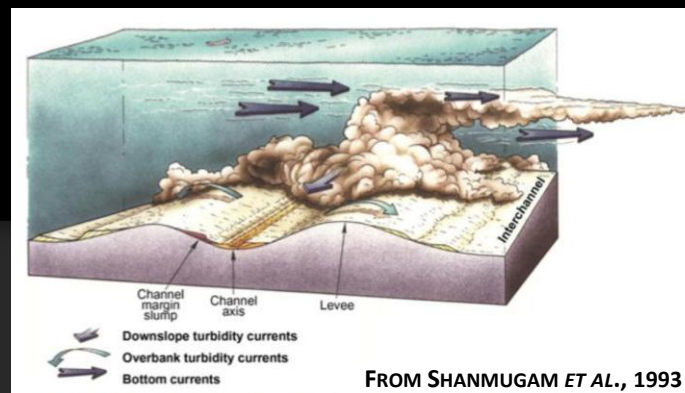
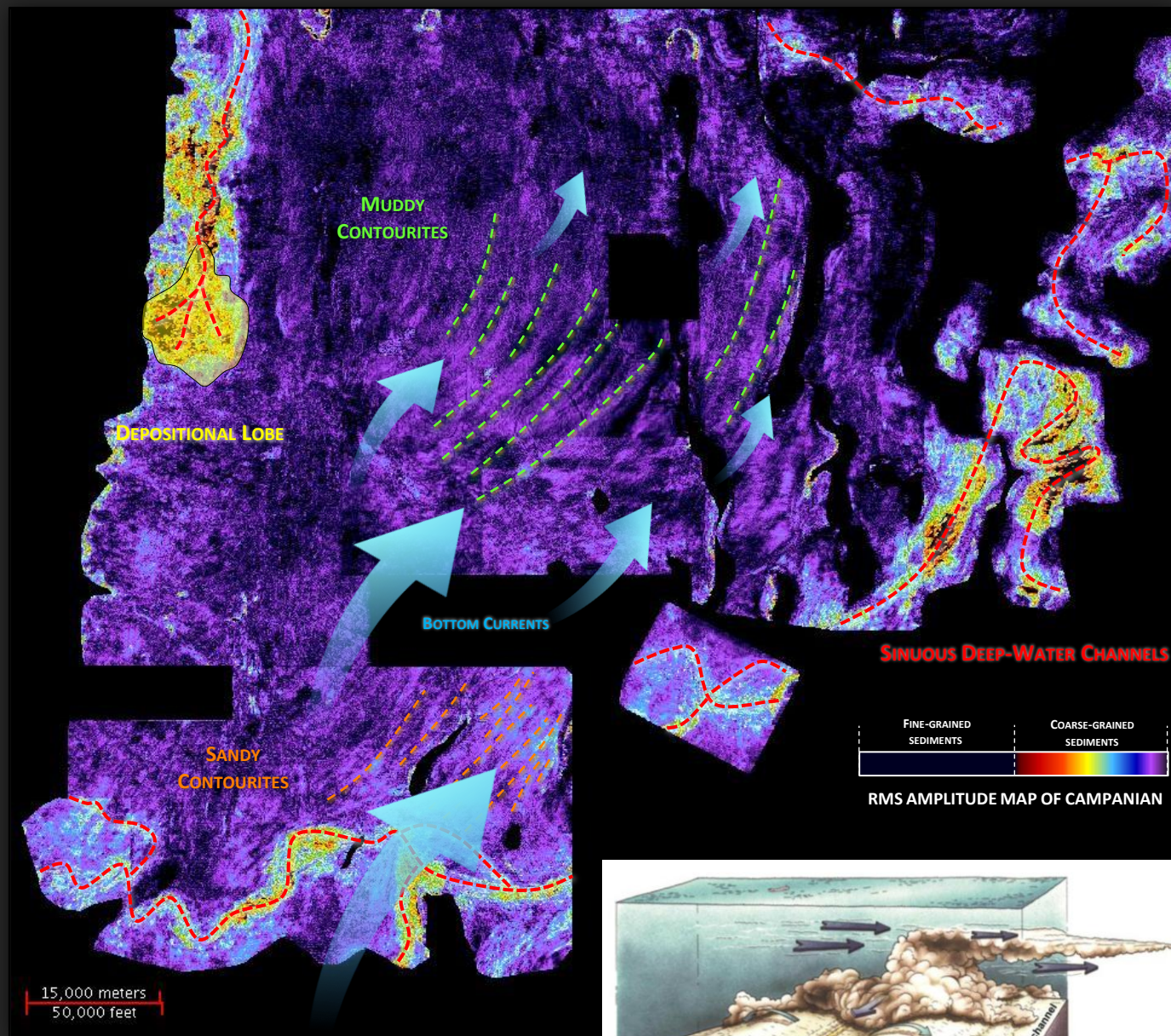
SANDY CONTOURITES

