Offshore Colombia: Highlights of Prospective Margin Segments Using Newly Reprocessed 2D Seismic Data

PART 1: The South Caribbean Deformed Belt

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ANH Webinar Series

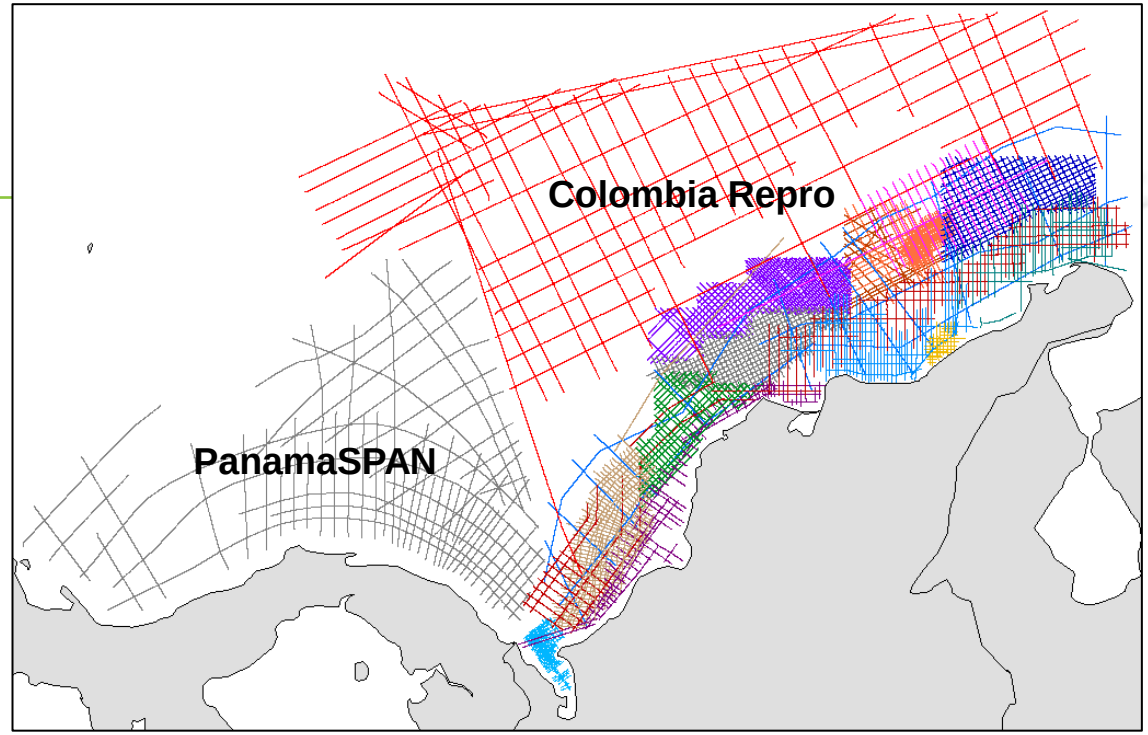
May 6th, 2022

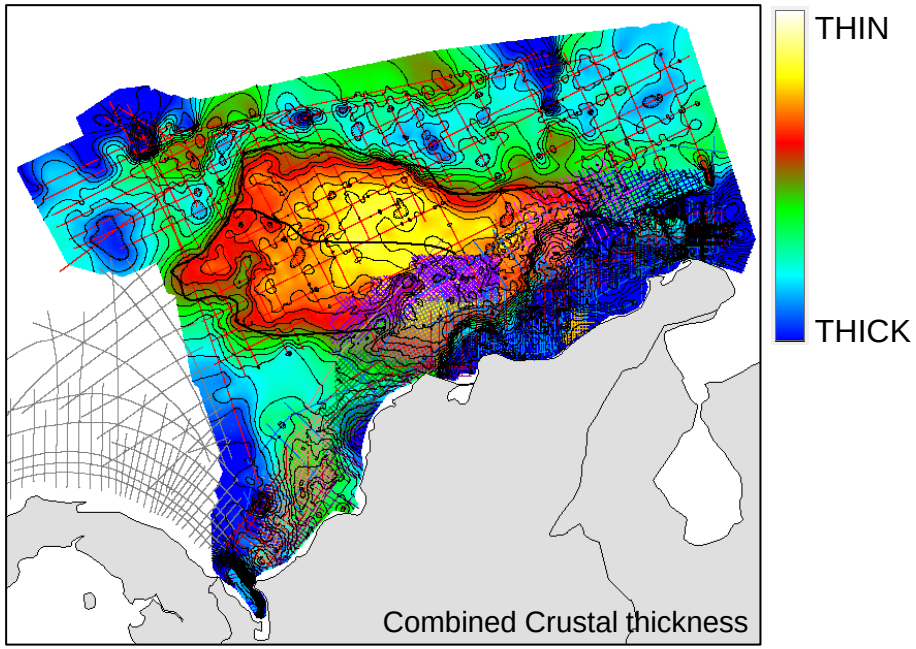
Agenda: Part 1

- Introduction
- Dataset
  - Legacy data example
  - Regional velocity and gravity sections
  - Offshore regional composite examples
- Data, Velocity, AVO Examples, and Implications for Hydrocarbon Exploration
  - Sinu Offshore
  - Magdalena Delta
  - Guajira Offshore
- Part 2: Deepwater and Ultradeepwater

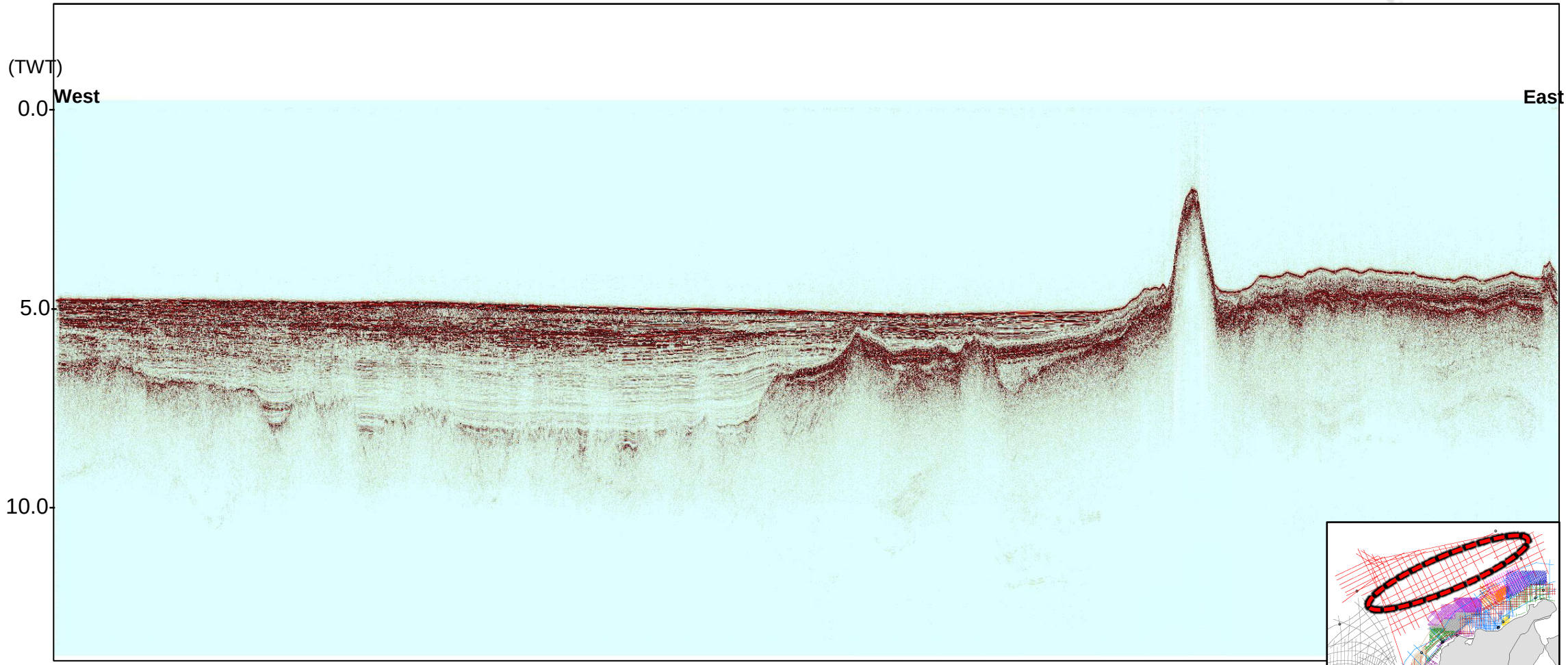
Dataset and Objectives

- Colombia Reprocessing
  - ~60,000 km
  - 18 surveys
  - Vintages range from 1982-2014
  - 13 Wells used in project for velocity model building and interpretation
- Extensive coverage allows regional analysis and comparison of structural styles with existing data in adjacent areas
- Observations of deformation styles from different areas within SCDB (Sinu Offshore, Magdalena Delta, Guajira Offshore)
- Observation of effects, if any, of presence of thin oceanic crust on deformed belt



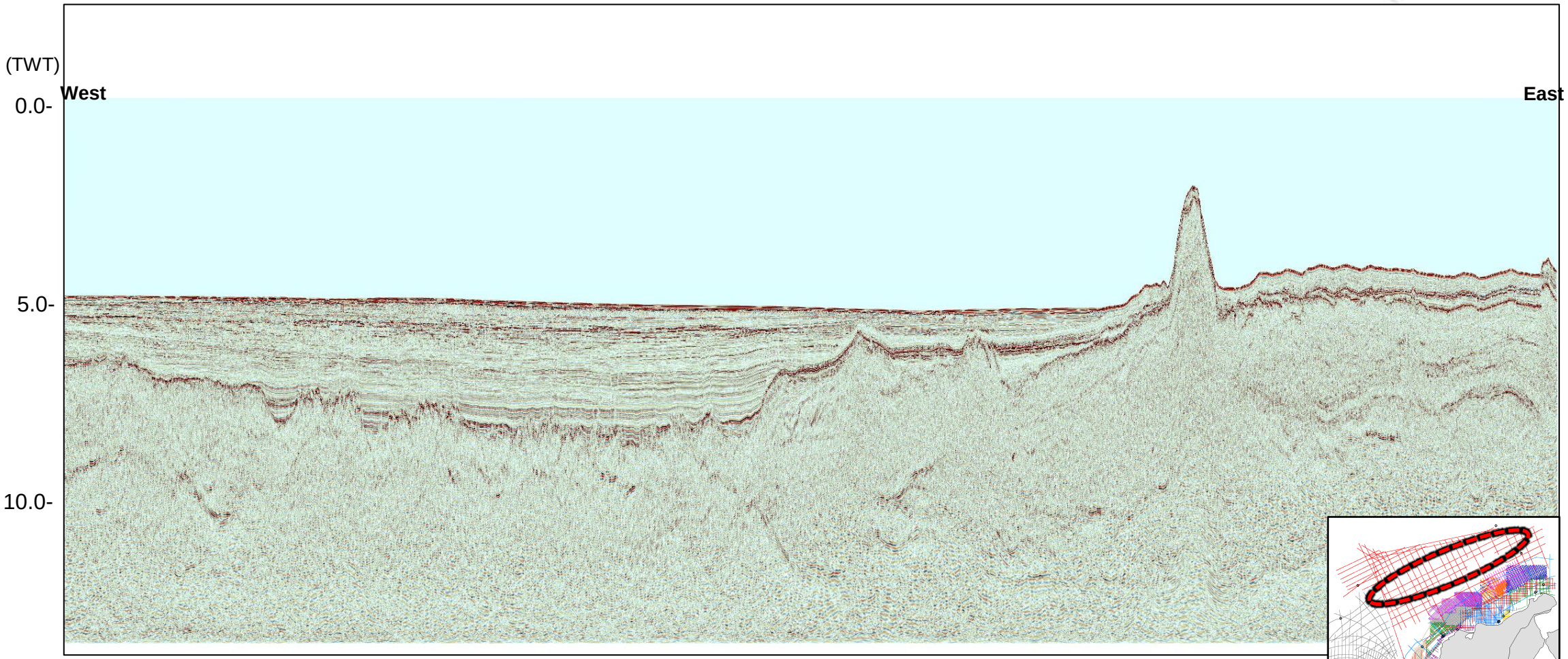


Dataset: Legacy Deepwater Line



- Legacy datasets, especially older vintages benefited from latest reprocessing techniques

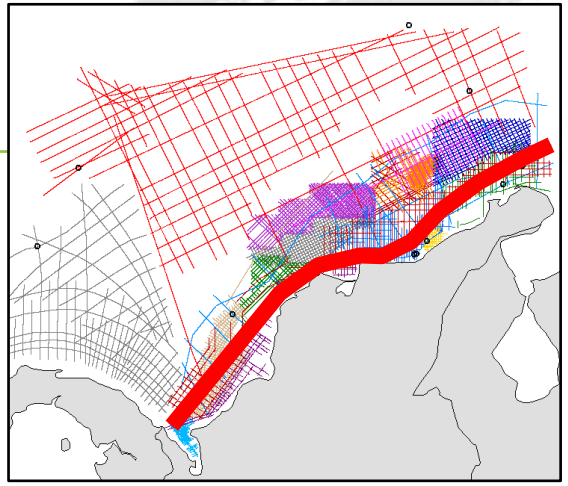
Dataset: Reprocessed Deepwater Line



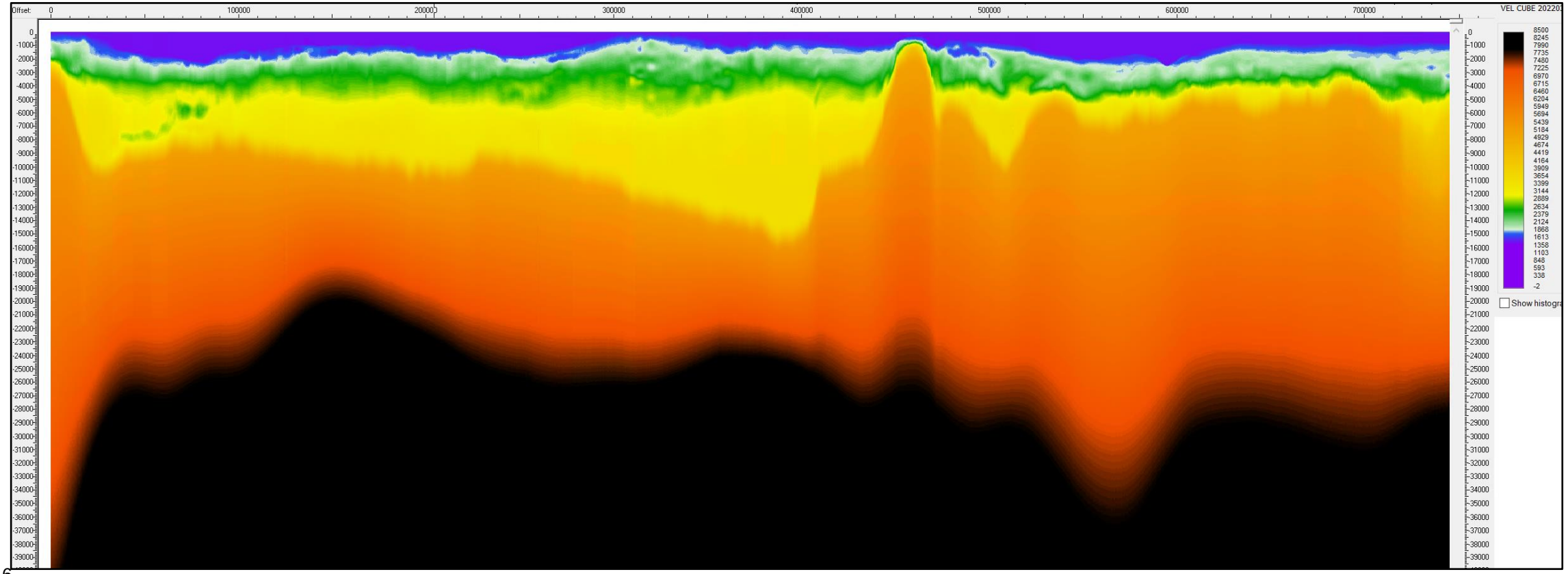
- Improvements in imaging, especially in the basement and sub-basement sections, allowed us to review and improve past interpretation and tectonic models

Dataset: Regional Models

- All 60,000-line km of data processed as a single project to produce unique basin-wide 3D Velocity and Gravity Models
- Well information constrains 3D imaging and tomography in areas of complex geology

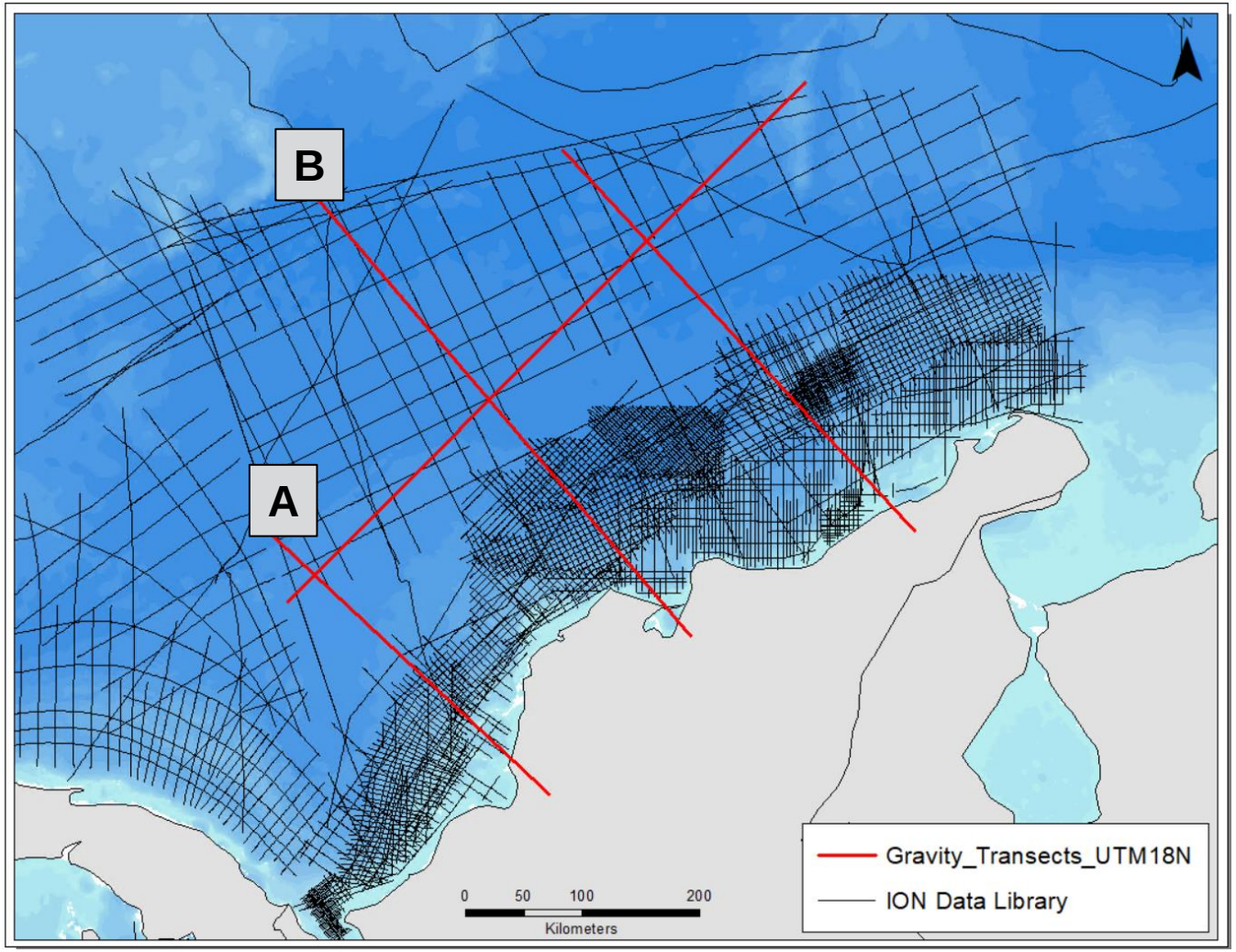


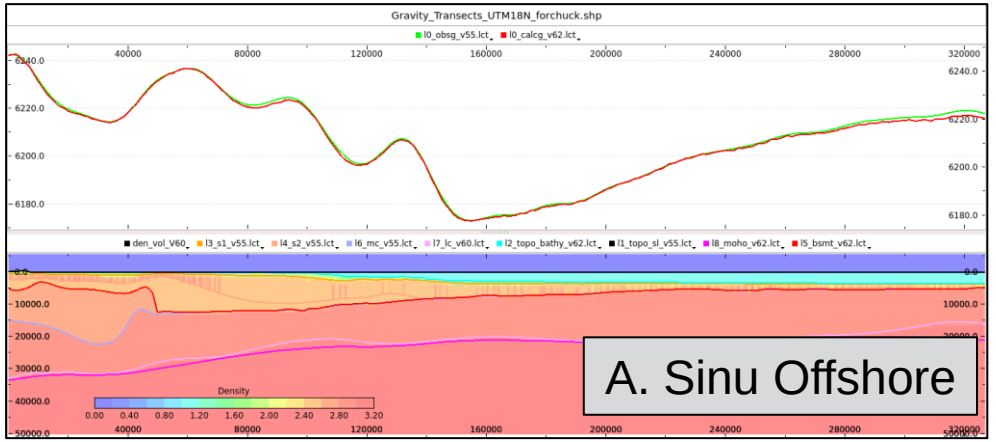
Uraba Sinu Offshore Magdalena Delta Santa Marta Massif Offshore Guajira

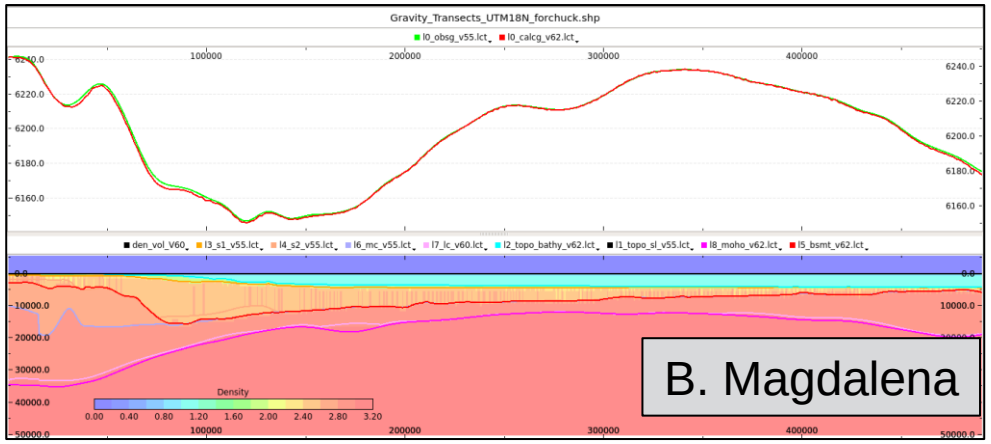


Dataset: Regional Gravity Models

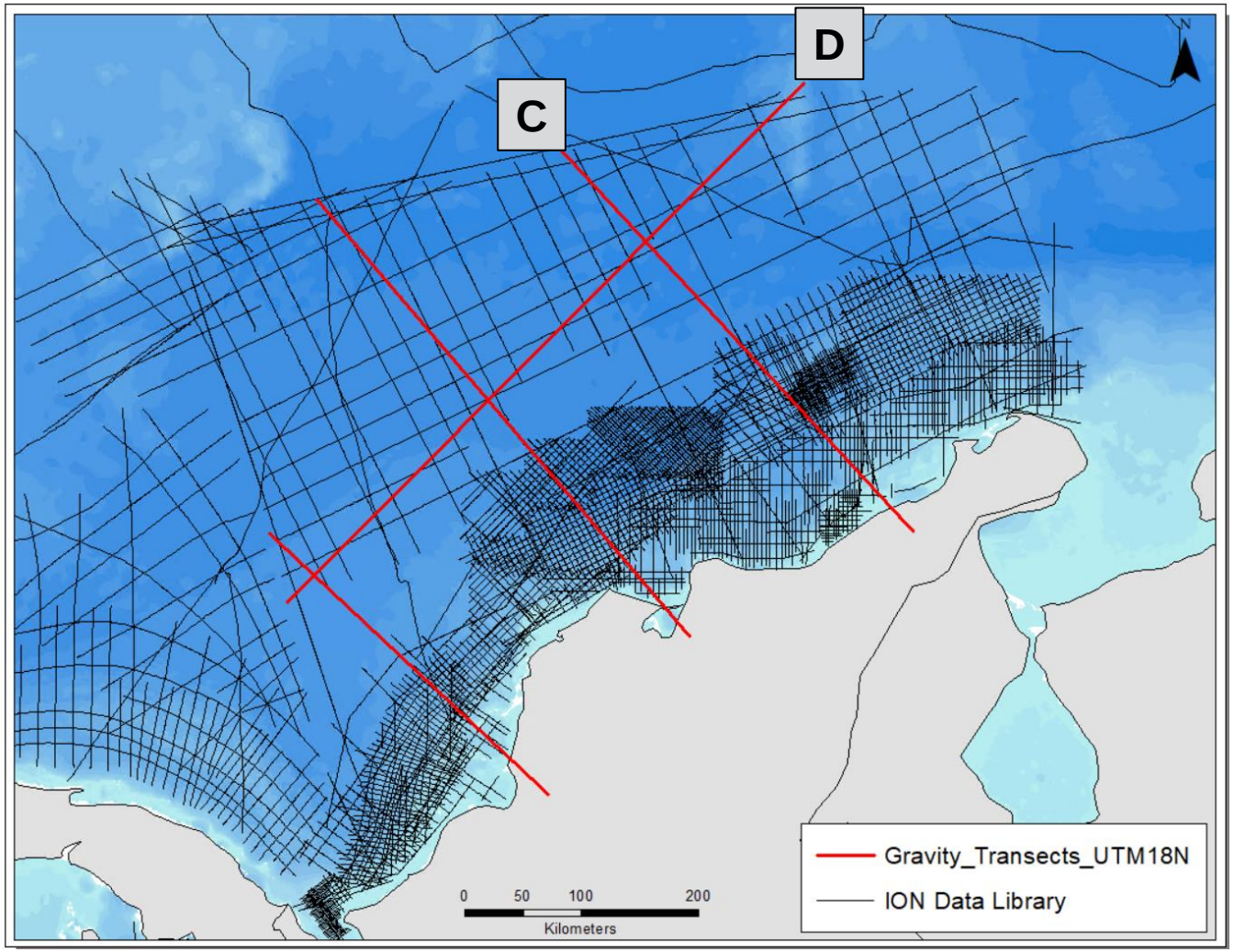
- Shipborne, Satellite data and global databases supplement the gravity model