TYPES OF GEOMETRY

- ELONGATED SANDSTONE BODIES
- SAND FURROWS
- SAND RIBBONS
- CONTOURITE DRIFTS

TURBIDITES DEPOSITIONAL ELEMENTS

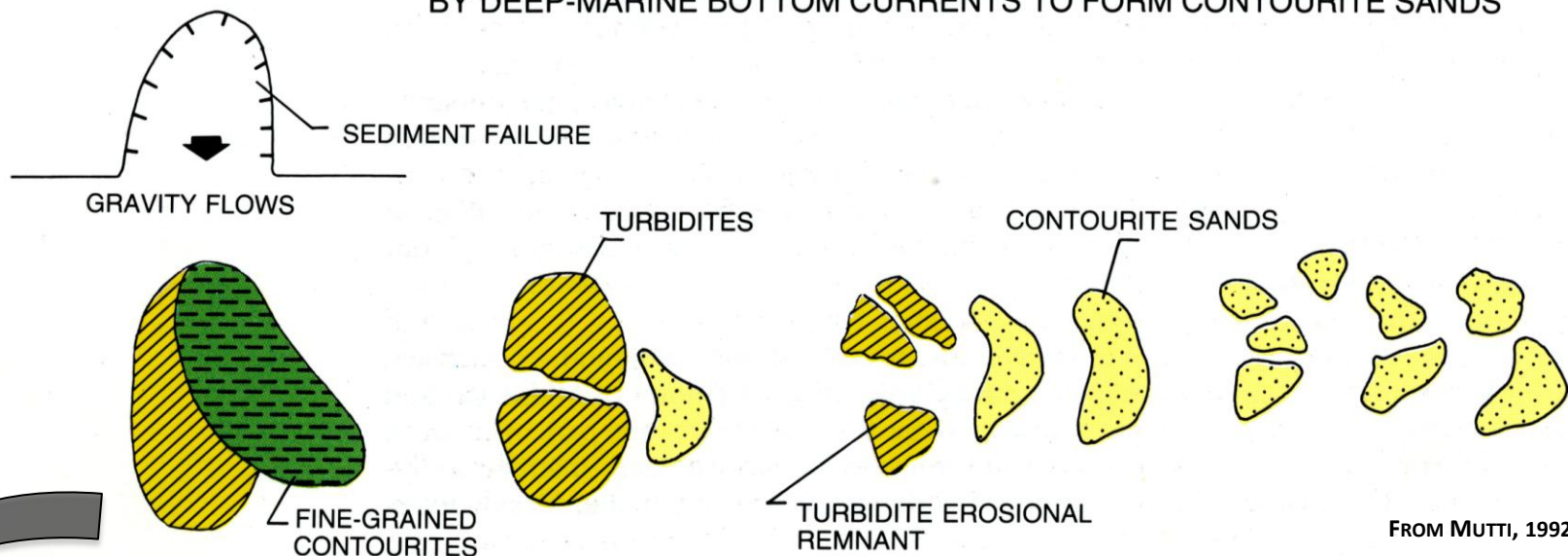
- SINUOUS DEEP-WATER CHANNELS
- DEPOSITIONAL LOBES



FROM SHANMUGAM ET AL., 1993

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.

TURBIDITE SANDS WINNOWED, ERODED AND REDISTRIBUTED BY DEEP-MARINE BOTTOM CURRENTS TO FORM CONTOURITE SANDS



THE MISSING TURBIDITE FACIES
(SENSU MUTTI & CARMINATTI, 2012)

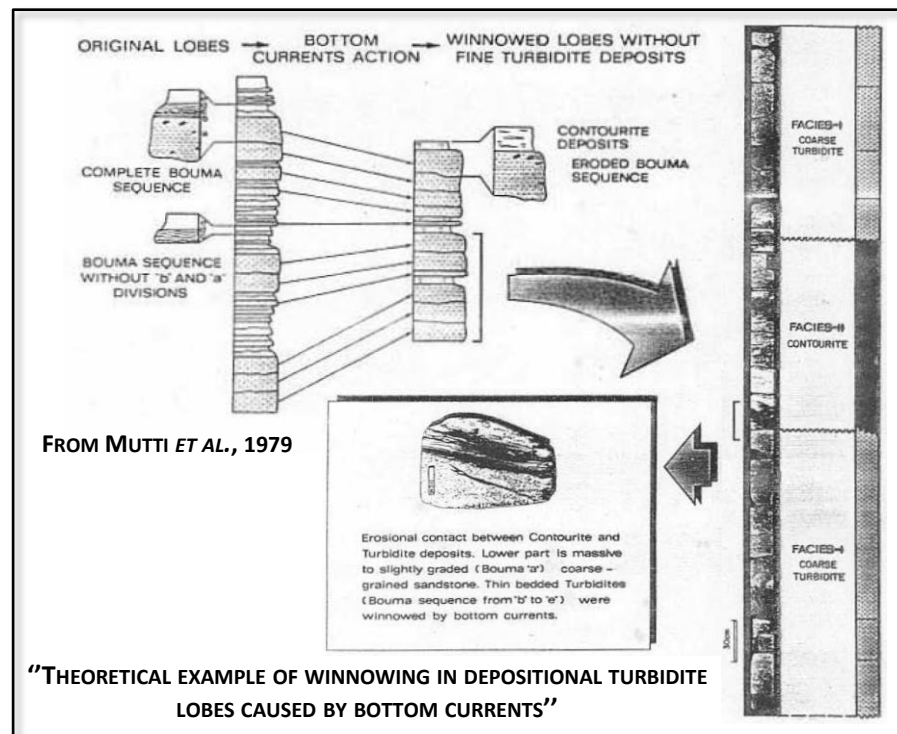
***HYBRID FACIES ASSOCIATION:** THE VERTICAL AND LATERAL ASSOCIATION OF FACIES PRODUCED BY GENETICALLY DISTINCT PROCESSES (TURBIDITY CURRENTS AND BOTTOM CURRENTS)

THE MISSING TURBIDITE FACIES !!!!!

TURBIDITY CURRENTS VS BOTTOM CURRENTS



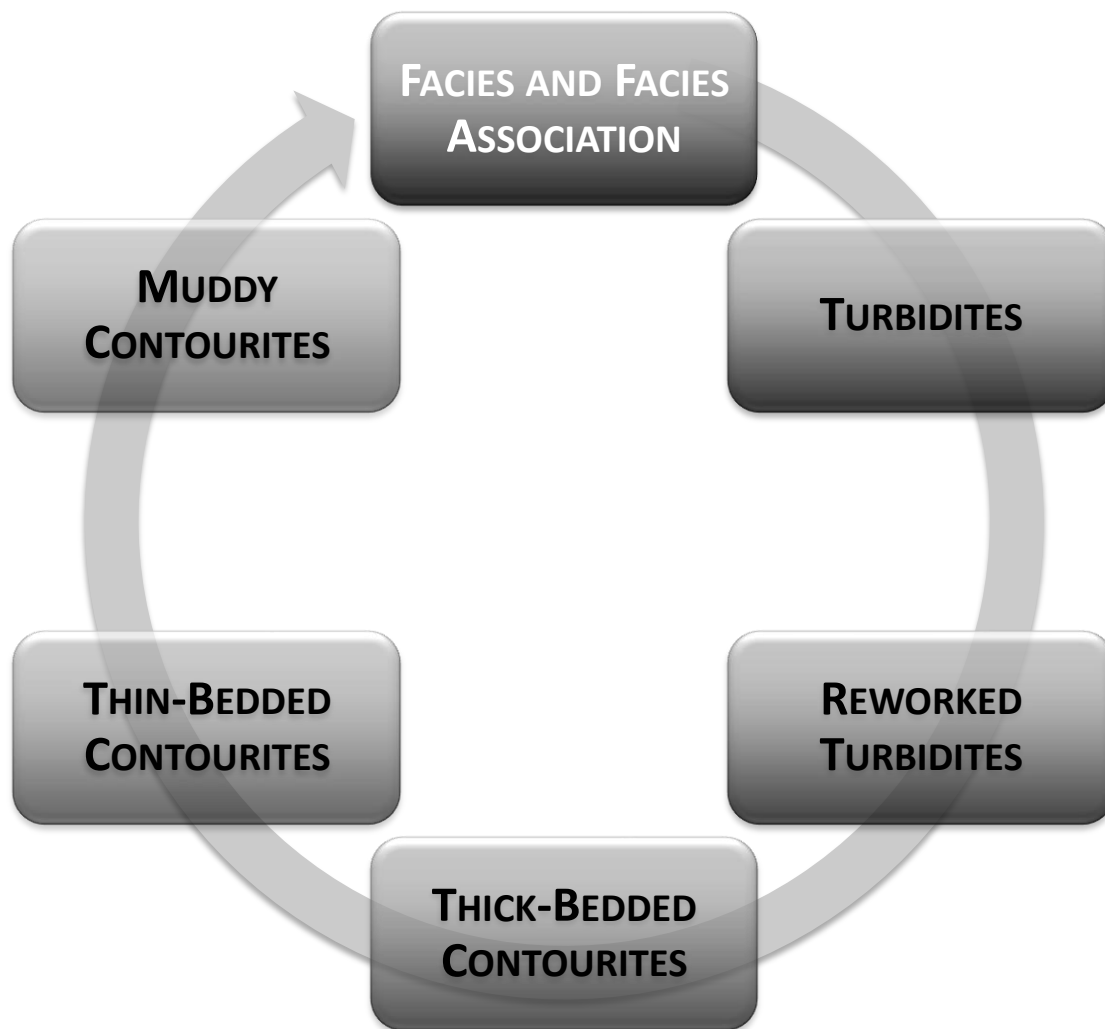
EXAMPLES OF CURRENT-LAMINATED FINE-GRAINED TURBIDITE
FACIES WITH ASSOCIATED THICK MUDSTONE DIVISIONS