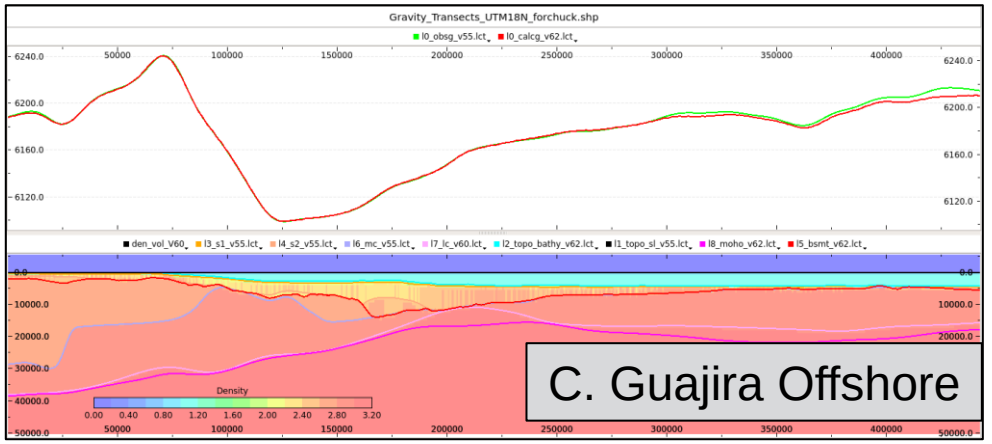


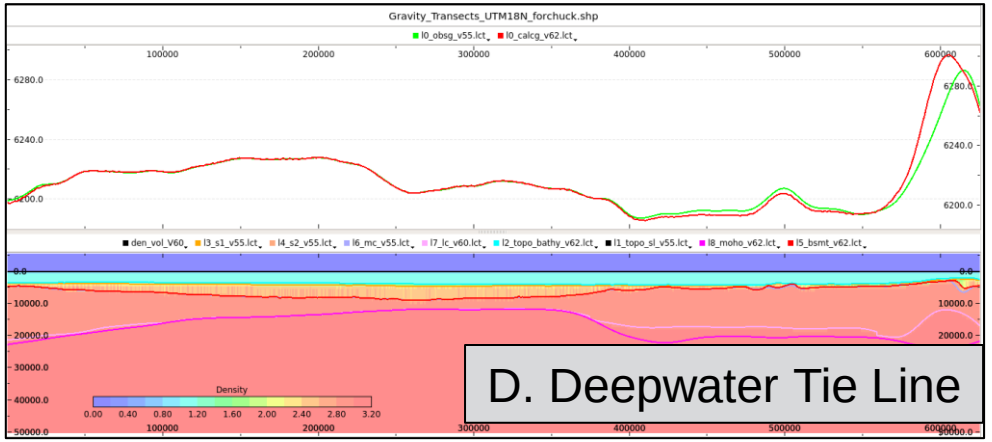




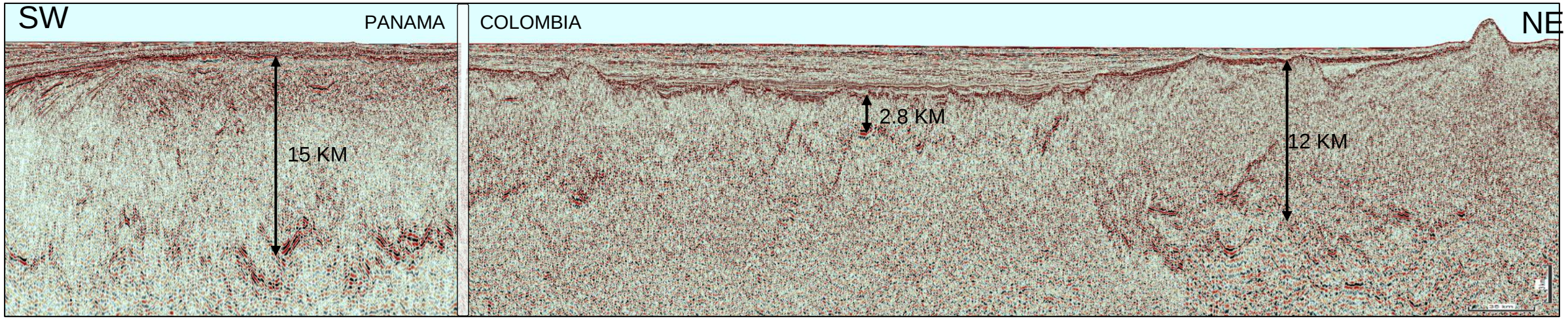
Dataset: Regional Gravity Models



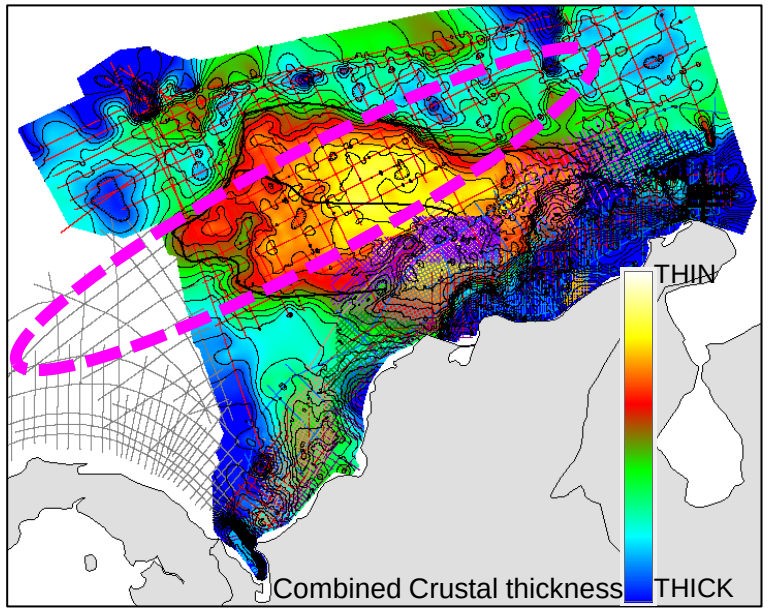




The Caribbean Plateau

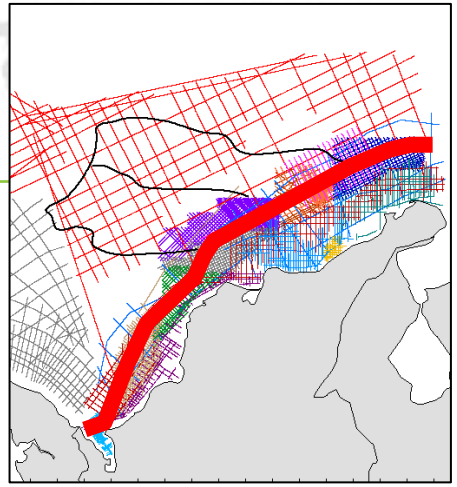


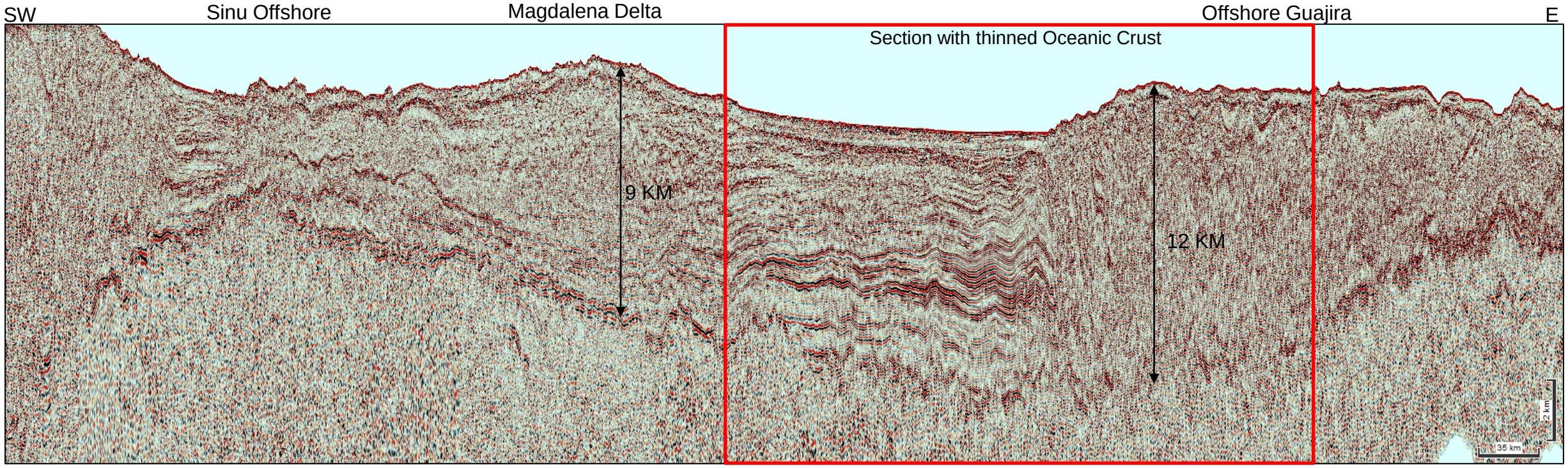
- Zone of relatively thin oceanic crust mapped in the ultra-deepwater Colombian basin in contrast to >15km thick adjacent plateau crust
- Onset of low-angle, oblique subduction of CLIP during lower-mid Eocene (Mora et al., 2017)
- Simultaneous cessation of arc magmatism, change in plate angle and velocity



Composite Strike Line along SCDB

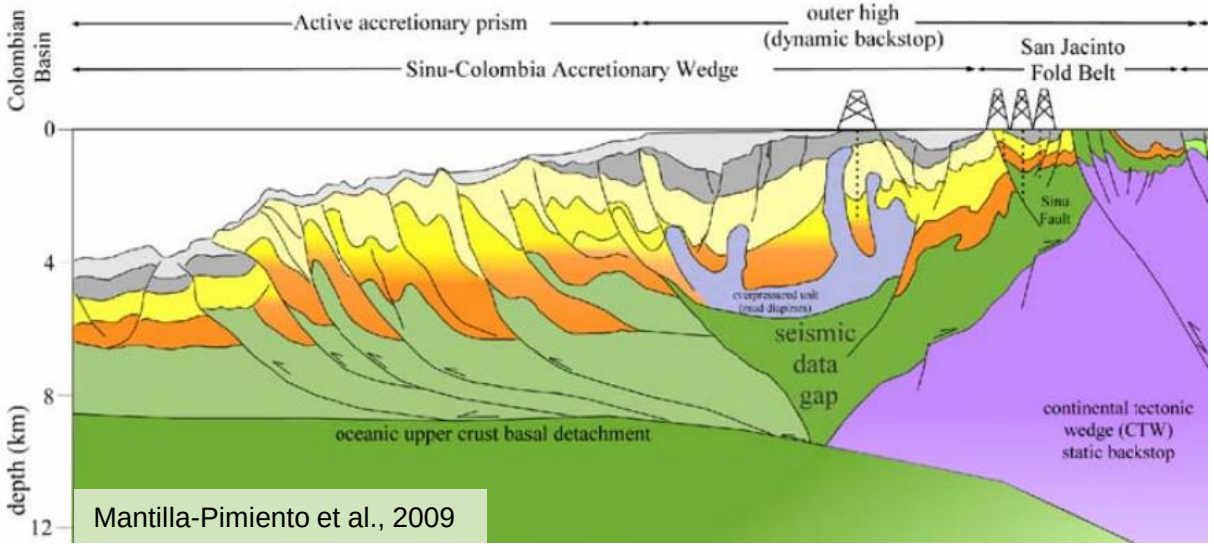
- Section of thinned crust coincides with basement ‘low’ in the offshore Bahia area and Guajira SCDB
- Zone of high sedimentation and thick sediment loading



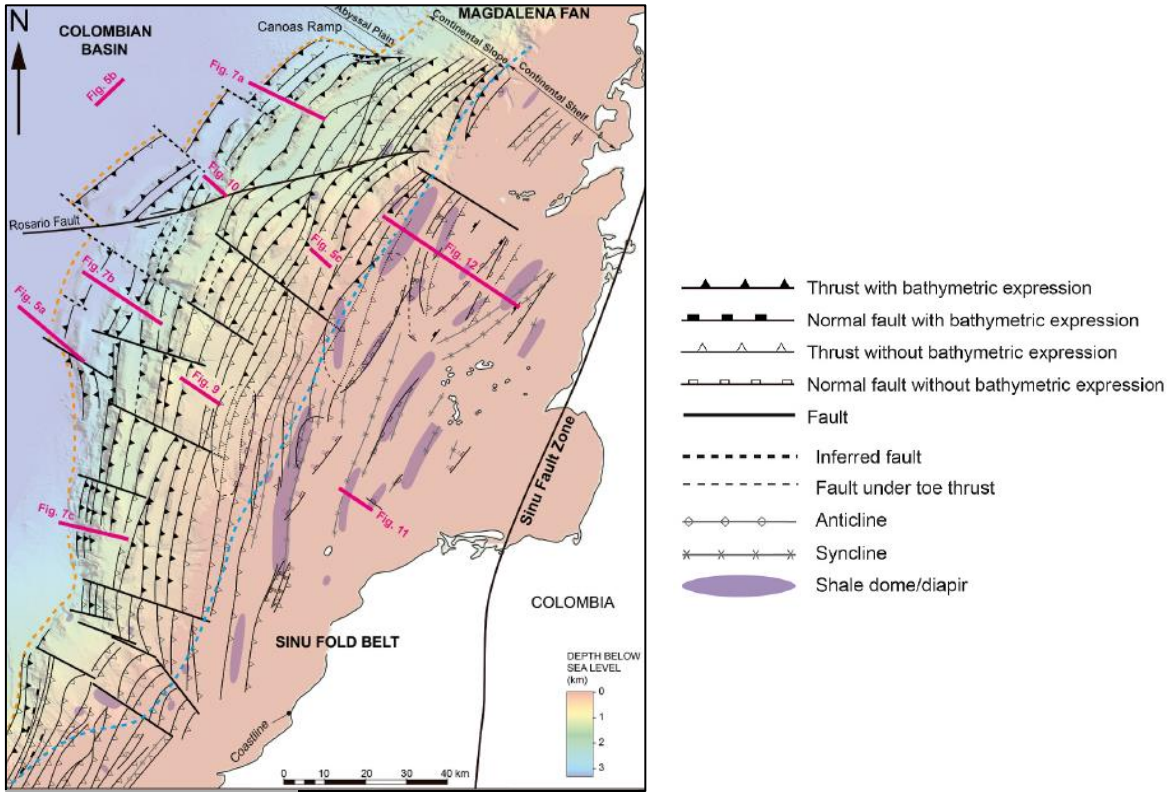


The Sinu Offshore Foldbelt

- Accretionary wedge
  - Sinu Fold Belt (offshore, active accretionary prism)
  - San Jacinto FB (onshore, fossilized prism acting as dynamic backstop along with outer high)
- Static backstop further inland near the Romeral Suture Zone
- Underlain by thick Caribbean plateau crust
- Frontal toe thrusts in the Central section change vergence from seaward to landward
- Distinct change along strike from highly deformed FB to undeformed Magdalena sediments to the east



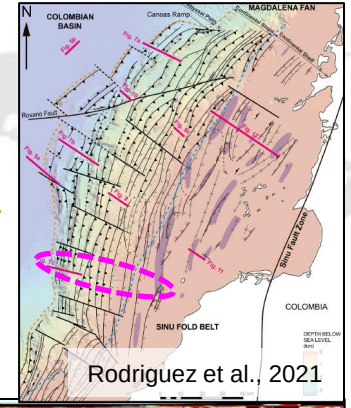
Mantilla-Pimiento et al., 2009



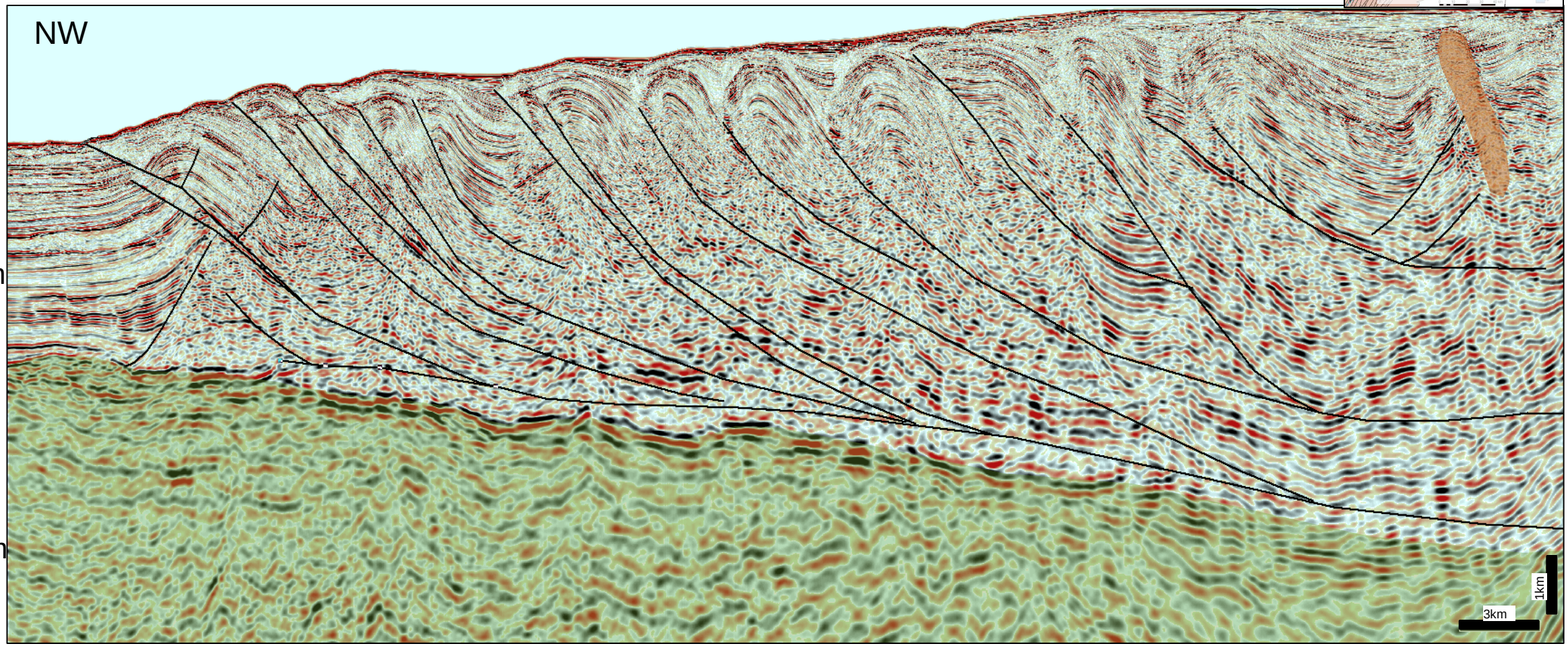
Rodriguez et al., 2021

Dip Section Through Southern Sinu Offshore FB

- Underlain by thick plateau crust
- Primarily seaward verging faults with shallower detachments near zones of shale movement and mud diapirs
- BSR mapped throughout the prism

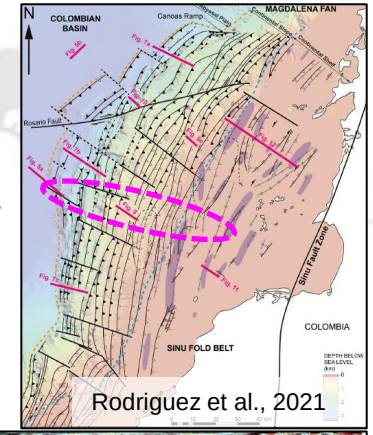


Rodriguez et al., 2021

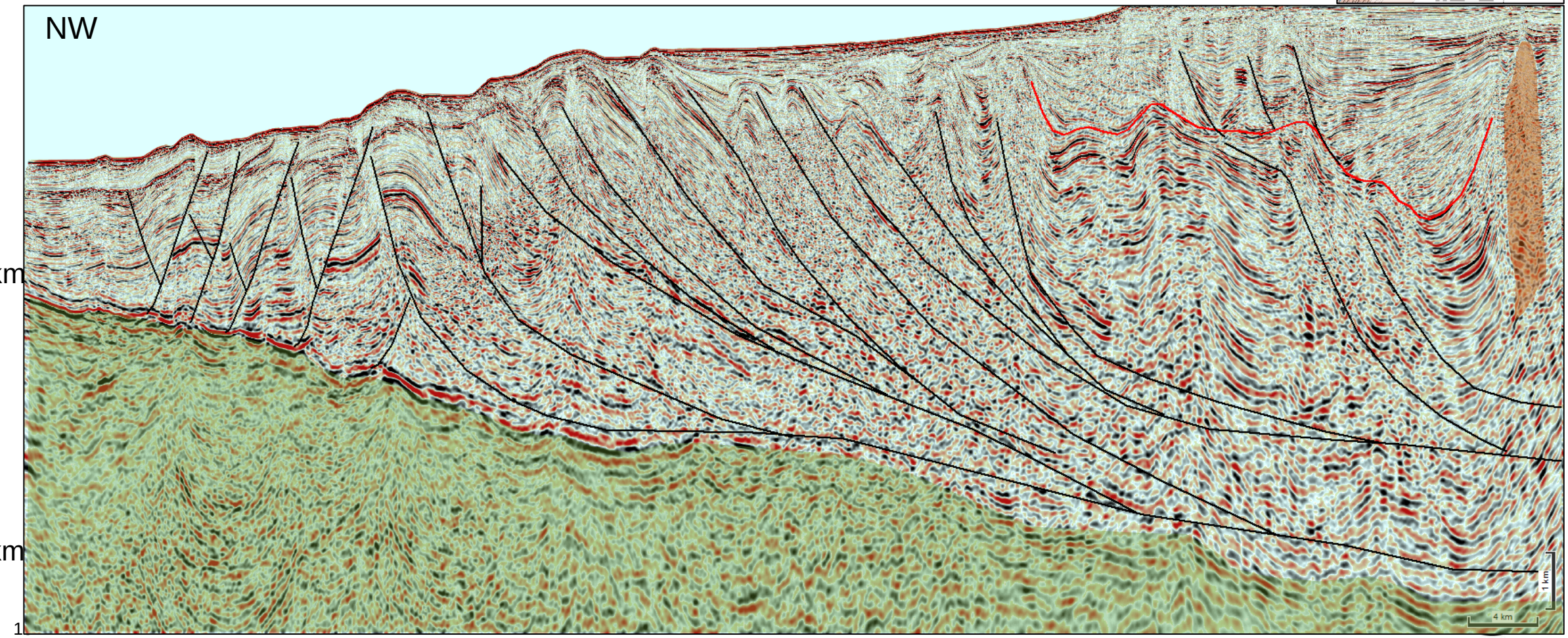


Dip Section Through Southern Sinu Offshore FB

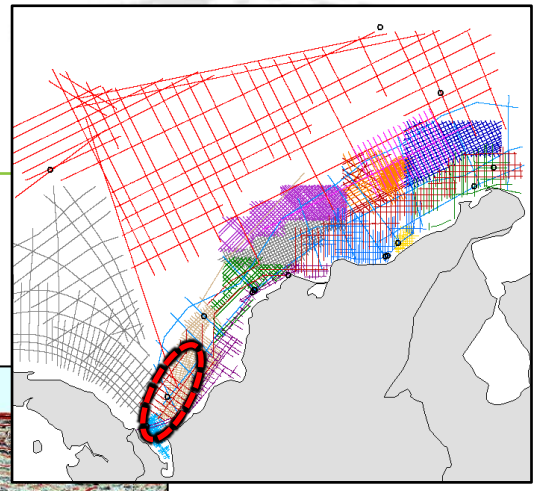
- Underlain by thick plateau crust
- Central section of foldbelt corresponds to relatively thicker sediment section and higher density of mud diapirs on the shelf
- Localized landward verging outer thrusts observed in the toe thrust section, ending at Rosario fault

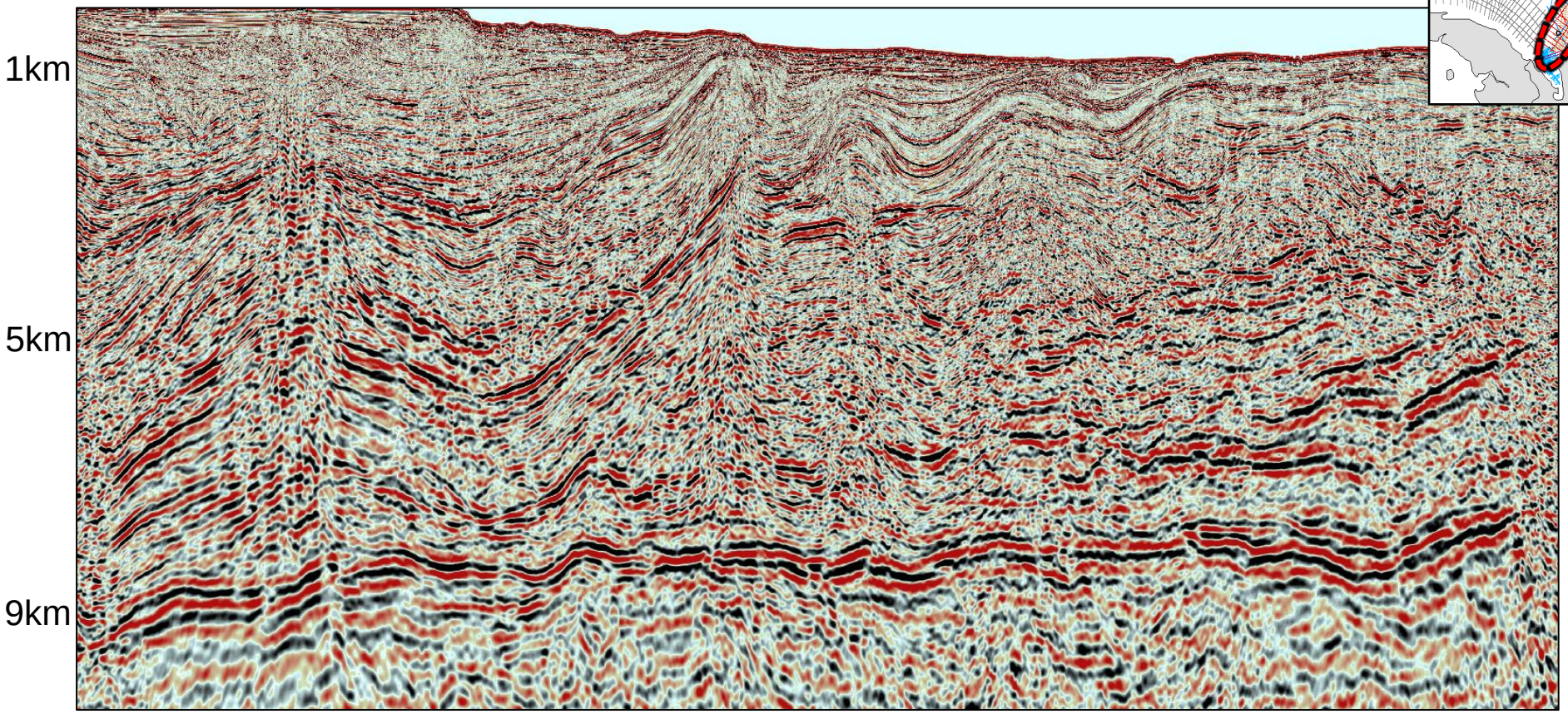


Rodriguez et al., 2021

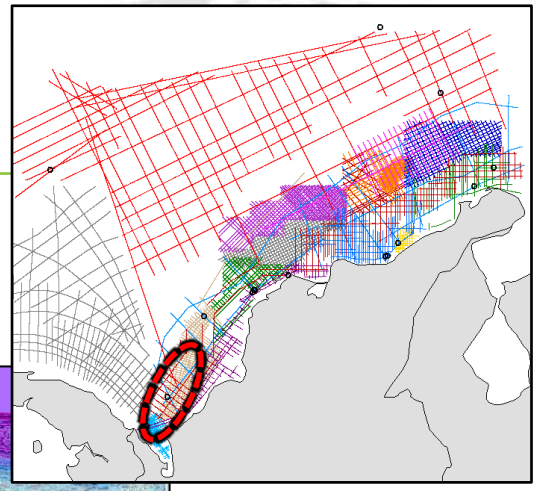


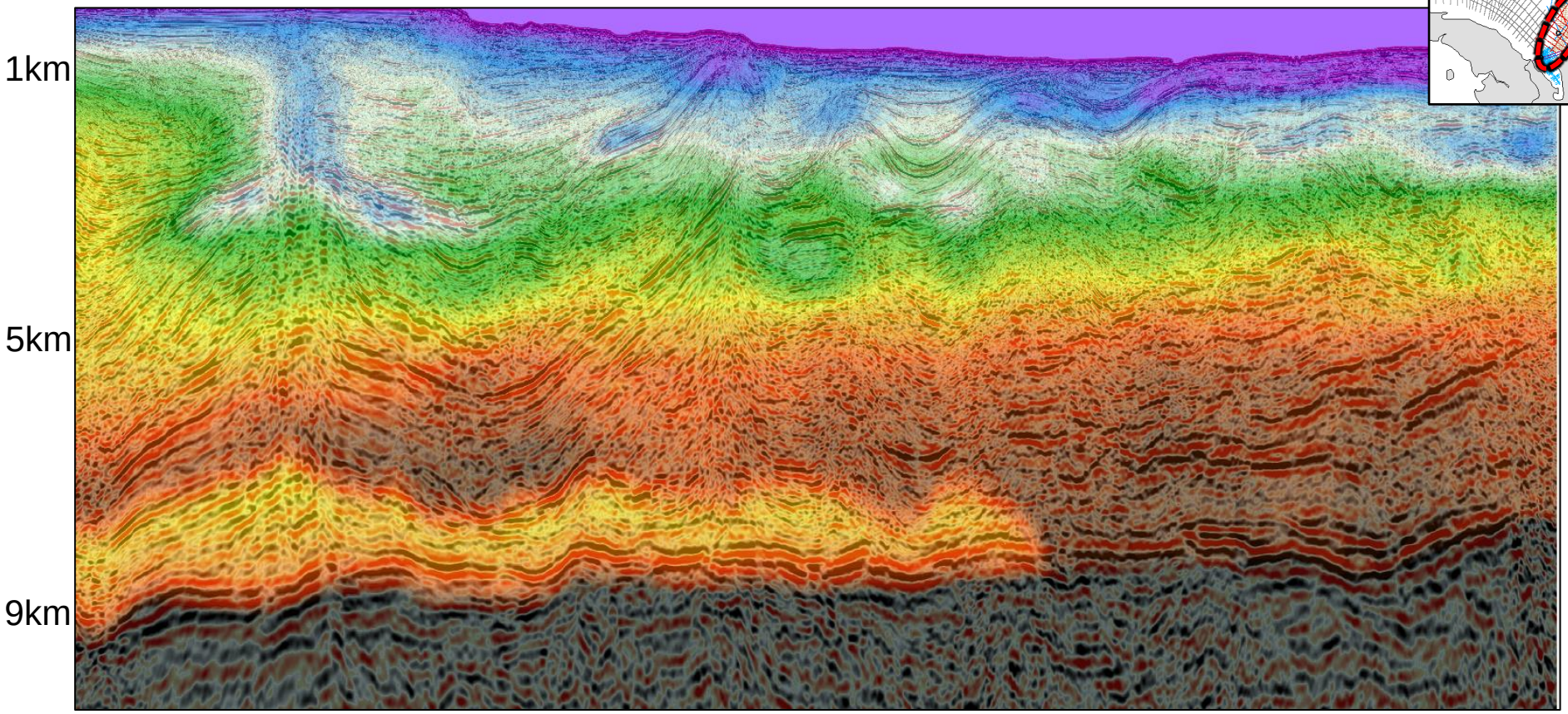
Sinu Offshore Strike Line



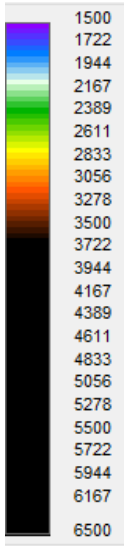


Sinu Offshore Strike Line: Velocity Overlay



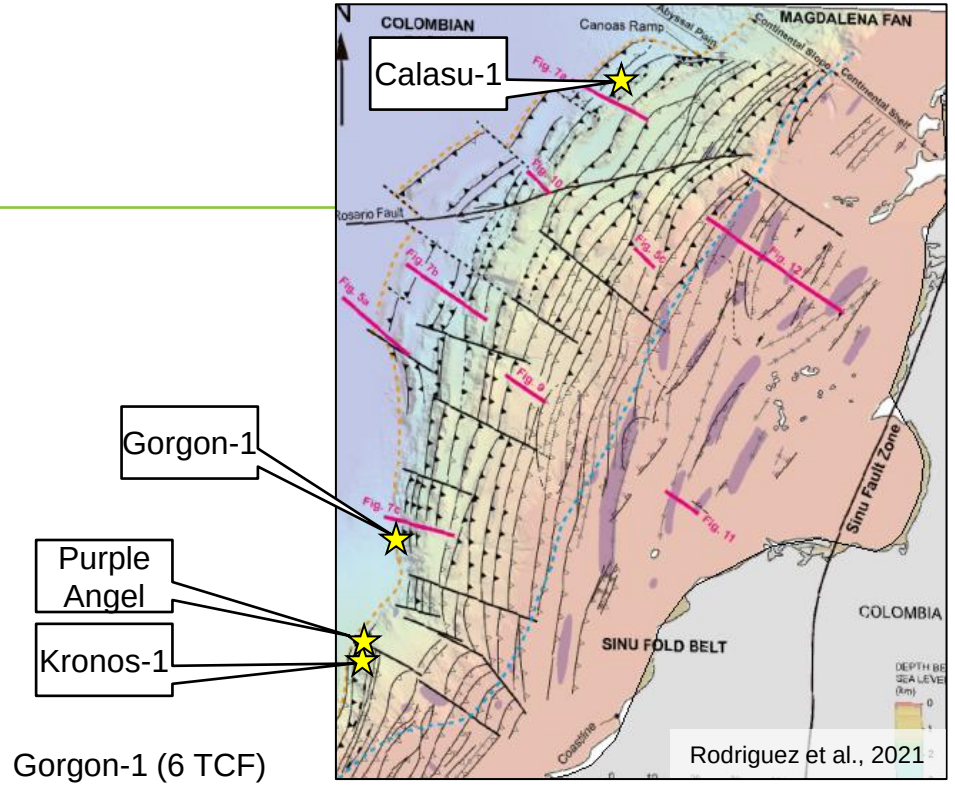


Interval Velocity
m/s

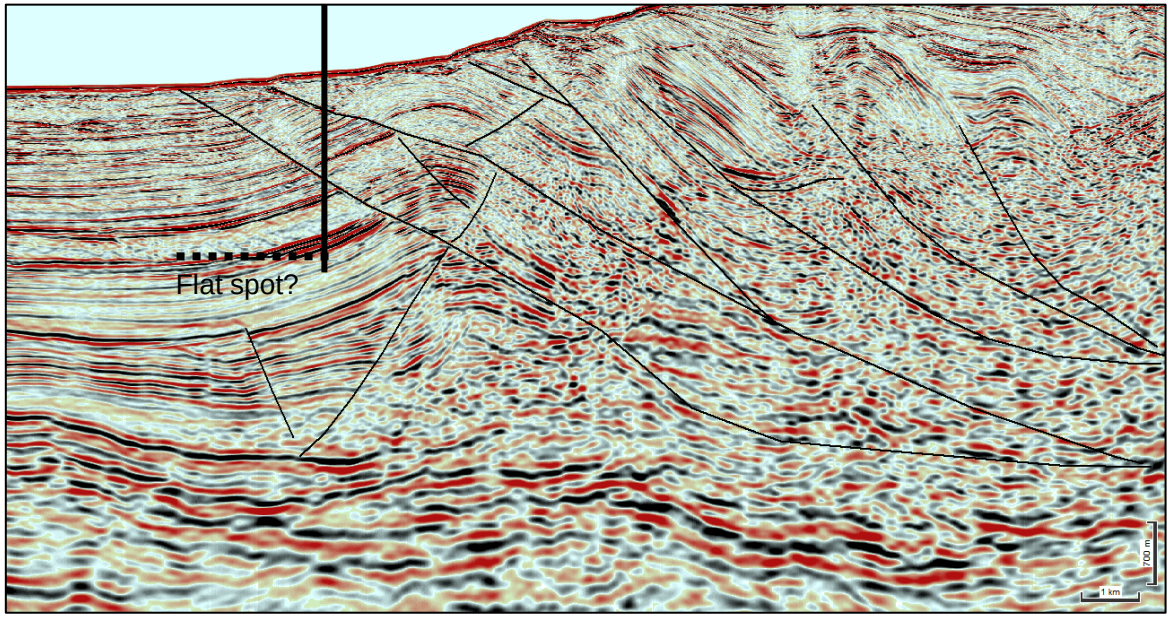


Implications for Hydrocarbon Exploration

- The Sinu Offshore area hosts giant gas accumulations at Gorgon, Purple Angel and Kronos
- All wells in toe-thrust section
- New analysis suggest dry gas accumulations contain a mixture of microbial and thermogenic gases
- Oil seeps onshore in the San Jacinto belt
- Continuous decollement surfaces could facilitate migration from deeper (UK?) kitchen
- Consistent BSR mapped within foldbelt
- Several trap types:
  - Thrust and related folds
  - Extensional structures updip on shelf
  - Mud diapirs and related pinchouts

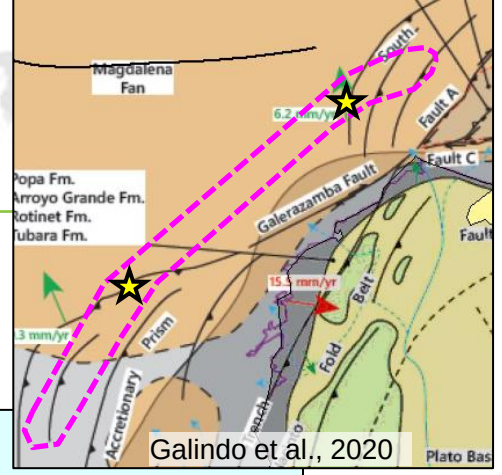


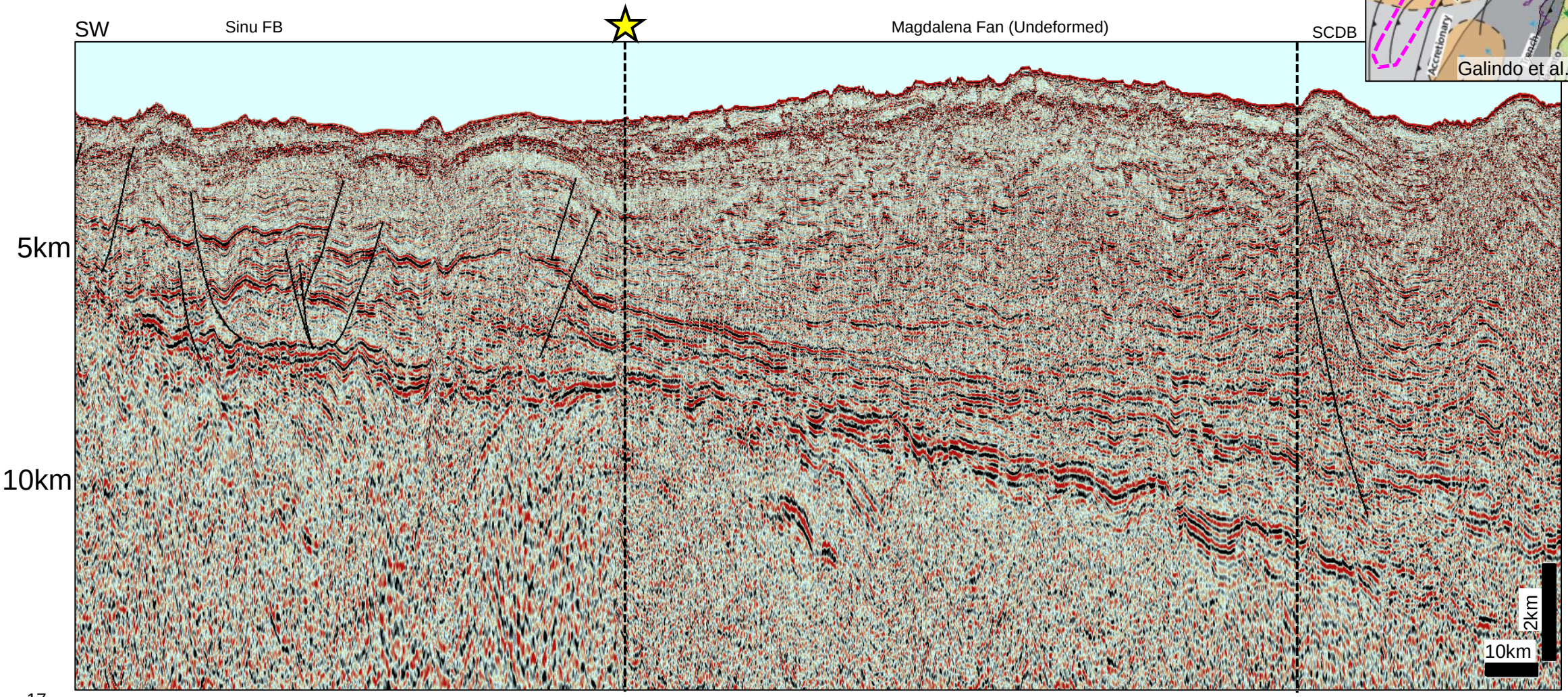
Gorgon-1 (6 TCF)



Along-strike Variation of Deformation at Magdalena Fan

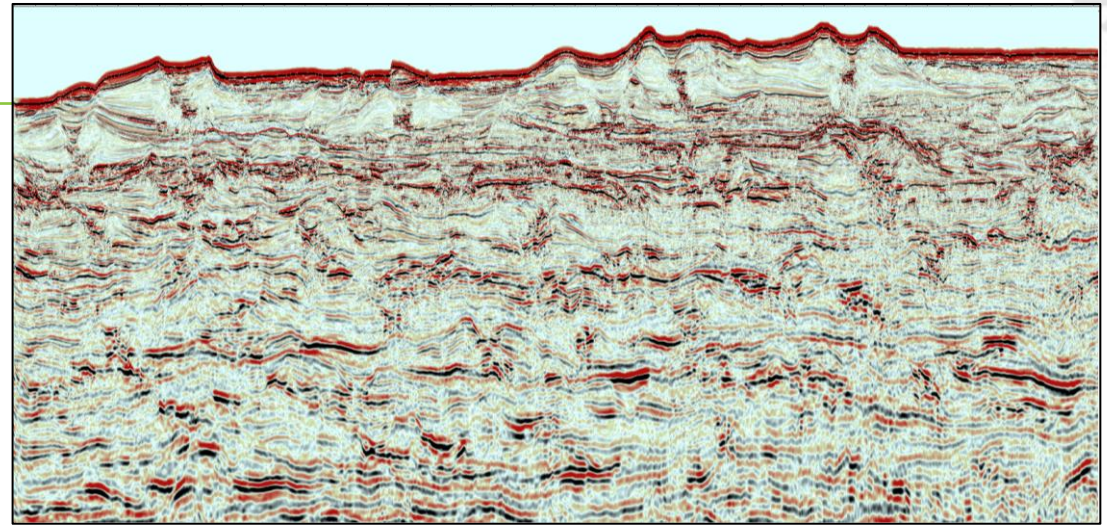
- Abrupt change to structure-less domain to the east of the Galerazamba fault

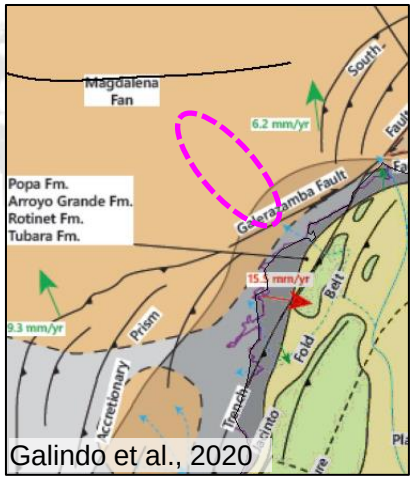




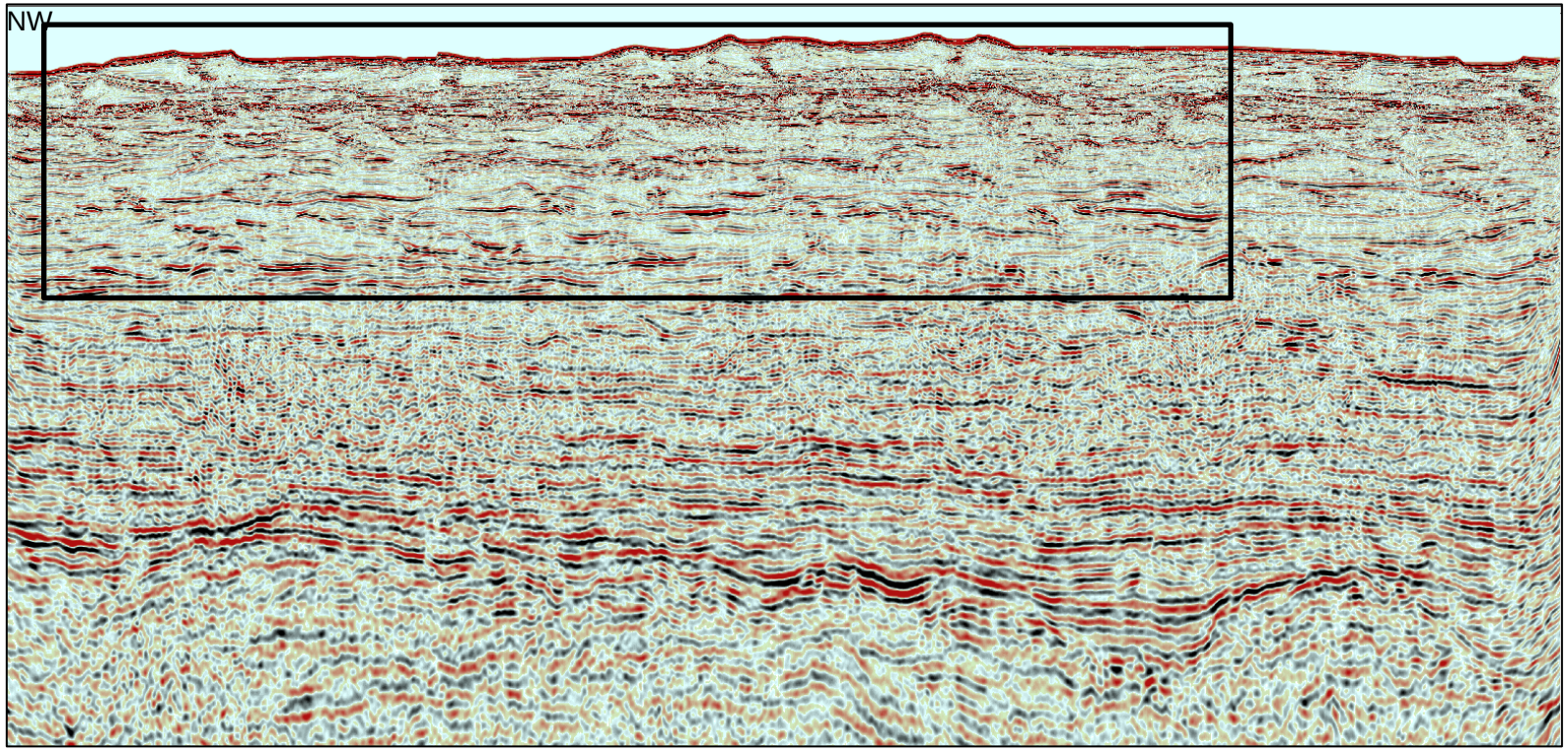
Magdalena Delta and Fan

- Fan deposition initiated in Late Miocene on the pre-existing accretionary wedge
- 11-12km thick sediment pile underlain by Caribbean plateau crust and thinned crust
- Deposited on active margin, but appears largely undeformed
- High sediment supply may have induced collapse of pre-existing compressional structures
- CLCs, erosional features and extensive MTCs observed