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.

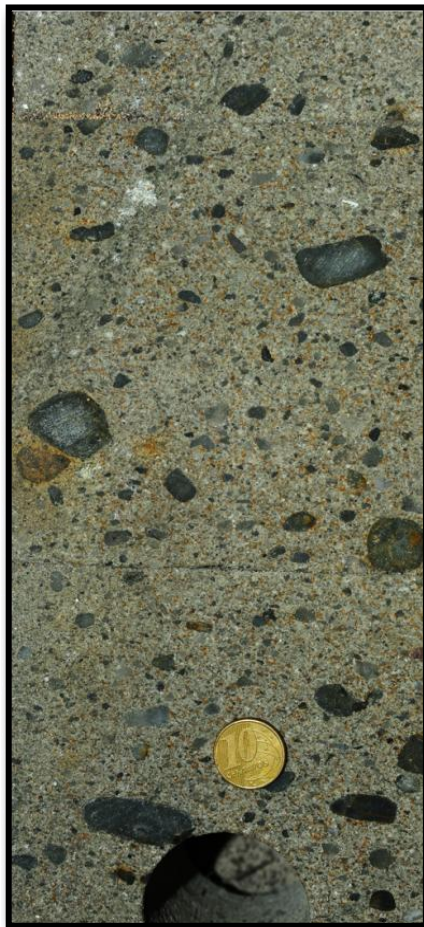
MORE GENERALLY, THIS FINE-GRAINED SEDIMENT WAS ENTIRELY INCORPORATED BY BOTTOM CURRENTS DURING TRANSPORT AND SEDIMENTATION.

“CAREFUL ANALYSIS OF FACIES AND FACIES ASSOCIATIONS WITHOUT PRECONCEIVED IDEAS (MODELS AND ANALOGS) STILL REMAINS A BASIC AND INEXPENSIVE TOOL FOR A BETTER UNDERSTANDING OF DEEP-WATER SEDIMENTATION, THUS LOWERING RISKS IN EXPLORATION AND PRODUCTION.” – MUTTI & CARMINATTI (2012)



FACIES AND FACIES ASSOCIATION

TURBIDITES AND REWORKED TURBIDITES



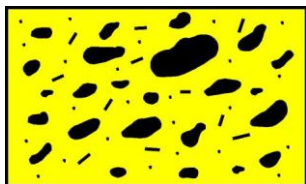
EXAMPLES OF TURBIDITE COARSE-GRAINED SANDSTONES, PEBBLY SANDSTONES AND MATRIX (SANDY)- SUPPORTED PEBBLY AND COBBLY CONGLOMERATES DEVOID OF INTERNAL STRUCTURES. GRADING MAY OR MAY NOT BE PRESENT. IN SOME BEDS, ABUNDANT SHELL FRAGMENTS CAN BE OBSERVED