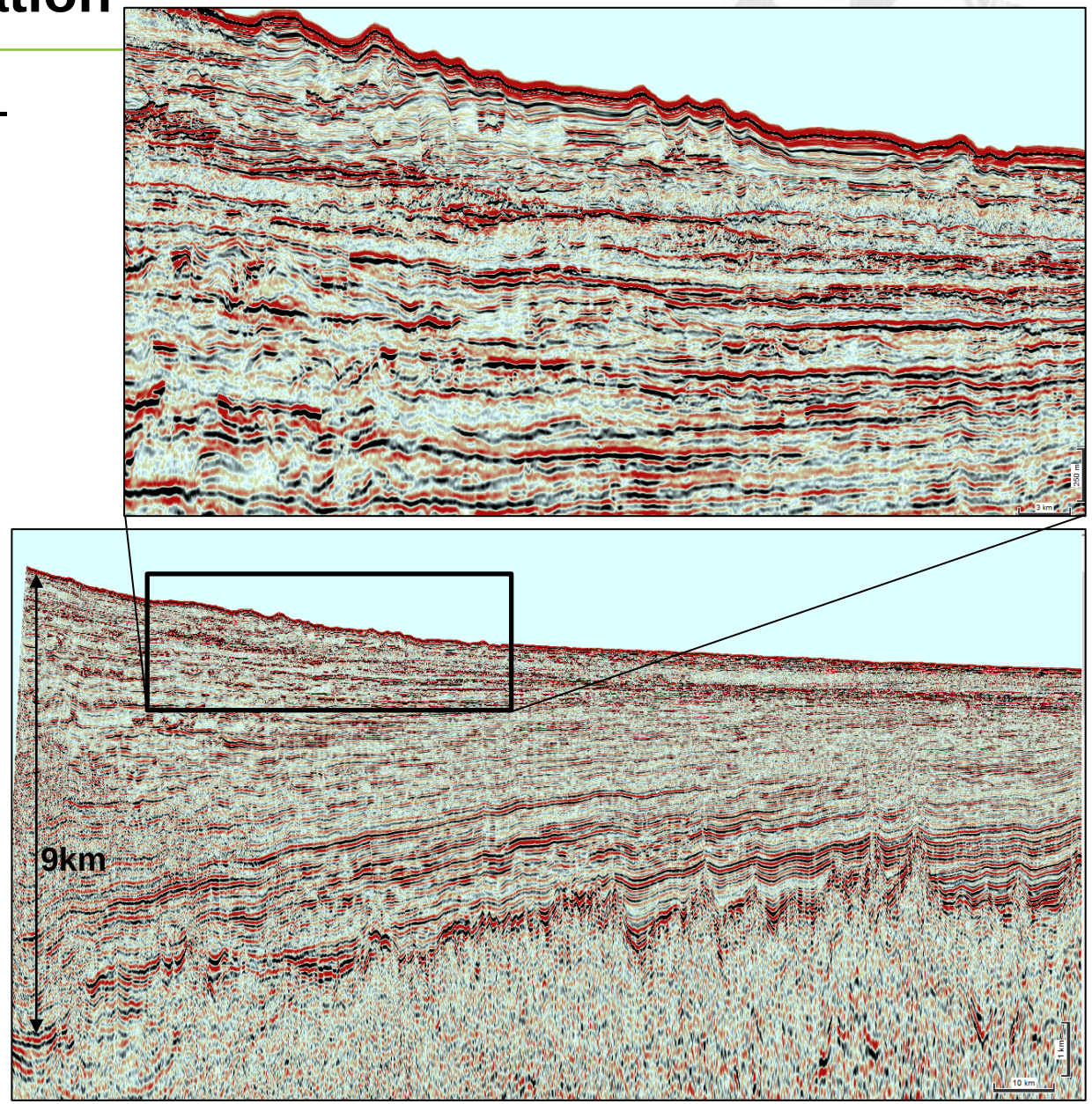


Galindo et al., 2020



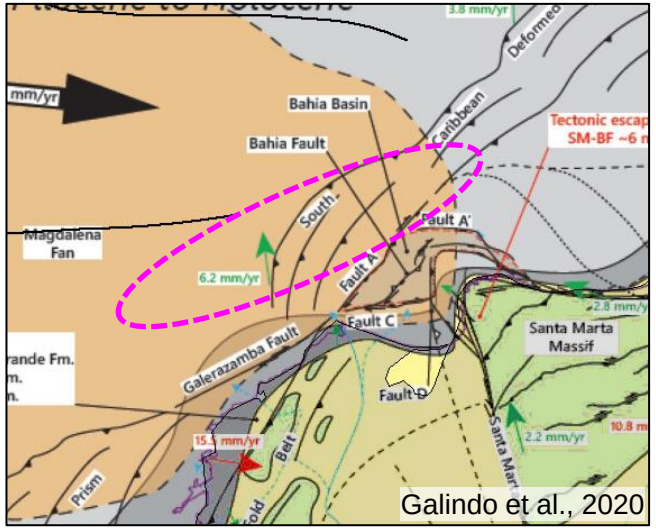
Implications for Hydrocarbon Exploration

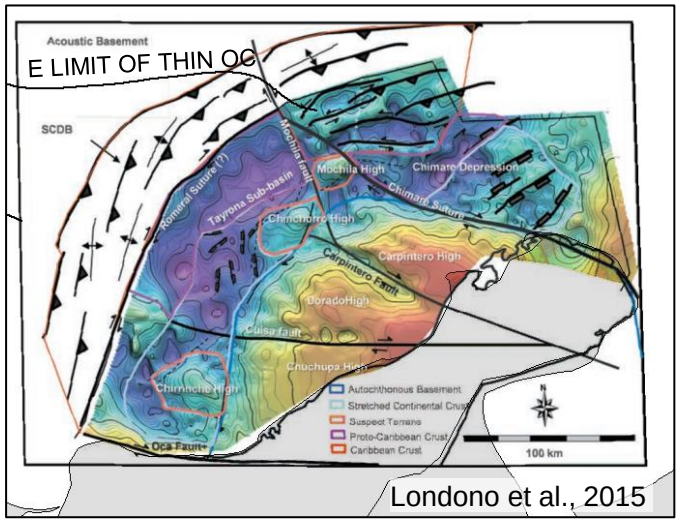
- Multiple deepwater trap types related to delta-fan system: nested channels, levees, MTDs, turbidite complexes, base of slope fans, etc.
- Sediment section thickness >11km
- Piston core and soil sample geochemistry at seep sites support thermogenic system
- Untested oil play sourced from Upper Cretaceous–Paleocene marine restricted shales (Martinez et al., 2015)

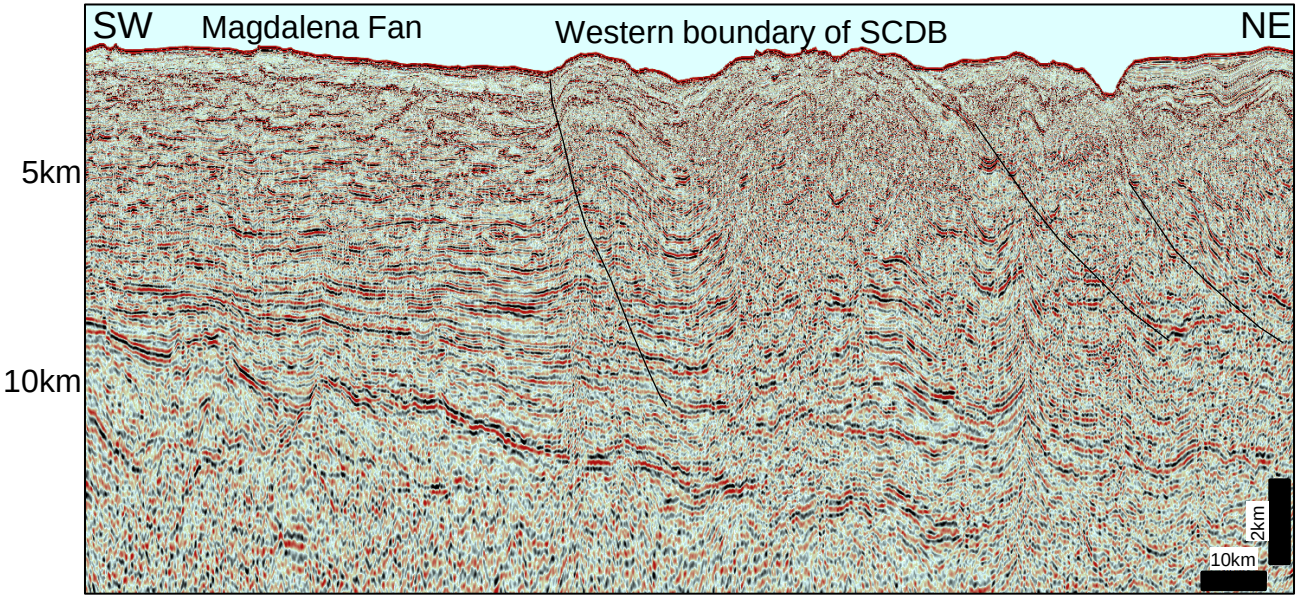


Offshore Guajira

- Eastern limb of the SCDB in Colombia
- Foldbelt changes orientation from N-S in the west to almost E-W at its northern limit
- Relatively narrow accretionary foldbelt
- Continental blocks (Static backstops) present offshore, with broad transcurrent Neogene sub-basins (Tayrona and Chimare)
- Tayrona lies within boundary of thin Oceanic Crust, whereas Chimare lies on plateau crust
- Eastern boundary of thin crust appears to line up with Chimare suture zone

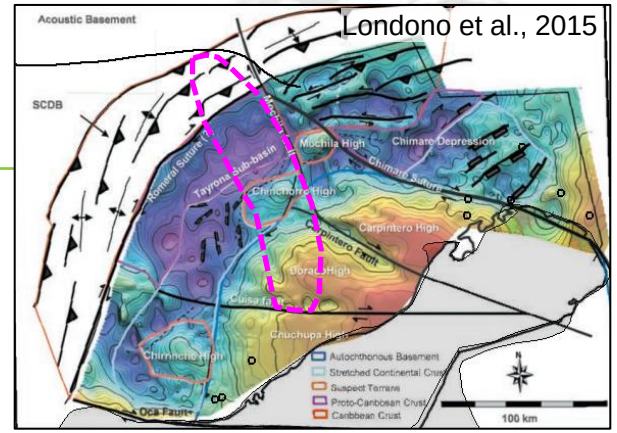


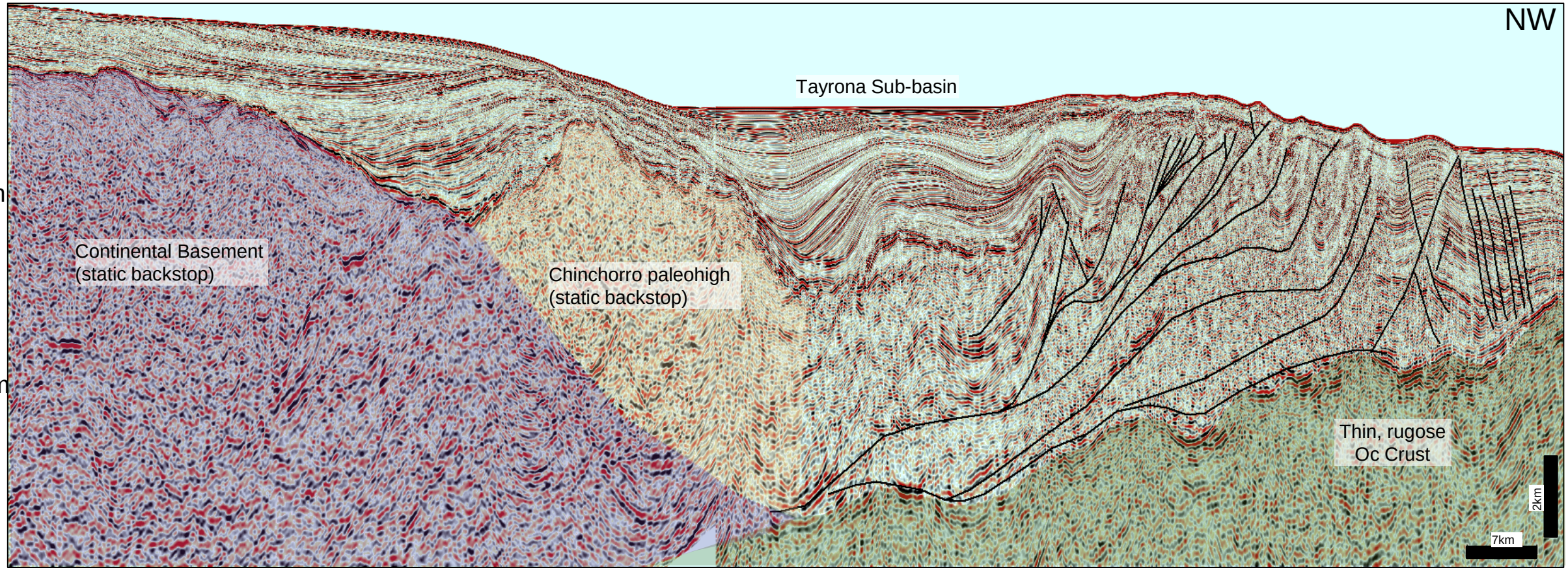




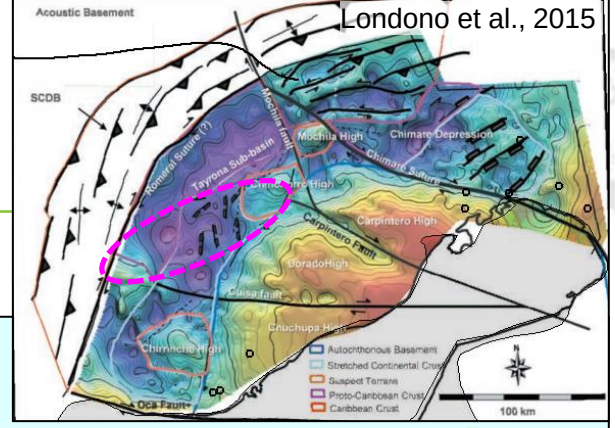
Dip Section through Tayrona

- Underlain by thin, rugose oceanic crust mapped from the ultra-deepwater
- Primarily seaward verging faults with multiple decollements
- Distance to static backstop on the Guajira side much lower than Sinu FB





Extensional Regime in Tayrona



Londono et al., 2015

SW

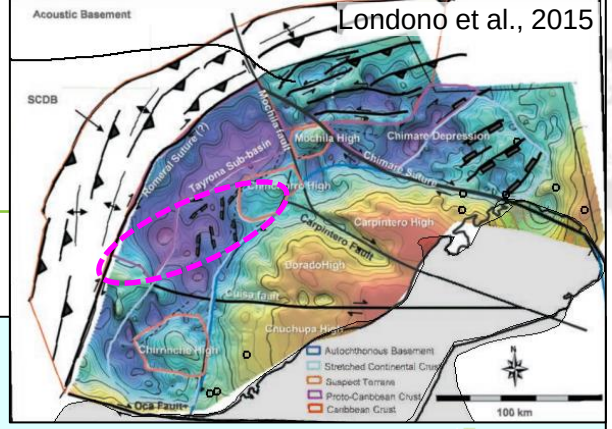
5km

10km

1 km

5 km

Tayrona Basin Amplitude Anomalies

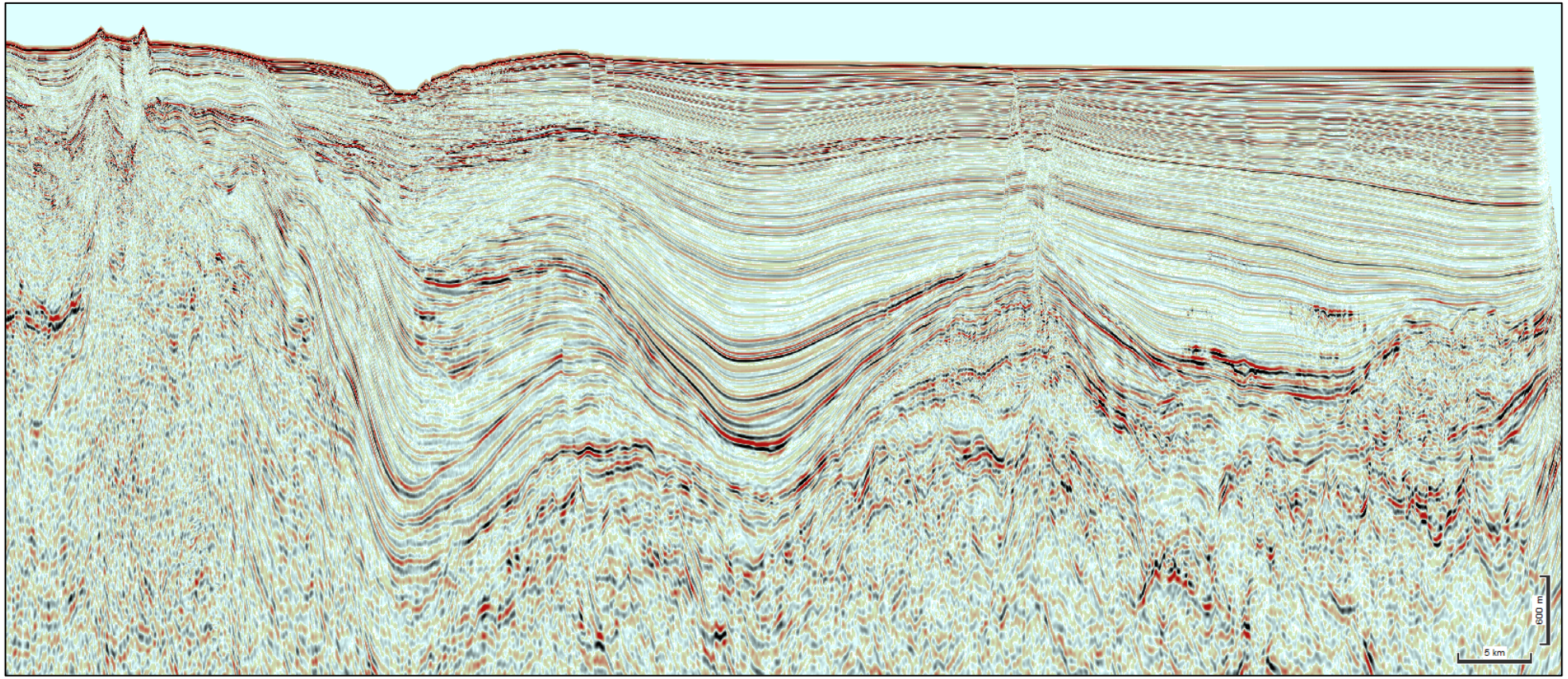


Londono et al., 2015

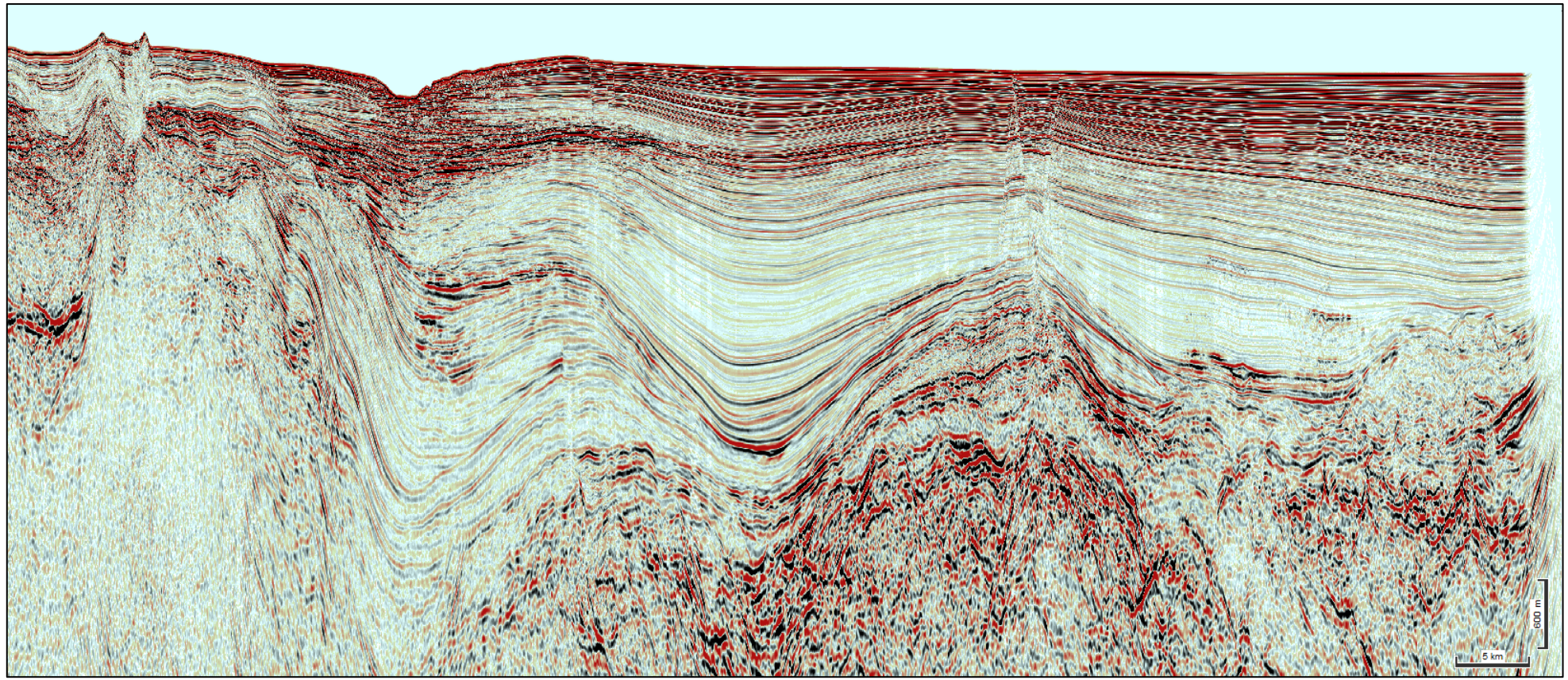
SW

10km

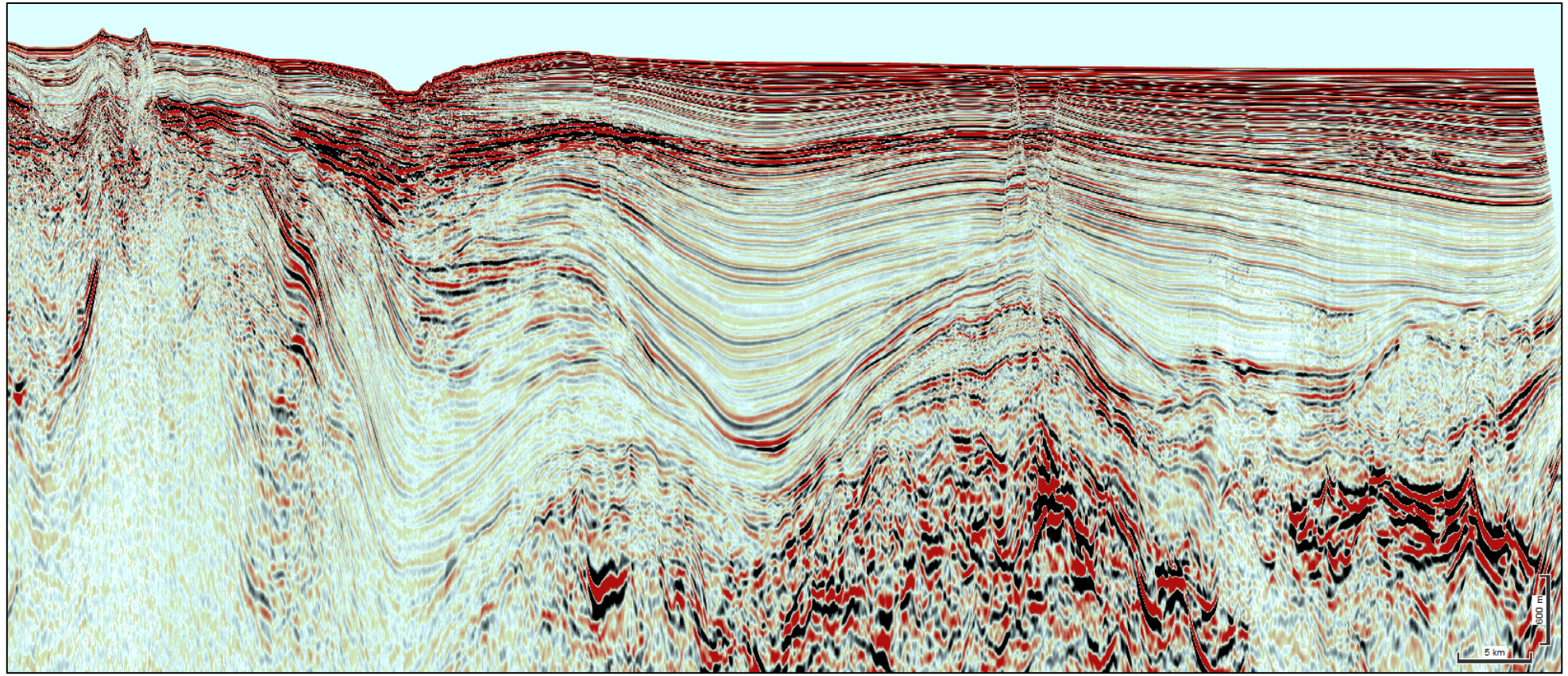
Tayrona Strike Line PSDM Stack



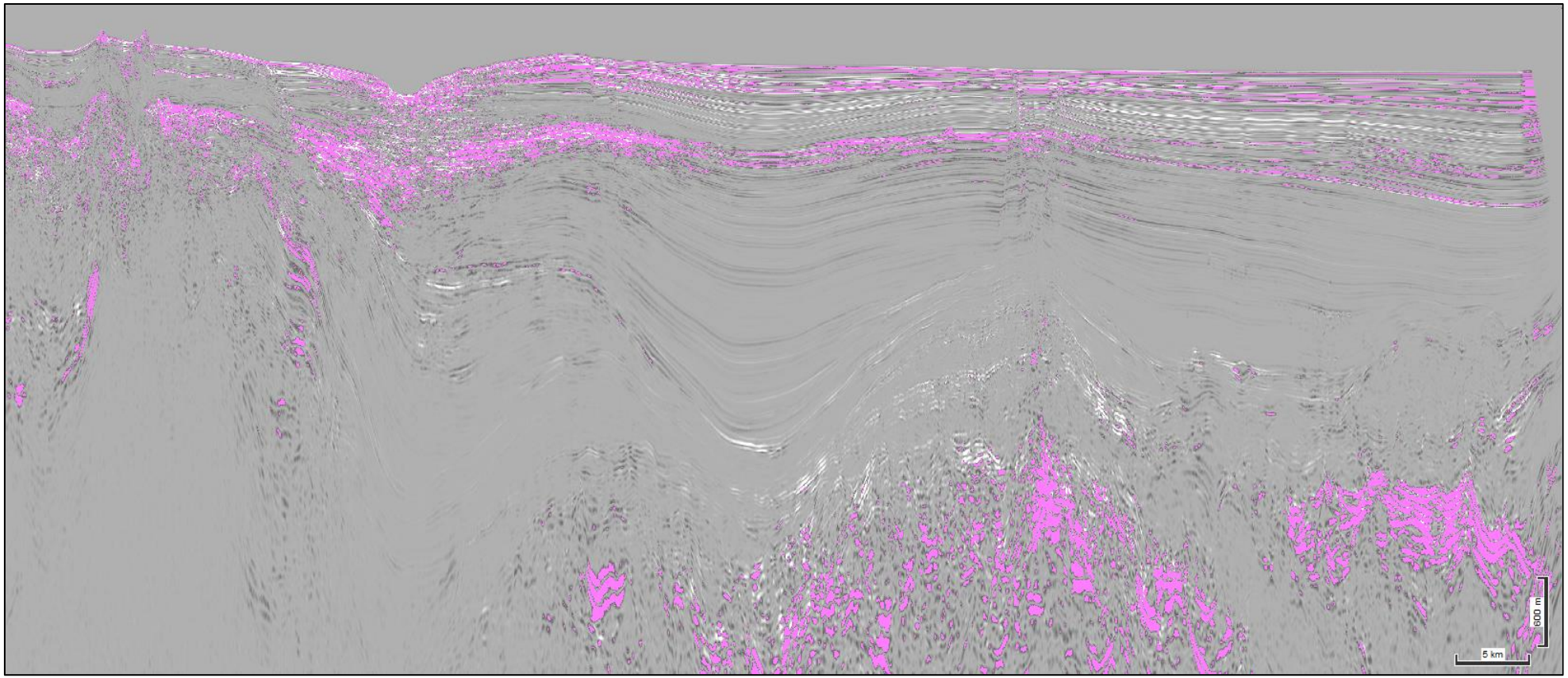
Tayrona PSDM 5-15 Ang



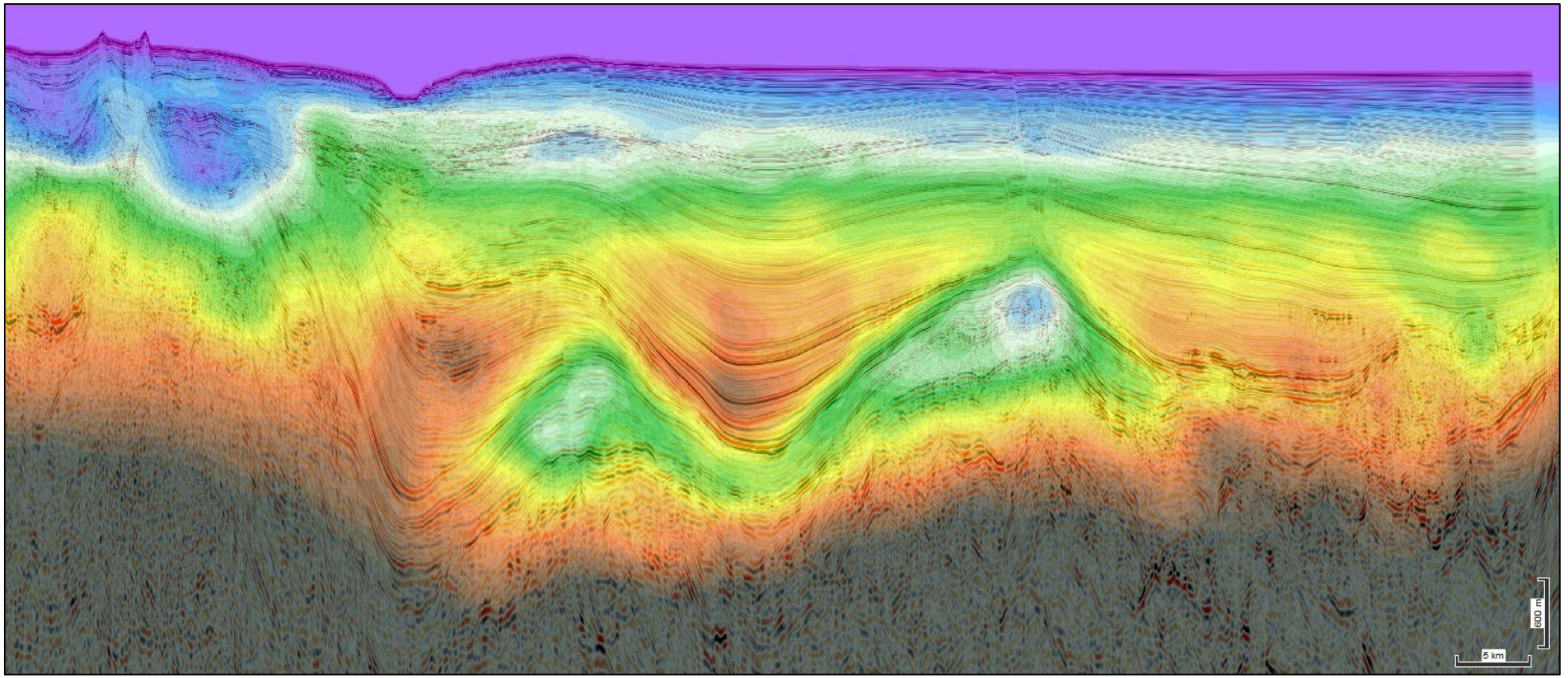
Tayrona PSDM 35-45 Ang



Tayrona PSDM AVO Attribute



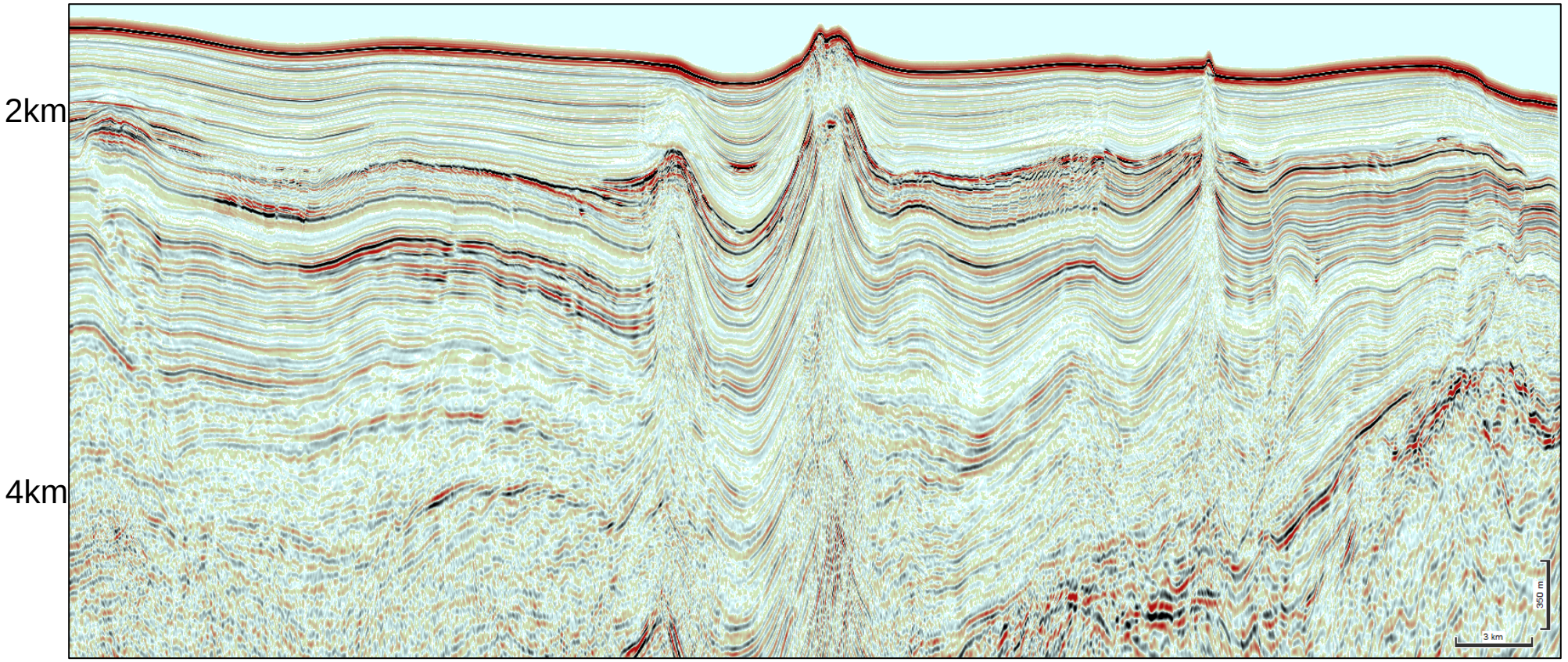
Tayrona PSDM Velocity



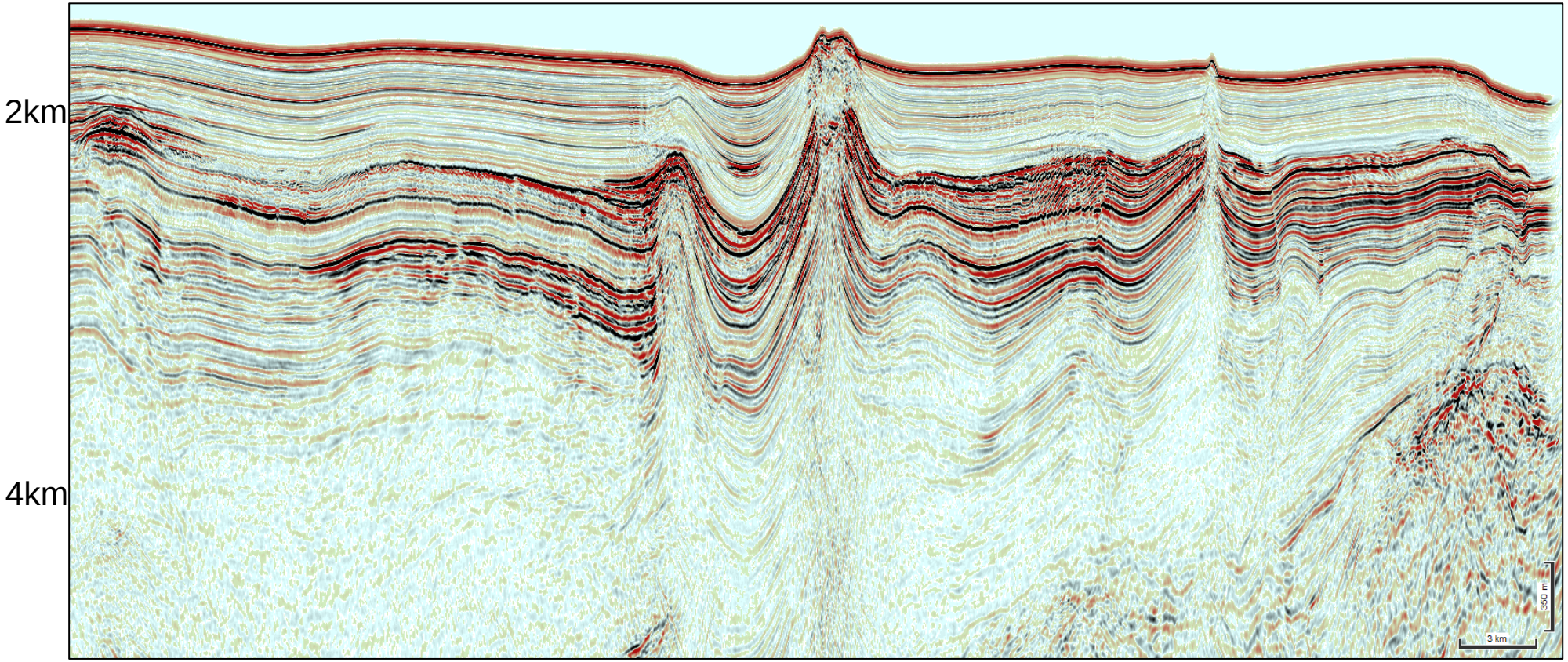
Interval Velocity
m/s

1500
1678
1856
2033
2211
2389
2567
2744
2922
3100
3278
3456
3633
3811
3989
4167
4344
4522
4700
4878
5056
5233
5500