COARSE-GRAINED TURBIDITE BEDS REWORKED BY TIDAL BOTTOM CURRENTS (HYBRID FACIES ASSOCIATION). THINNER AND LENTICULAR COARSE-GRAINED UNITS WERE LOCALLY RETRANSPORTED BY BOTTOM CURRENTS. NOTE MUDSTONE PARTINGS, MUD COUPLETS, AND SMALL ANGULAR MUDSTONE CLASTS. BIOTURBATION IS PRESENT IN BOTTOM-CURRENT DEPOSITS. REWORKING OF COARSE SAND SUGGESTS CONSIDERABLE BOTTOM-CURRENT VELOCITIES.

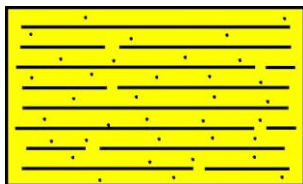


PRELIMINARY CONTOURITE FACIES TRACT INFERRED FROM CORE OBSERVATIONS

SLIGHTLY MODIFIED FROM MUTTI & CARMINATTI, 2012

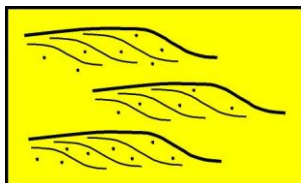


(CFA) MUDDY FINE SAND WITH ABUNDANT MUDSTONE CLASTS



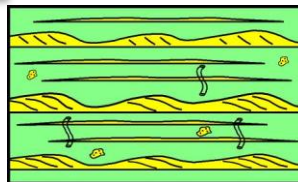
(CFB) M-THICK WELL SORTED HORIZONTALLY LAMINATED FINE AND VERY FINE SAND

Flow direction

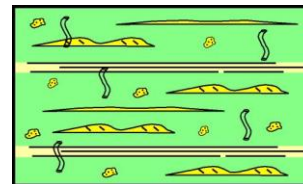


(CFC) M-THICK WELL SORTED FINE AND VERY FINE SAND WITH RIPPLES DISPLAYING INTERNAL SIGMOIDAL LAMINAE

(CFD) ALTERNATING CM-THICK PACKAGES OF RIPPLE-LAMINATED FINE-GRAINED SAND AND BIOTURBATED MUDDIER UNITS WITH SAND STREAKS

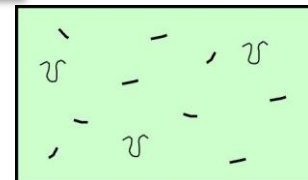


(CFE) CM-THICK PACKAGES OF LENTICULAR RIPPLED SAND AND SAND STREAKS ALTERNATING WITH MUDSTONES. BIOTURBATION IS VERY COMMON. THESE THIN UNITS STRONGLY RESEMBLE CONTOURITE FACIES CYCLES OF THE CLASSIC STOW'S MODEL (STOW ET AL., 2002)



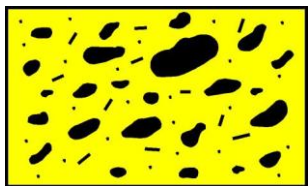
Flow direction

(CFF) HIGHLY BIOTURBATED TERRIGENOUS, MIXED AND BIOGENIC (CALCAREOUS) MUDSTONES

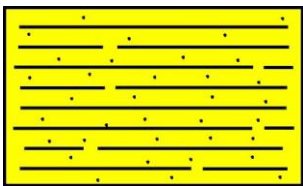


PRELIMINARY CONTOURITE FACIES TRACT INFERRED FROM CORE OBSERVATIONS

SLIGHTLY MODIFIED FROM MUTTI & CARMINATTI, 2012



(CFA) MUDDY FINE SAND WITH ABUNDANT MUDSTONE CLASTS



(CFB) M-THICK WELL-SORTED HORIZONTAL

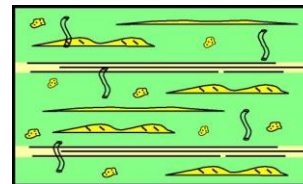
Flow direction

(CFD) ALTERNATING CM-SCALE
FINE-GRAINED SAND STREAKS...RY FINE SAND WITH
TIDAL LAMINAE

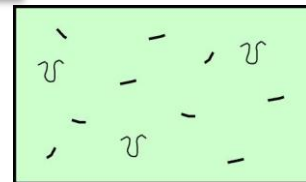
Flow direction



...ULAR RIPPLED SAND AND SAND STREAKS ALTERNATING

W... RES...
...ATION IS VERY COMMON. THESE THIN UNITS STRONGLY
...E FACIES CYCLES OF THE CLASSIC STOW'S MODEL (STOW ET AL., 2002)