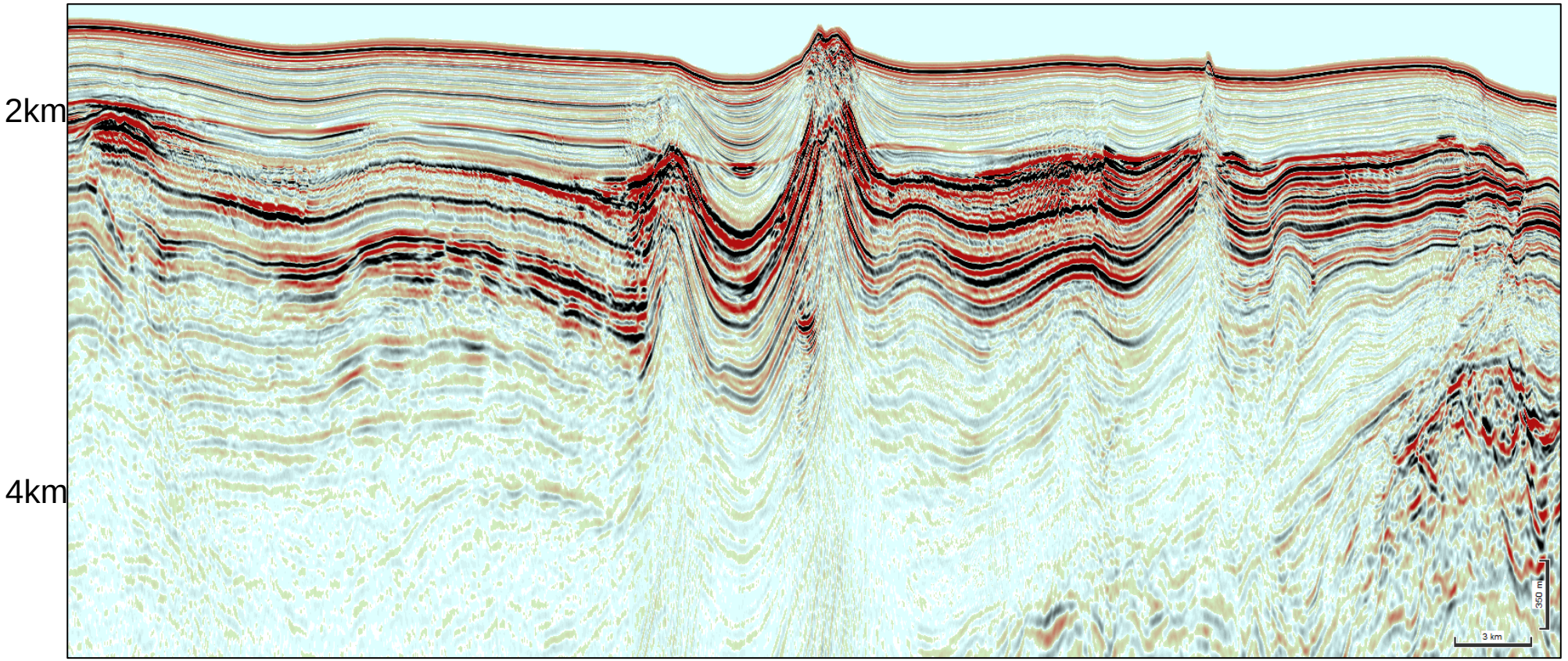
Offshore Guajira Strike Line PSDM



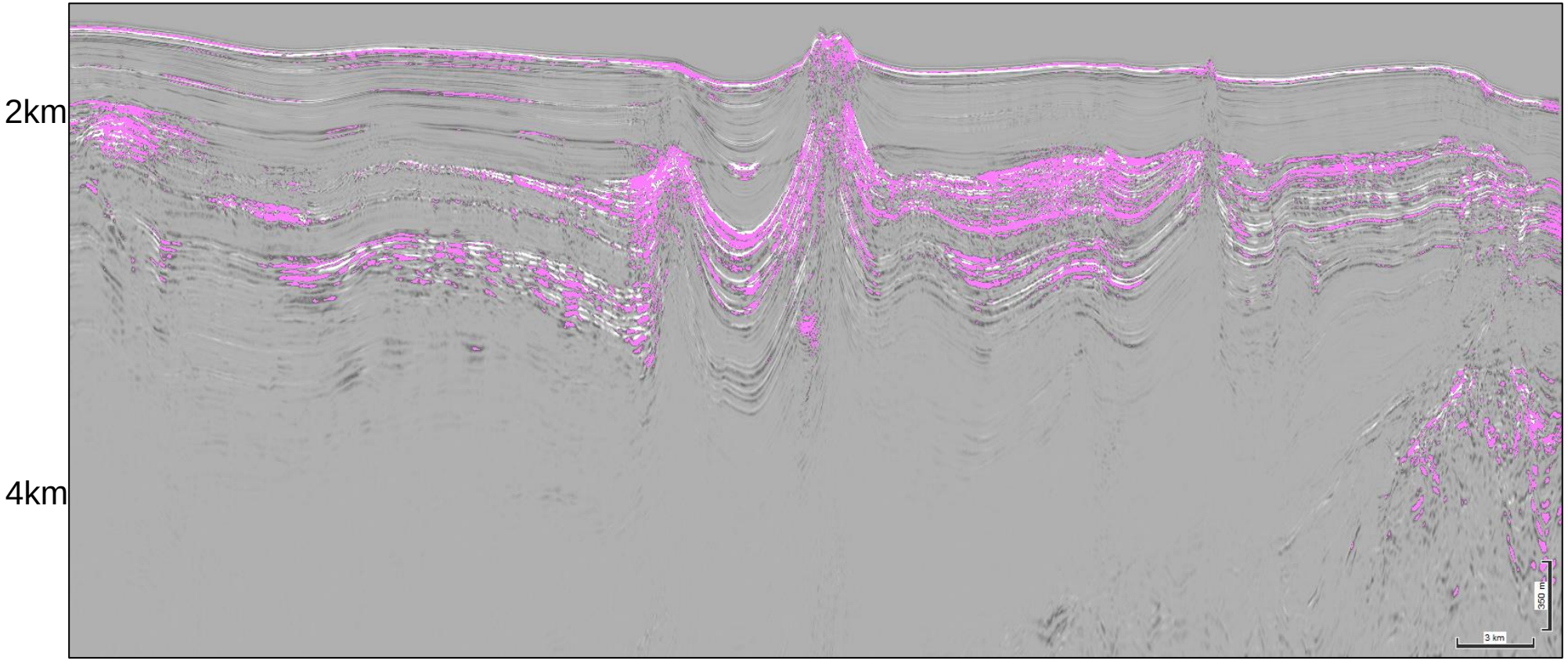
Offshore Guajira PSDM 5-15 Ang



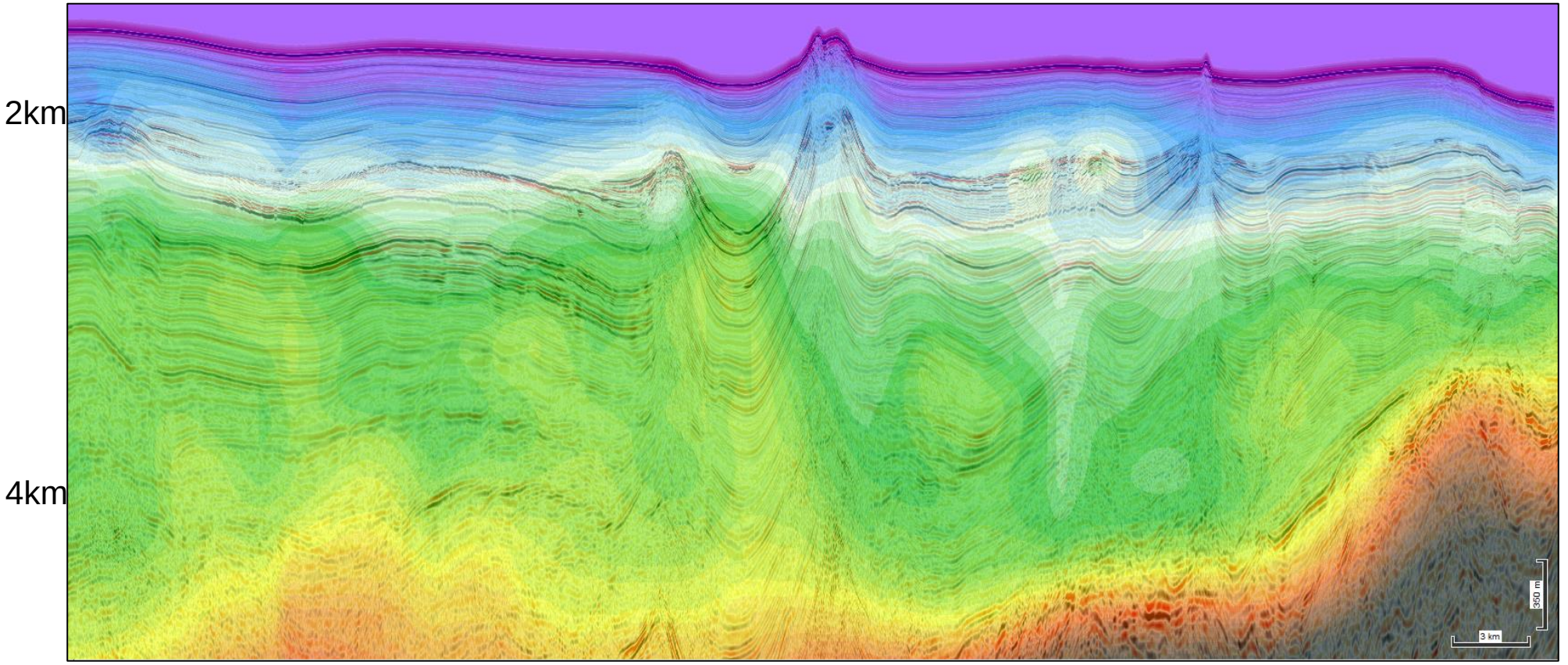
Offshore Guajira PSDM 35-45 Ang



Offshore Guajira PSDM AVO Attribute

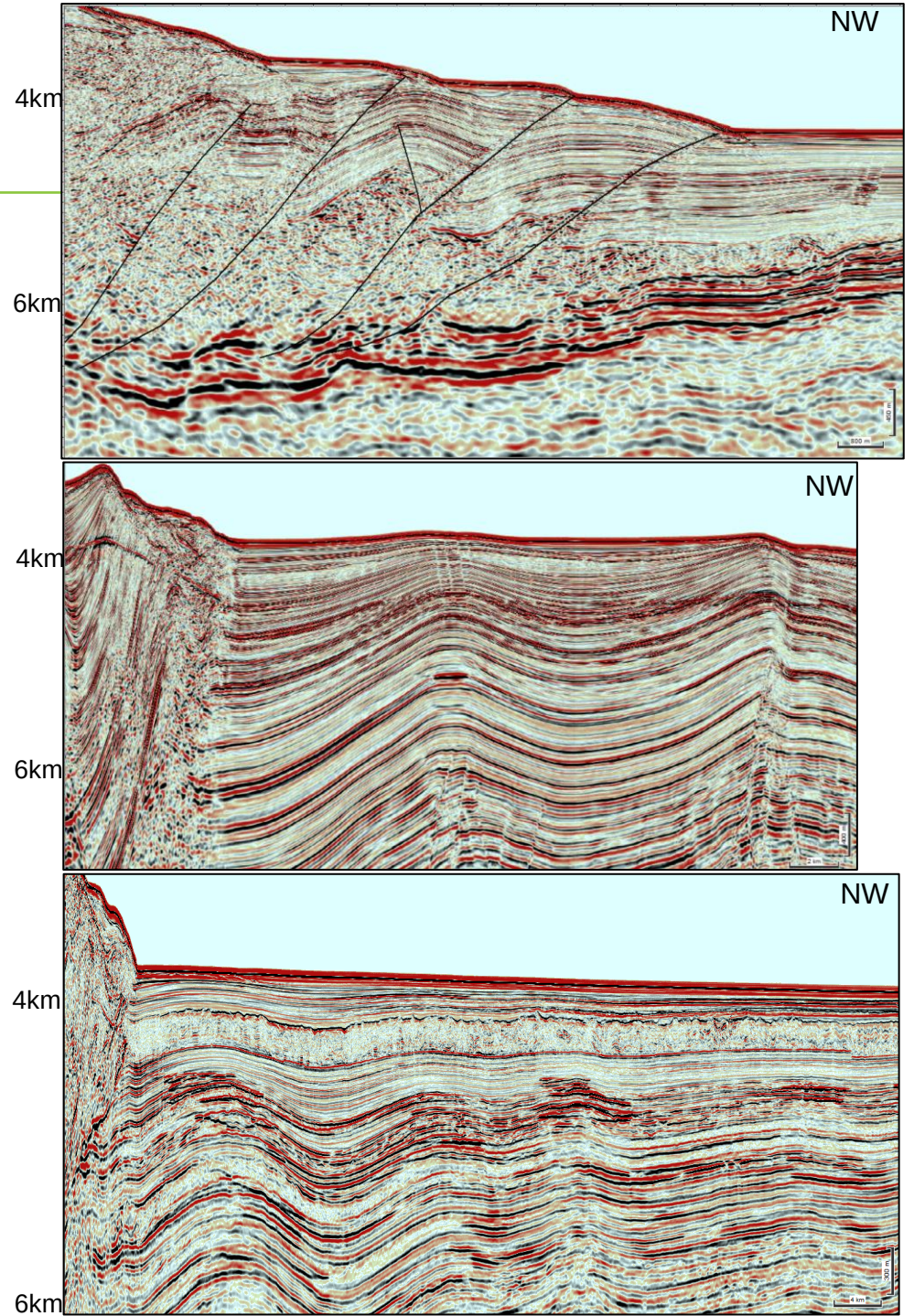


Offshore Guajira PSDM Velocity



Implications for Hydrocarbon Exploration

- Several separate provinces in terms of trapping mechanisms:
  - Thrust-related folds in SCDB
  - Incipient folds with DHIs downdip of toe thrust structures
  - Shale diapirs and shale escape structures in Tayrona
  - Block faulting in Tayrona with UK-Paleogene graben fill
- Giant gas fields (Chuchupa-Ballena)
- Presence of thermogenic hydrocarbons in piston cores in offshore Guajira



Powering data-driven decisions

Offshore Colombia: Highlights of Prospective Margin Segments Using Newly Reprocessed 2D Seismic Data
PART 2: Deepwater Colombia

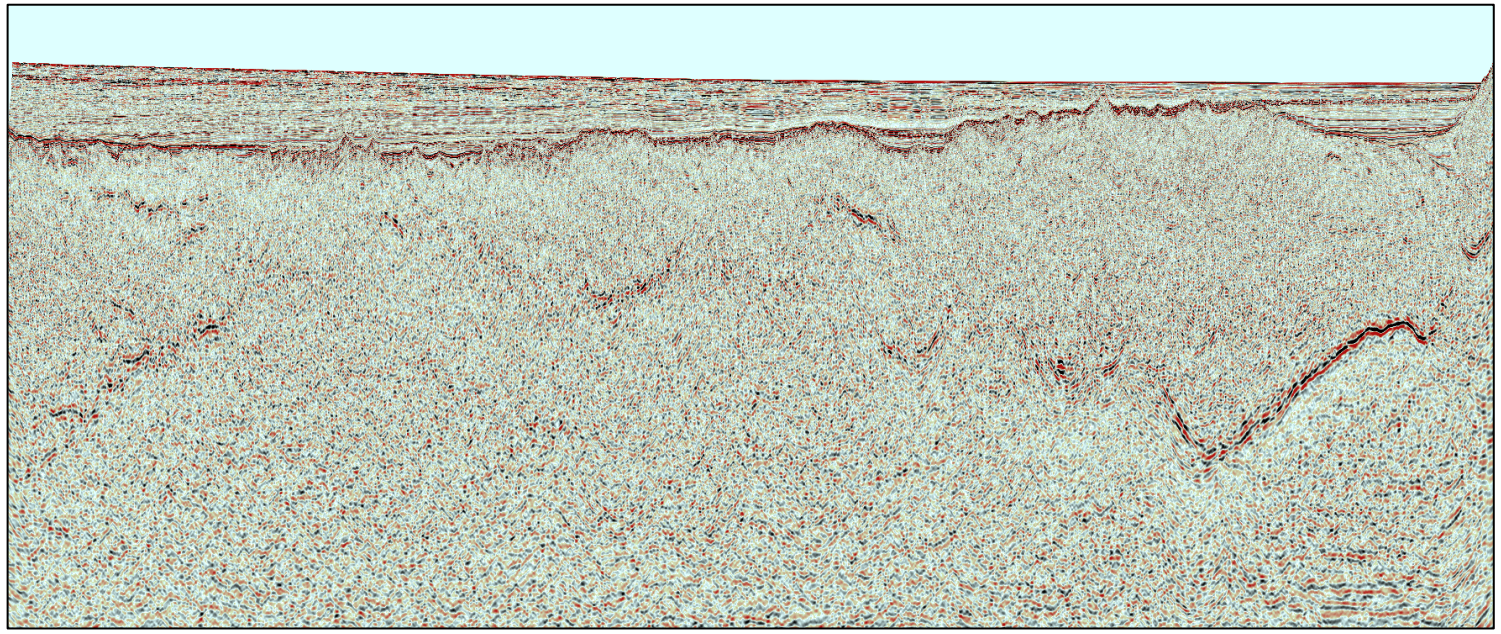
Kyle Reuber*, Antara Goswami, Chuck Campbell

ANH Webinar Series

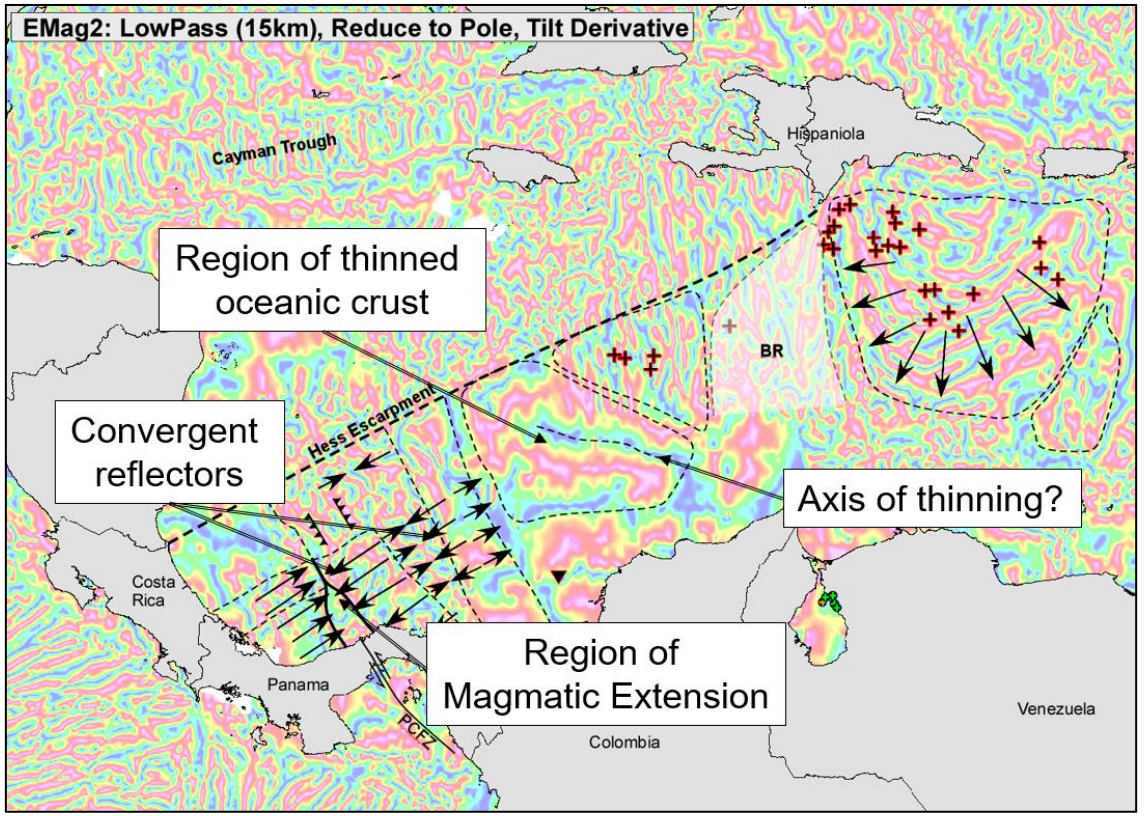
May 6th, 2022

Part 2 Overview

- Previous Work
- Observations
- Discussion
- AVO Analysis
- Wrap Up

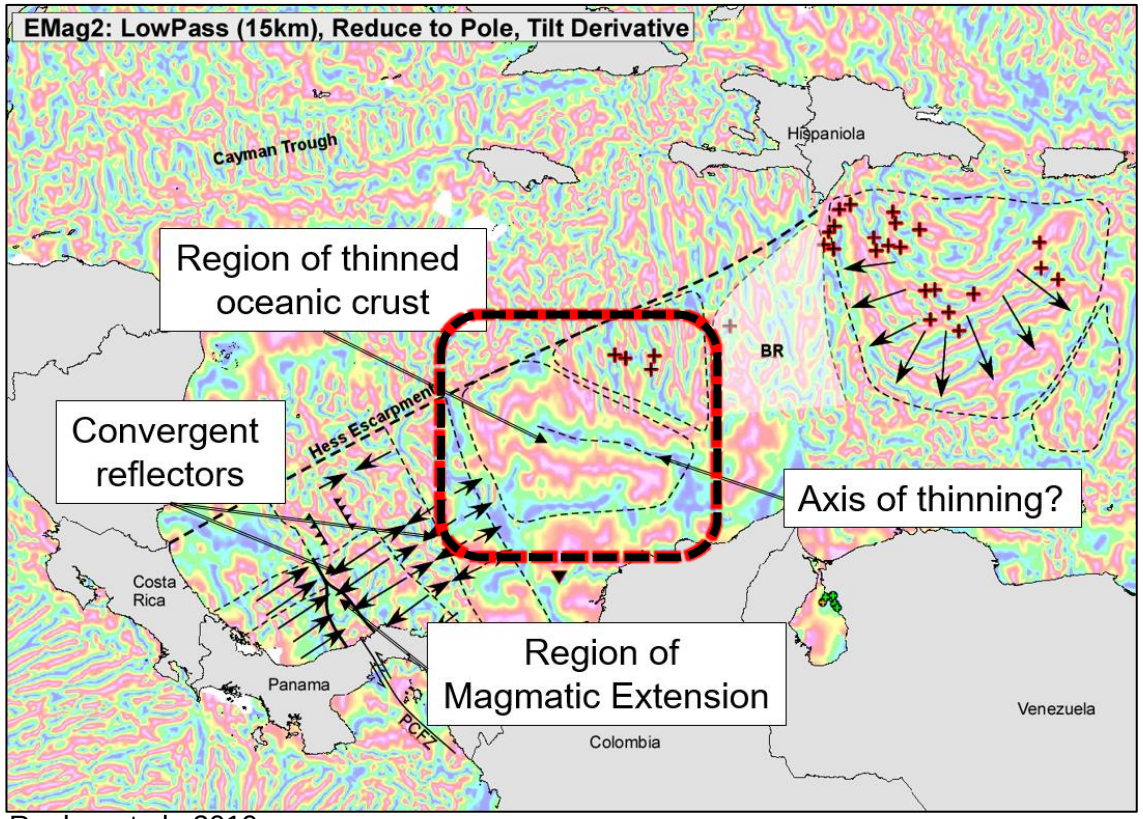


Previous Work



Reuber et al., 2019

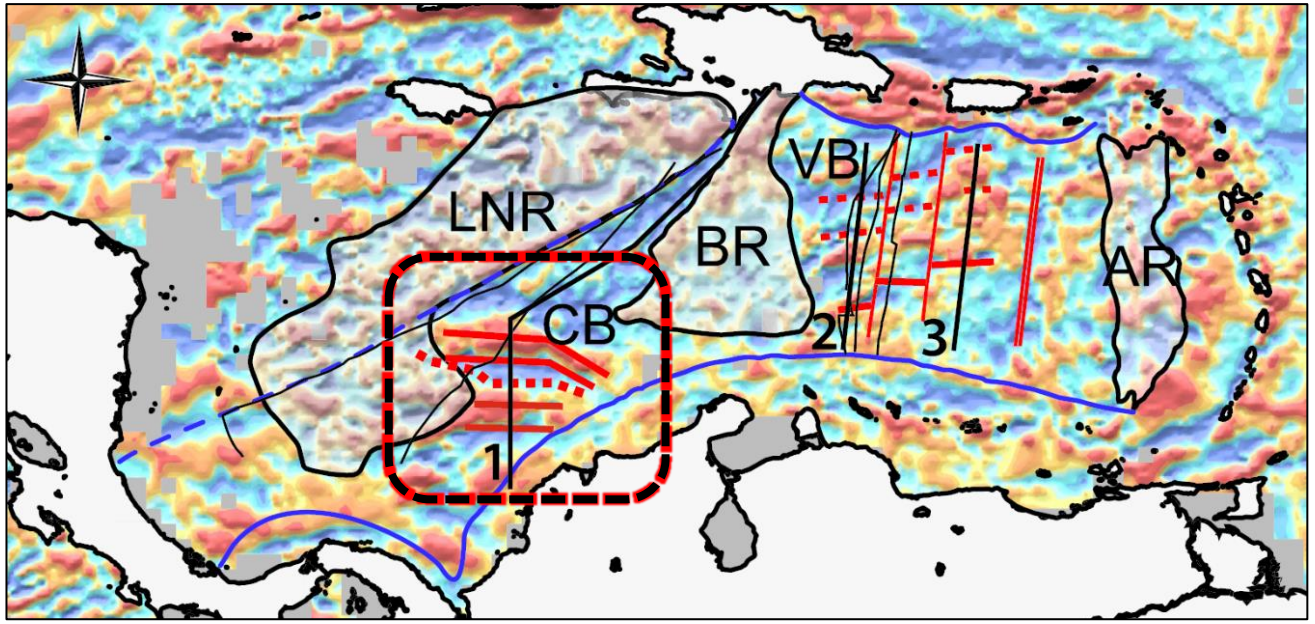
Previous Work
Evidence for a Late-Stage Spreading Center



Reuber et al., 2019

- Presented at GeoGulf 2019
  - Using sparse reprocessed 2D lines and filtered gravity/magnetic data
  - Weak to absent Moho expression in data
  - Top Basement character correlated with gravity anomalies

- Manuscript published in 2021
  - Used compilation of marine magnetics
  - Pacific Origin for location and timing of spreading
  - Proposed a 108-73 Ma age formation of the Caribbean Large Igneous Province (CLIP) and a 73-92 Ma age for the Colombian Basin



Garcia-Reyes and Dyment, 2021

Previous Work
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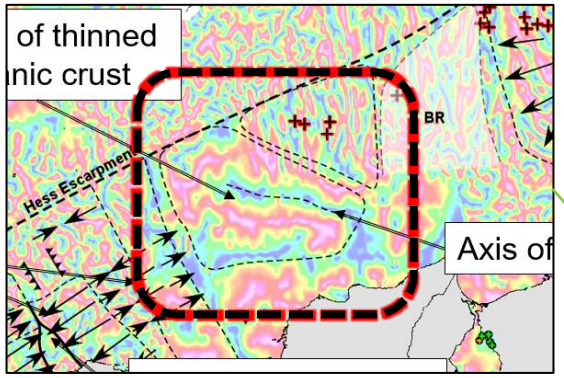
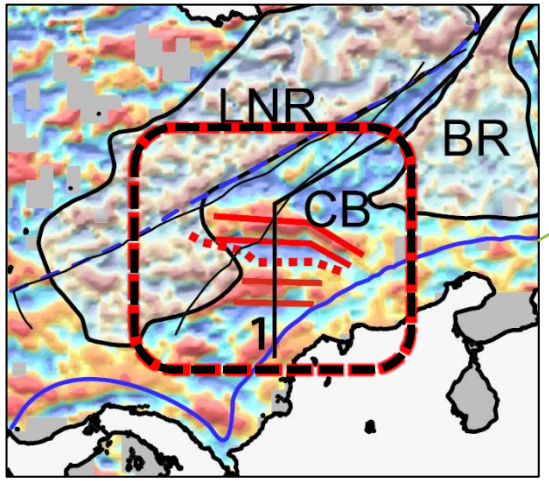
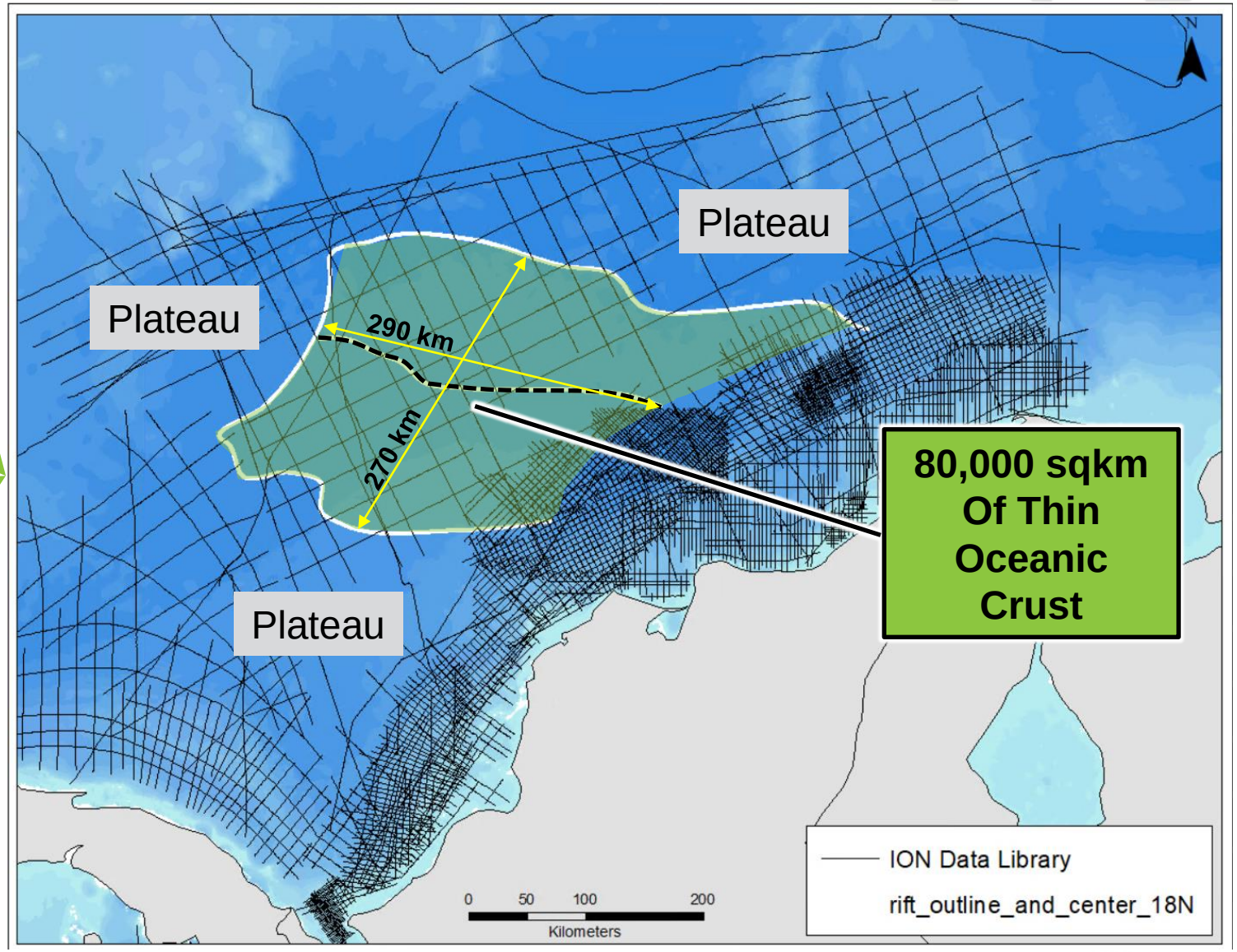


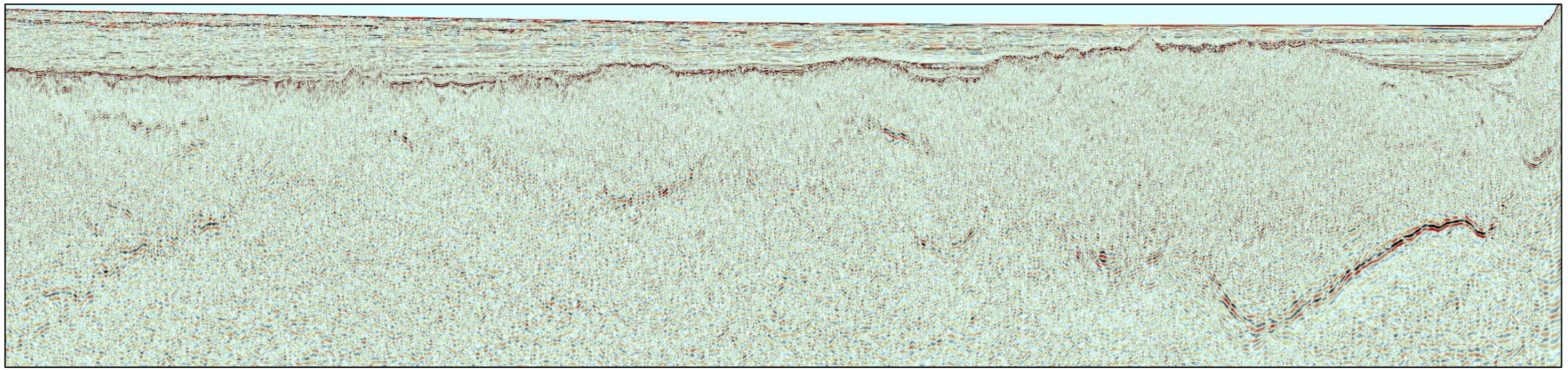
Reuber et al., 2019



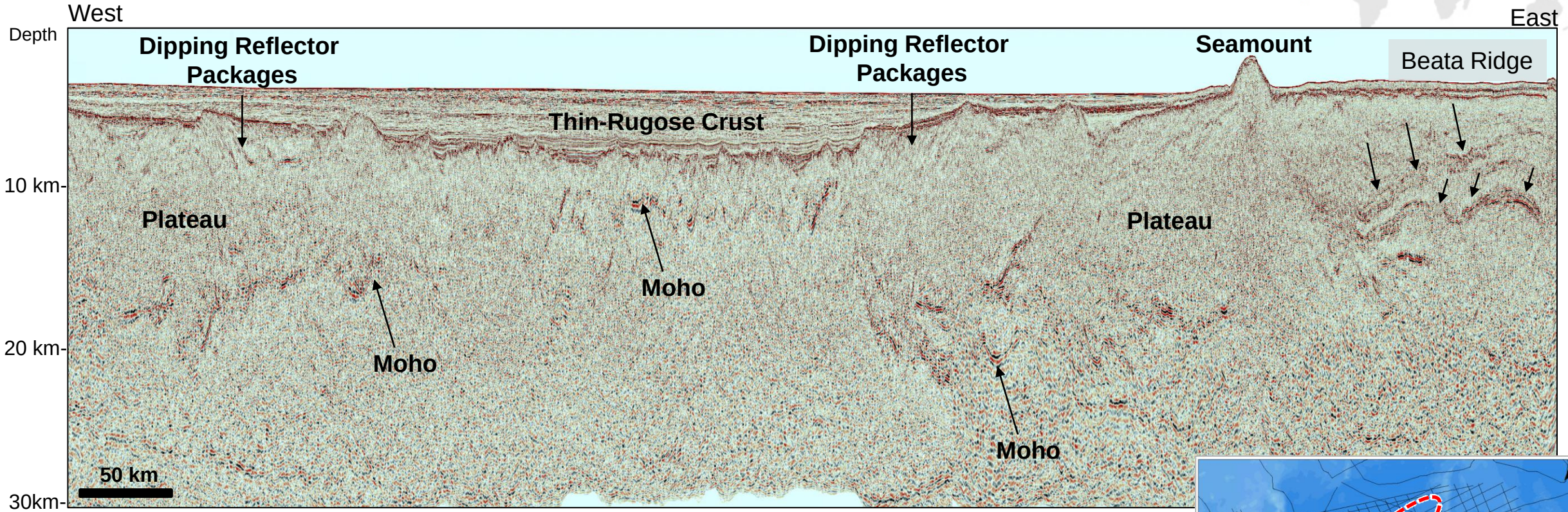
Garcia-Reyes and Dyment, 2021

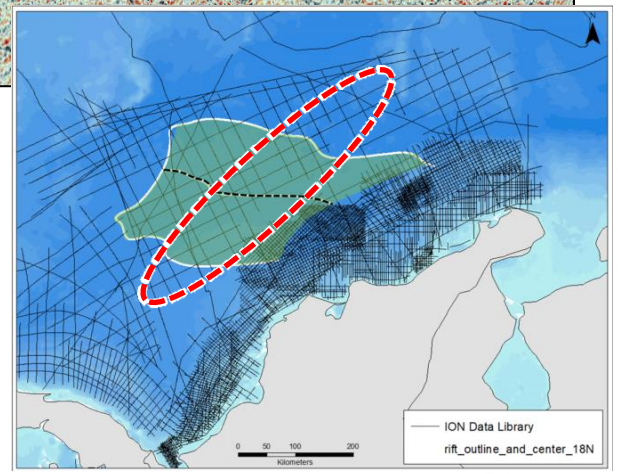


Observations

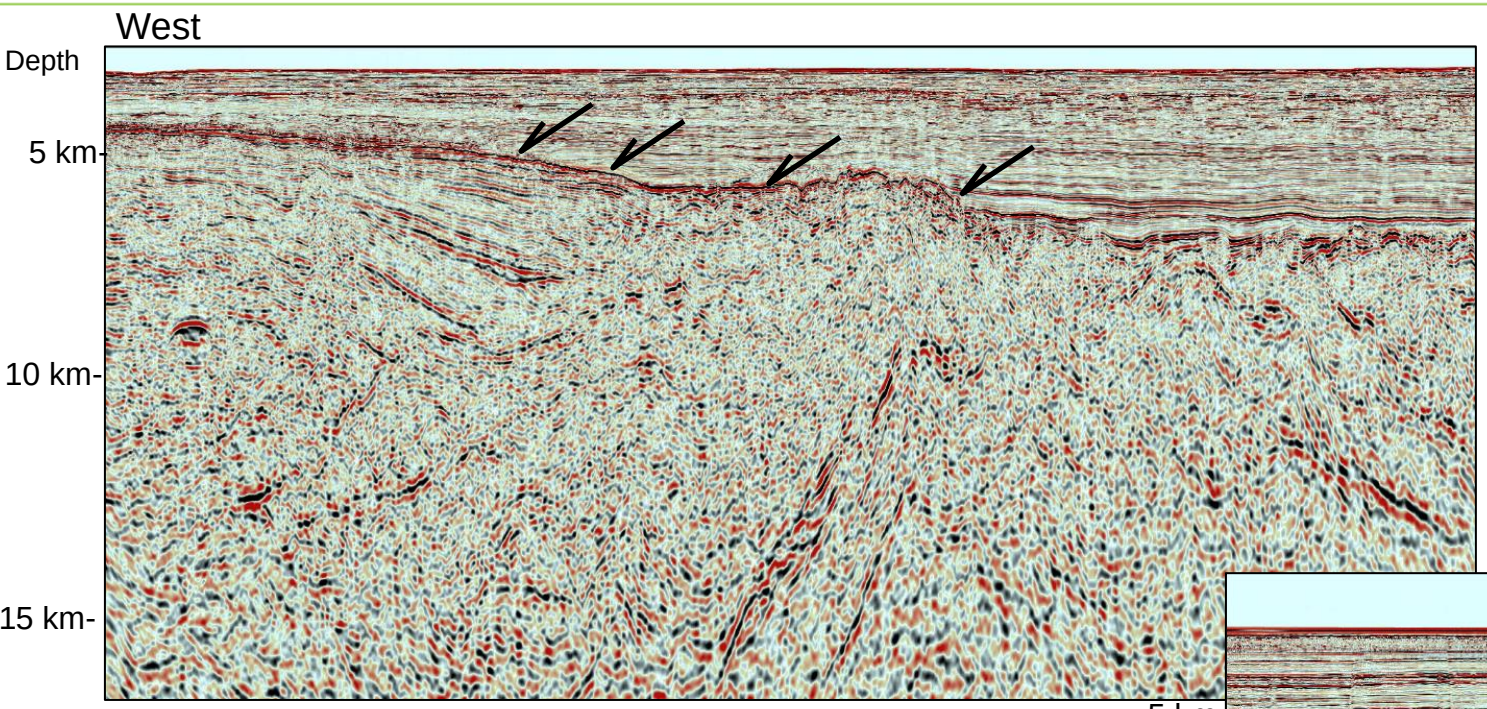


Observations
Deepwater Transect Across Deepwater Colombia

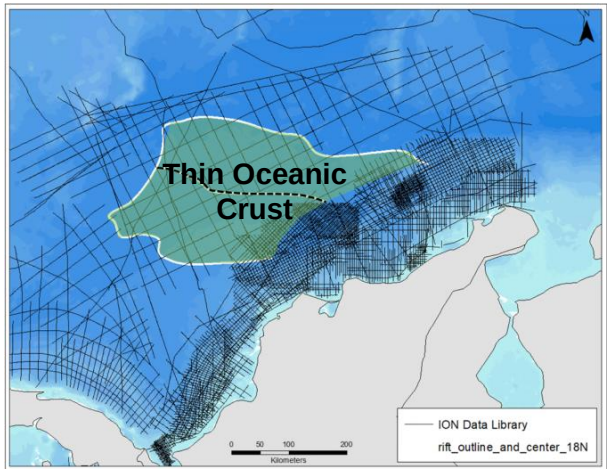




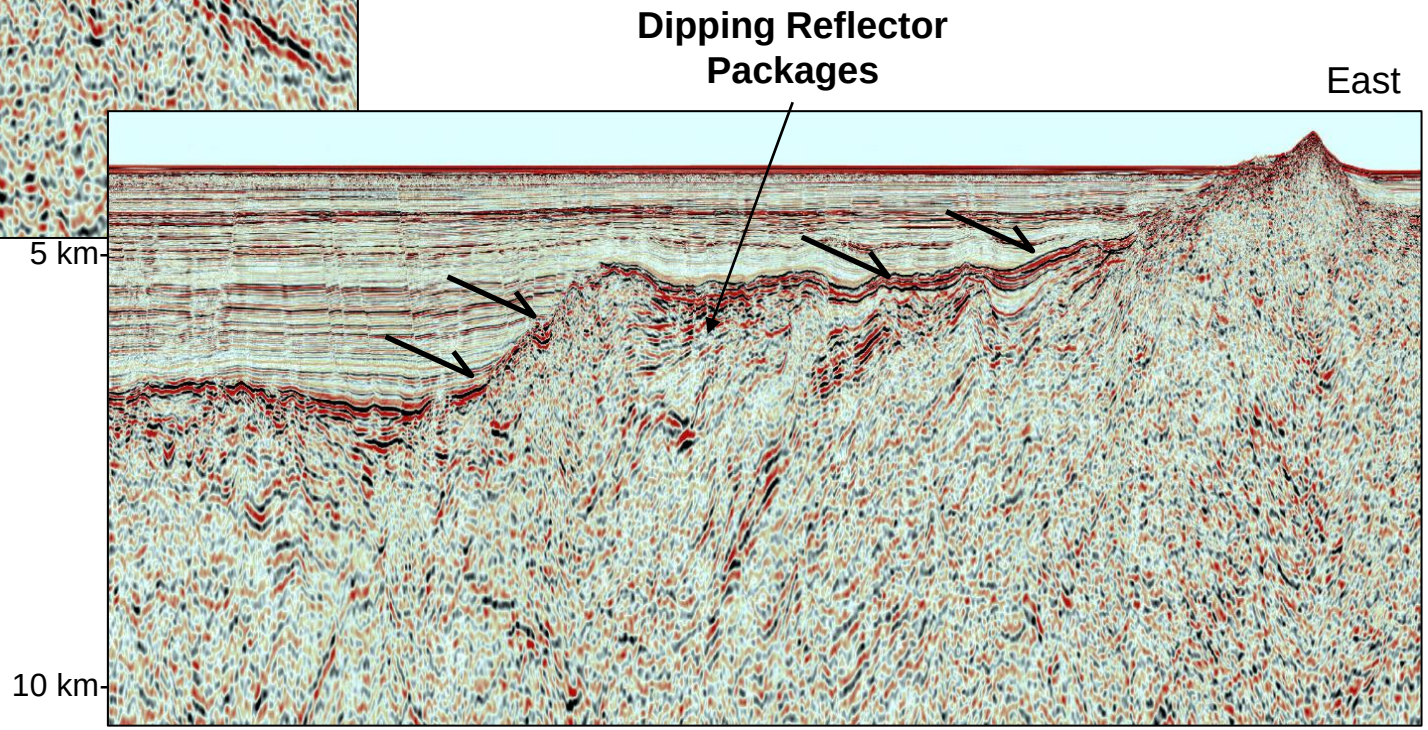
Observations
Character of Pre-Existing Two-Layer CLIP



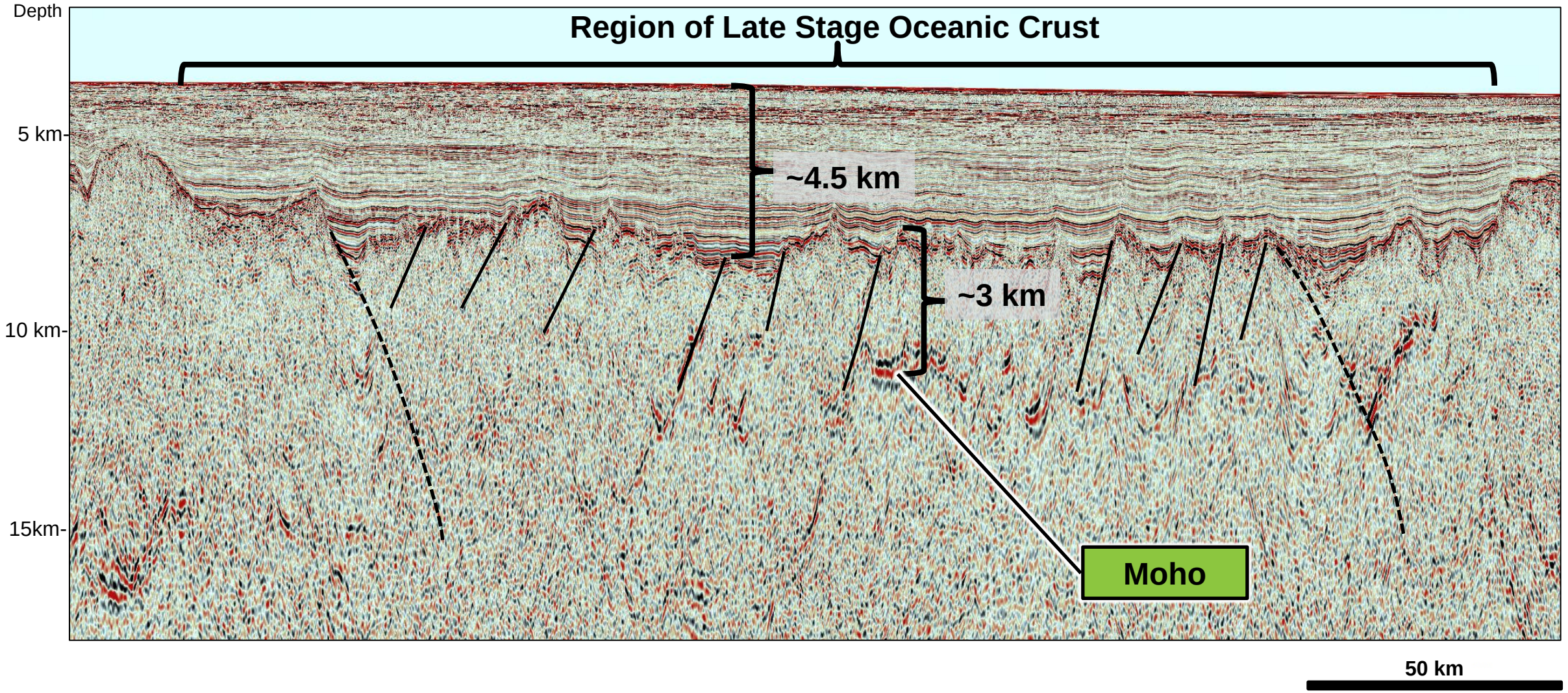
- Dipping Reflector Packages = “inner SDRs” (Seaward Dipping Reflectors) (Platt, 2010)
- Magmatic packages associated with initial stages of volcanism during crustal rupture.



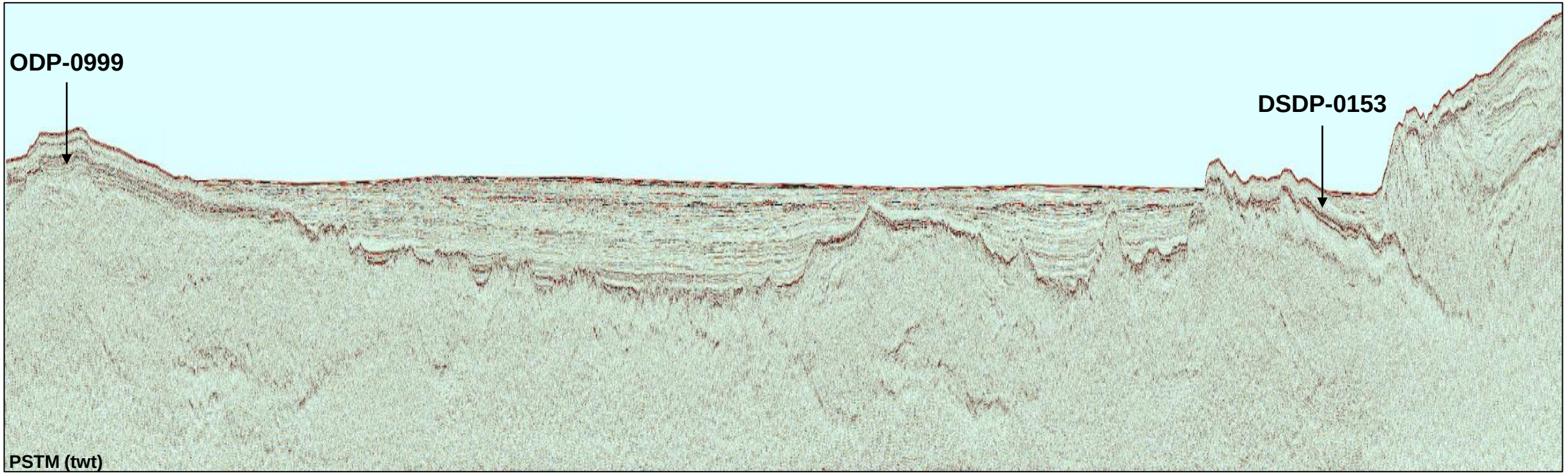
Examples shown here are outside of/ flank green shaded area



Observations
Nature of Spreading

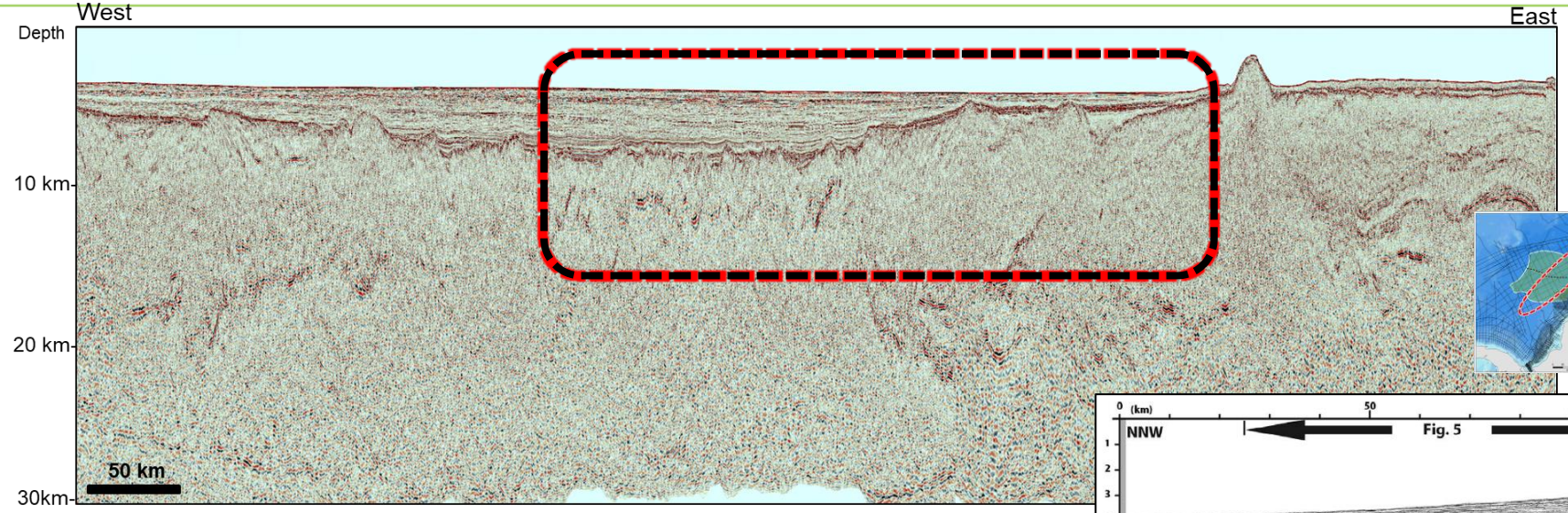


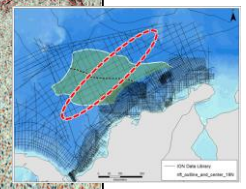
Discussion

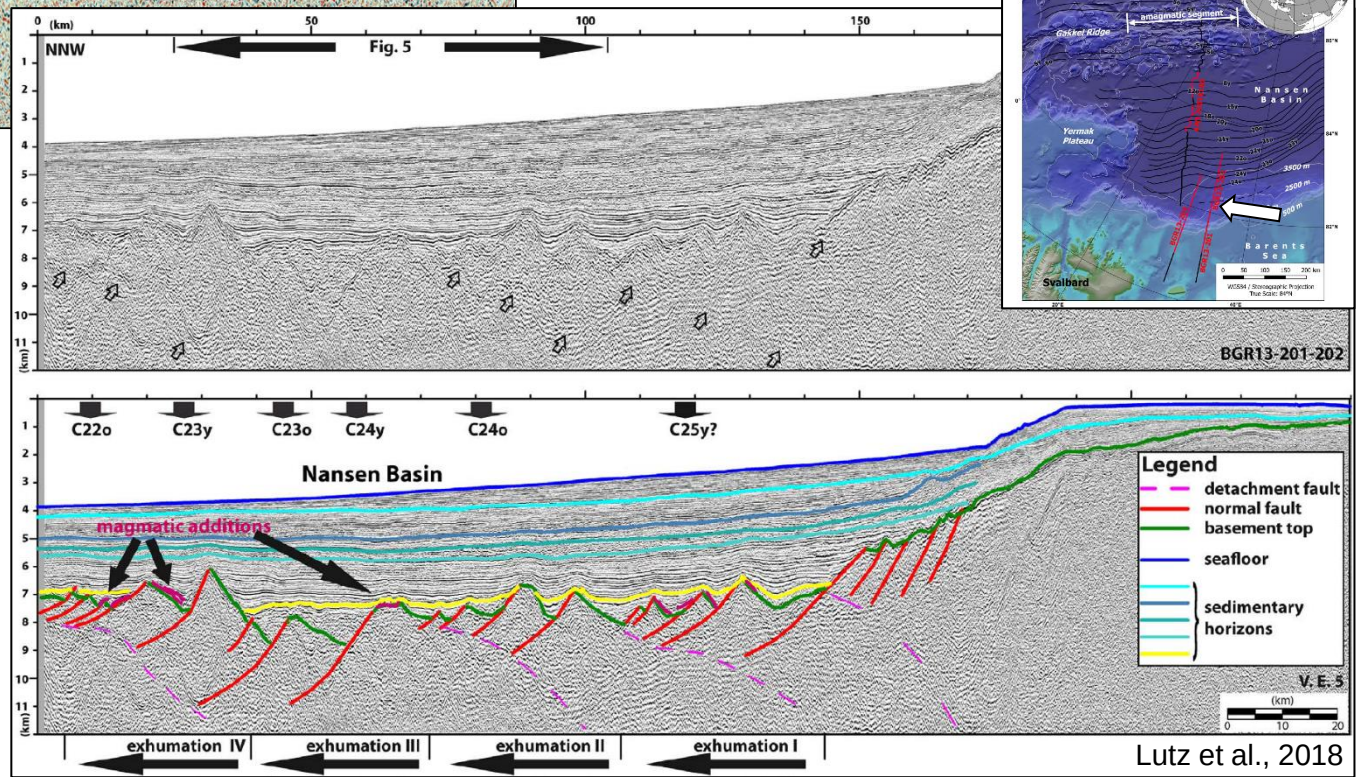


How do you get this high variability in crustal architecture?