(CFF) HIGHLY BIOTURBATED TERRIGENOUS, MIXED AND BIOGENIC (CALCAREOUS) MUDSTONES



WE DEFINE CONTOURITES ALL THOSE SANDY AND MUDDY SEDIMENTS SHOWING EVIDENCE OF DEPOSITION
FROM CURRENTS DIFFERENT FROM TURBIDITY CURRENTS AND MORE GENERALLY SEDIMENT GRAVITY FLOWS,
EFFECTIVE ON THE SEAFLOOR WITHIN A WIDE RANGE OF VELOCITIES.

FACIES AND FACIES ASSOCIATION

THICK-BEDDED, THIN-BEDDED AND MUDDY CONTOURITES



CFA



CFB



CFC

THICK-BEDDED SANDY CONTOURITES

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

THIN-BEDDED SANDY CONTOURITES

CYCLICALLY STACKED THIN-BEDDED CONTOURITES. RELATIVELY STRONG AND WEAK CURRENTS ALTERNATE WITH TIME IN BOTH CASES.

CFD



CFE



CFF



MUDDY CONTOURITES

SEDIMENT DRIFTS PRODUCED BY WEAK BOTTOM CURRENTS AND MAINLY CONSISTING OF BIOGENIC AND TERRIGENOUS MUD

- **IN MOST CASES, THE FACIES F8 AND F9 (SENSU MUTTI, 1992) IS ENTIRELY INCORPORATED BY BOTTOM CURRENTS DURING TRANSPORT AND SEDIMENTATION;**
- **THE CONSISTENT LACK OF THIS FACIES IMPROVES COMMUNICATION BETWEEN SAND LAMINAE AND VERTICAL PERMEABILITY;**
- **SANDY CONTOURITES OCCUR AS EXTENSIVE DEPOSITS WITH GREAT LATERAL CONNECTIVITY;**
- **SANDY CONTOURITES CAN REACH SEVERAL HUNDREDS OF METERS IN THICKNESS, AS SEEN IN SANTOS AND CAMPOS BASINS;**
- **HIGH-ENERGY BOTTOM CURRENT SYSTEMS CAN PRODUCE CLEAN, POROUS AND WELL SORTED SANDS WITH EXCELLENT PERMO-POROSITY PROPERTIES;**
- **DATA FROM THE BRAZILIAN OFFSHORE BASINS PRESENTED HERE AND PRELIMINARILY DISCUSSED BY MUTTI AND CARMINATTI (2012) SHOW THAT SANDY CONTOURITES NOT ONLY EXIST, BUT FORM PROLIFIC RESERVOIRS FOR HYDROCARBON ACCUMULATIONS SINCE LATE CRETACEOUS. A BETTER UNDERSTANDING OF THESE SYSTEMS MAY OPEN NEW STRATEGIES FOR HYDROCARBON EXPLORATION AND PRODUCTION IN MANY CONTINENTAL MARGINS.**



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PETROBRAS

ACKNOWLEDGEMENTS

ANGÉLICA ALIDA ZACHARIAS GARCIA

ARNALDO SANTOS BIASSUSI

ARY GUSTAVO CANDIDO

CARLOS LOPO VARELA

FERNANDO COLLO

JONÍLTON PESSOA

MARÍLIA RODRIGUES DE CASTRO

MÁRIO CARMINATTI

RICARDO JORGE JAHNERT

PIERRE MUZZI MAGALHÃES

ROBERTO TINTERRI

SABRINA HELENA DINIZ GILABERTE BEZERRA

SYLVIA MARIA COUTO DOS ANJOS

WALDEMAR DE ALMEIDA JUNIOR



THE AUTHORS WOULD LIKE TO THANK PETROBRAS FOR ALLOWING THE PUBLICATION OF THIS
STUDY AND TO AAPG FOR THIS UNIQUE OPPORTUNITY TO PUBLISH.

THANK YOU!