Discussion
Analog to Deepwater Colombia?



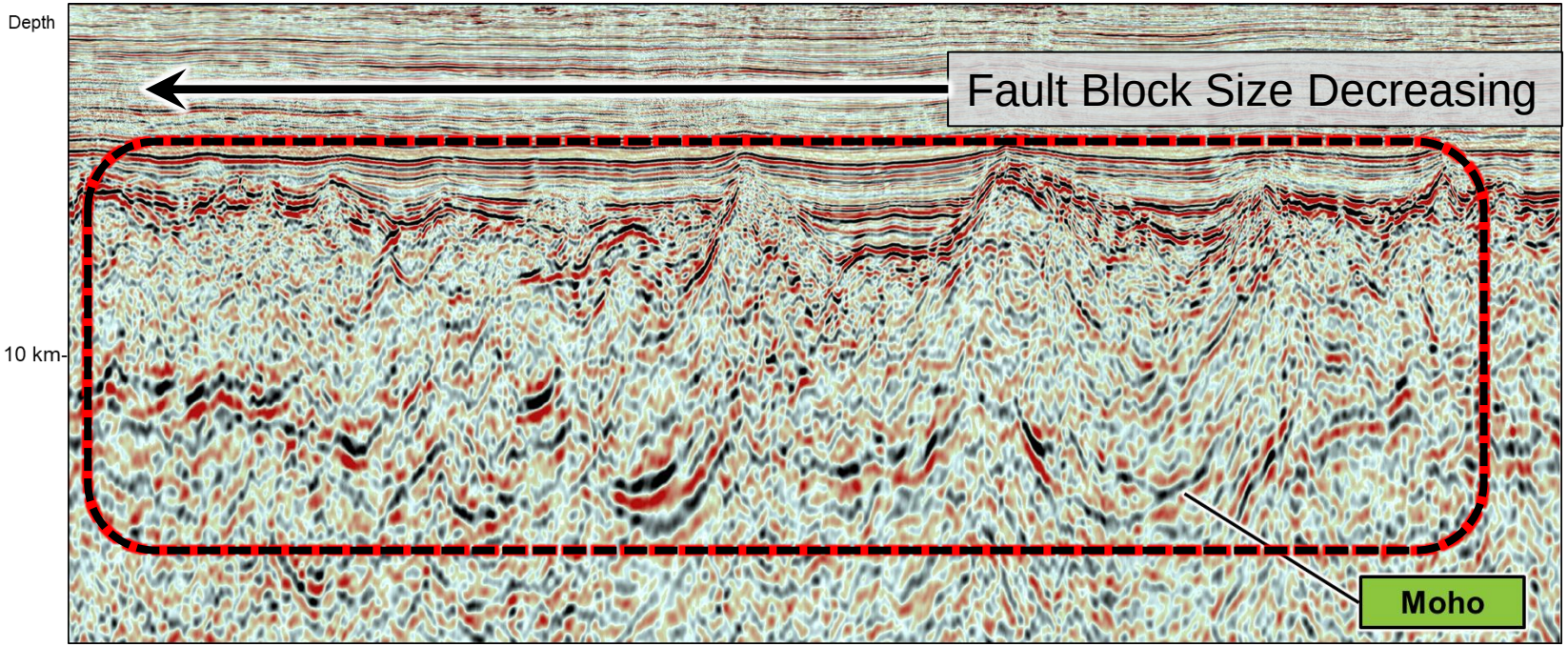


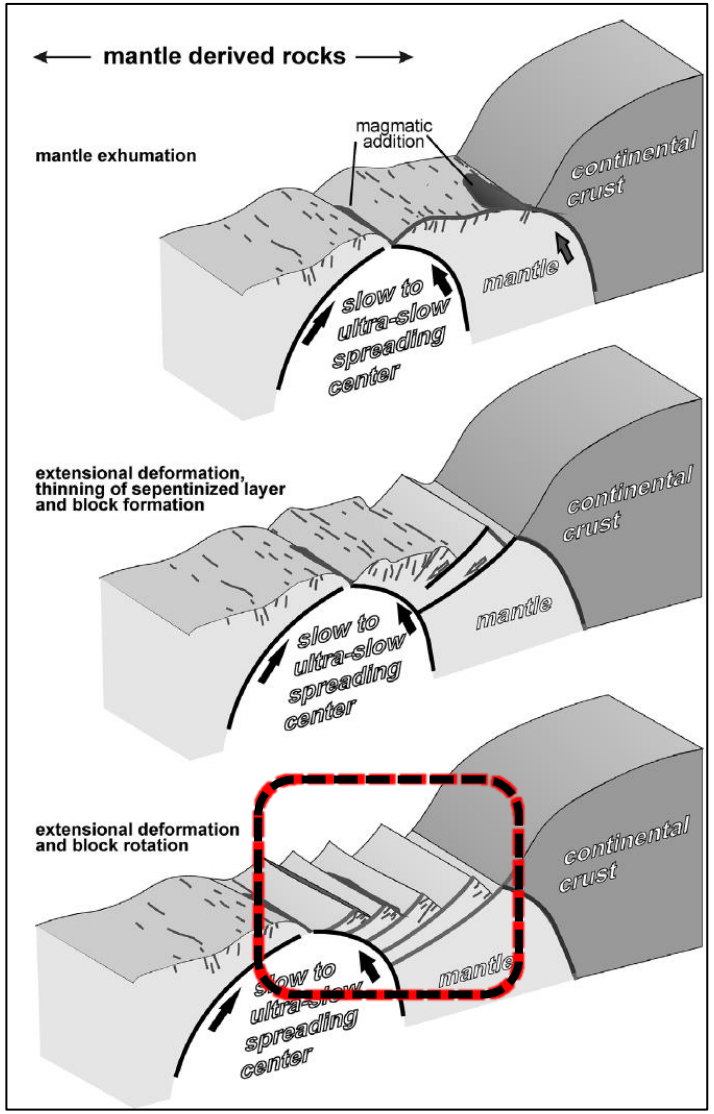


- Nansen Basin (Barents Sea)
  - Gakkel Spreading Ridge
    - Ultra-Slow spreading ridge (~2cm/year….same as CLIP plate motion)
    - Amagmatic
    - Dredged samples indicate serpentinized peridotites at seafloor
    - Magnetization is weak
    - Seismic character is analogous to Colombia Deepwater

Lutz et al., 2018

Discussion
Mantle Exhumation via Detachment Style Seafloor Spreading





- Large rotated blocks, bounded by listric faults (prev slide)
- Repeated, gradual decreasing size of fault blocks

Lutz et al., 2018

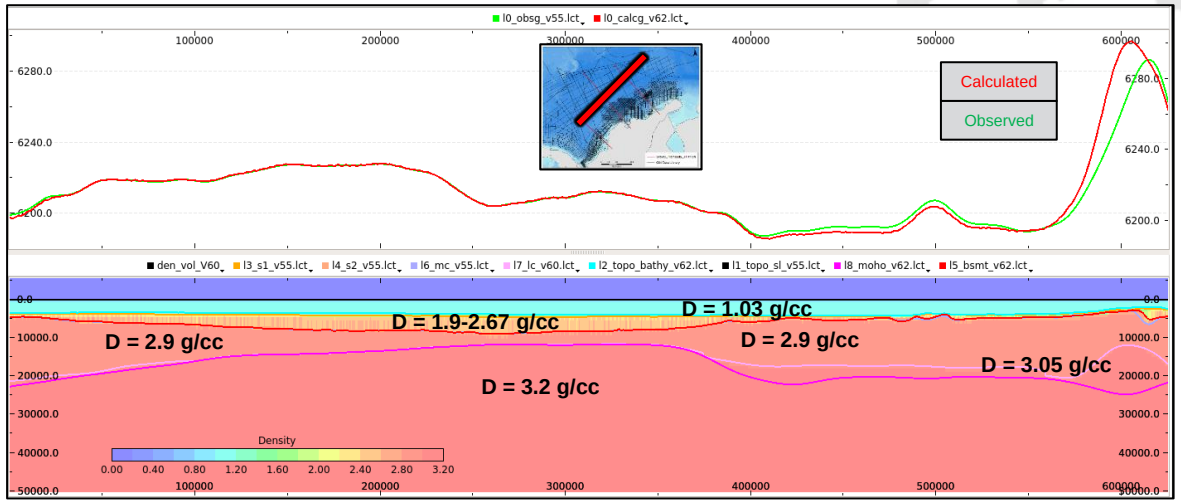
Discussion
Gravity Model Comparison

- Model layer densities
  - Calculated and Observed curves for both models match well
  - Deepwater Colombia Basin (A) and Nansen Basin (B) models are generally in agreement for applied layer densities
  - Nansen Basin data includes serpentinzed peridotite samples to further constrain the model

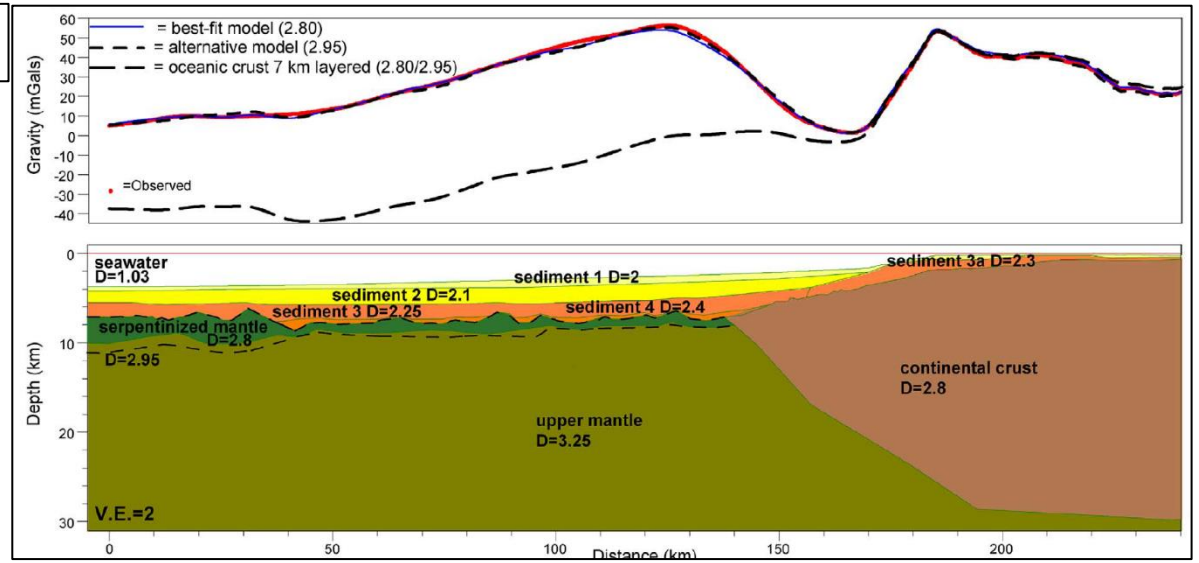
Gravity Model Densities

	Gakkel Ridge/Nansen Basin	Colombian Deepwater/CLIP	
Model Layer	Lutz et al., 2018	This Study	
Sea Water	1.03	1.03	g/cm^3
Sediments	2.1-2.4	1.9-2.67	
Oceanic Crust/CLIP	2.8	2.9	
Lower Crust	n/a	3.05	
Upper Mantle	3.25	3.2	

A

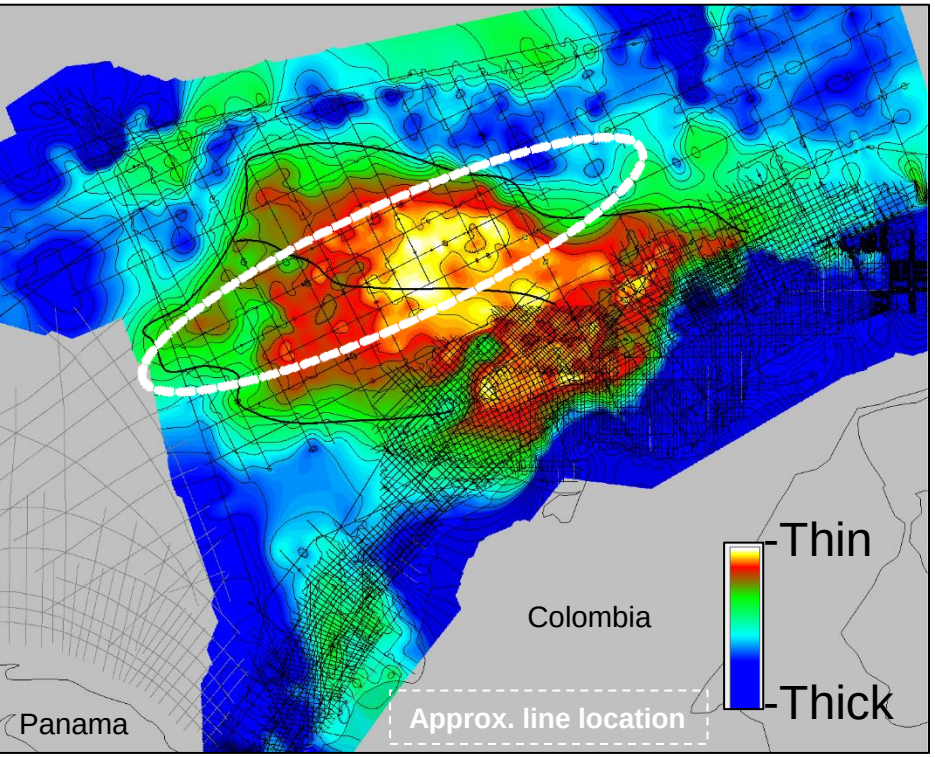


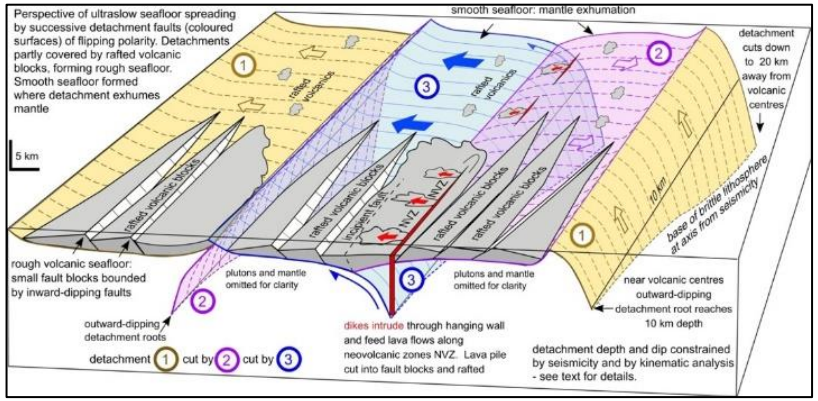
B



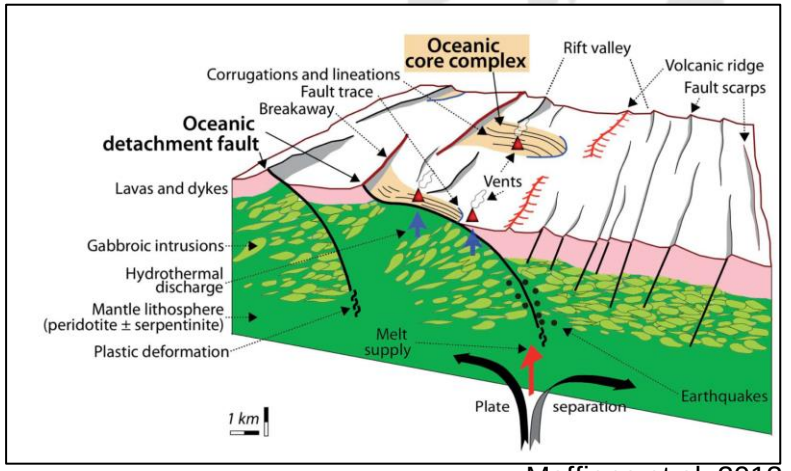
Lutz et al., 2018

Discussion
Asymmetry Derived from Detachment Style Spreading



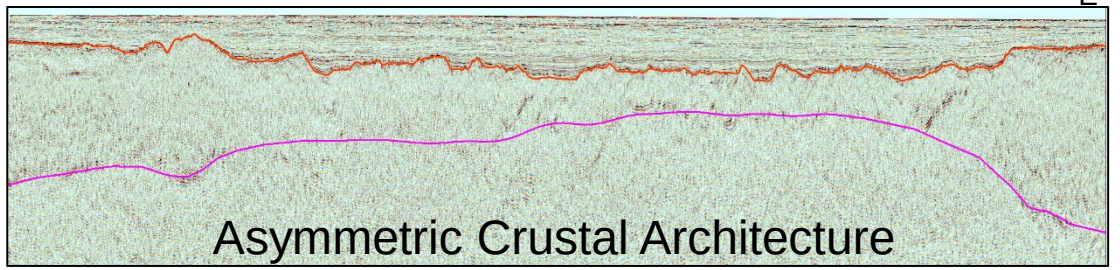


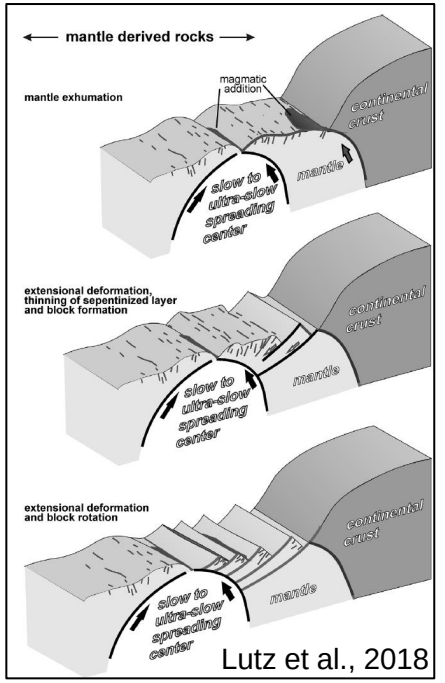
Reston., 2018



Maffione et al, 2013

W E



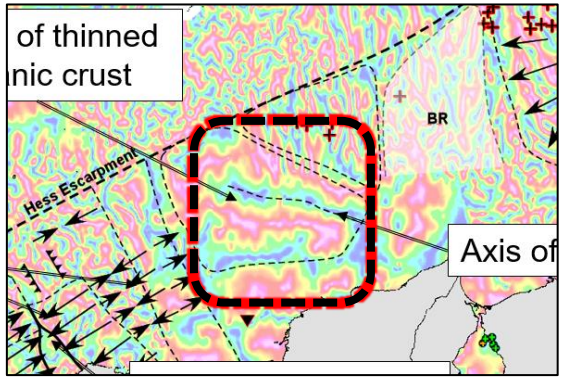


Lutz et al., 2018

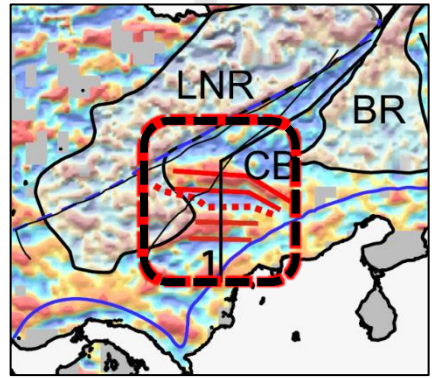
- Detachment style spreading (aka – “Chapman Detachment-Mode”)
  - Creates asymmetrical conjugates
  - Total extension rate is primarily attributed to the large detachment surfaces

Discussion
Magnetic Signature of Exhumed Mantle

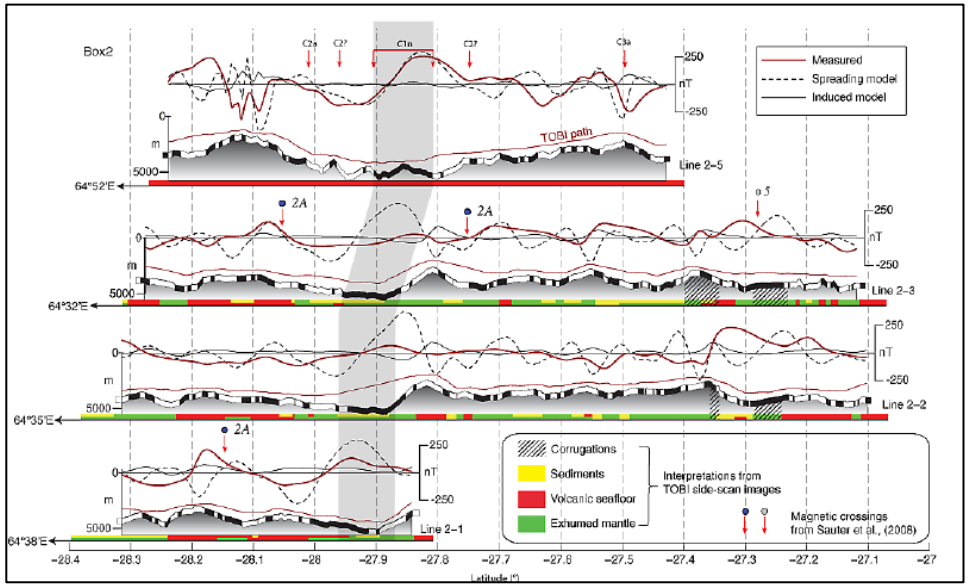
- Lack of Magnetic Signature
  - Why do the magnetic data not show evidence anomalies in the area of exhumed mantle?
- Bronner et al., 2013
  - Southwest Indian Ridge (SWIR)
  - Dredge samples confirm the presence of mantle derived segments of the ocean floor.
  - Deeptow magnetic survey results:
    - Serpentinized peridotites lacked sufficient stable remnant magnetization to produce magnetic spreading anomalies in exhumed mantle domains.



Reuber et al., 2019

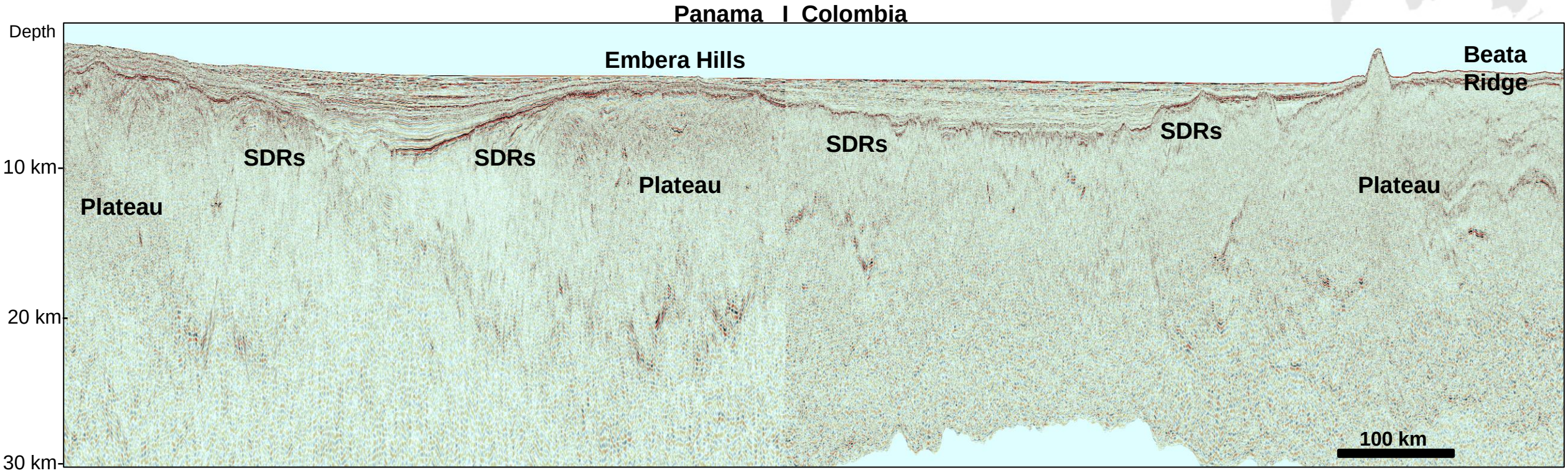


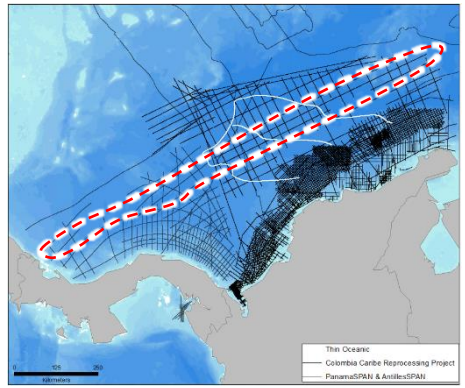
Garcia-Reyes and Dyment, 2021



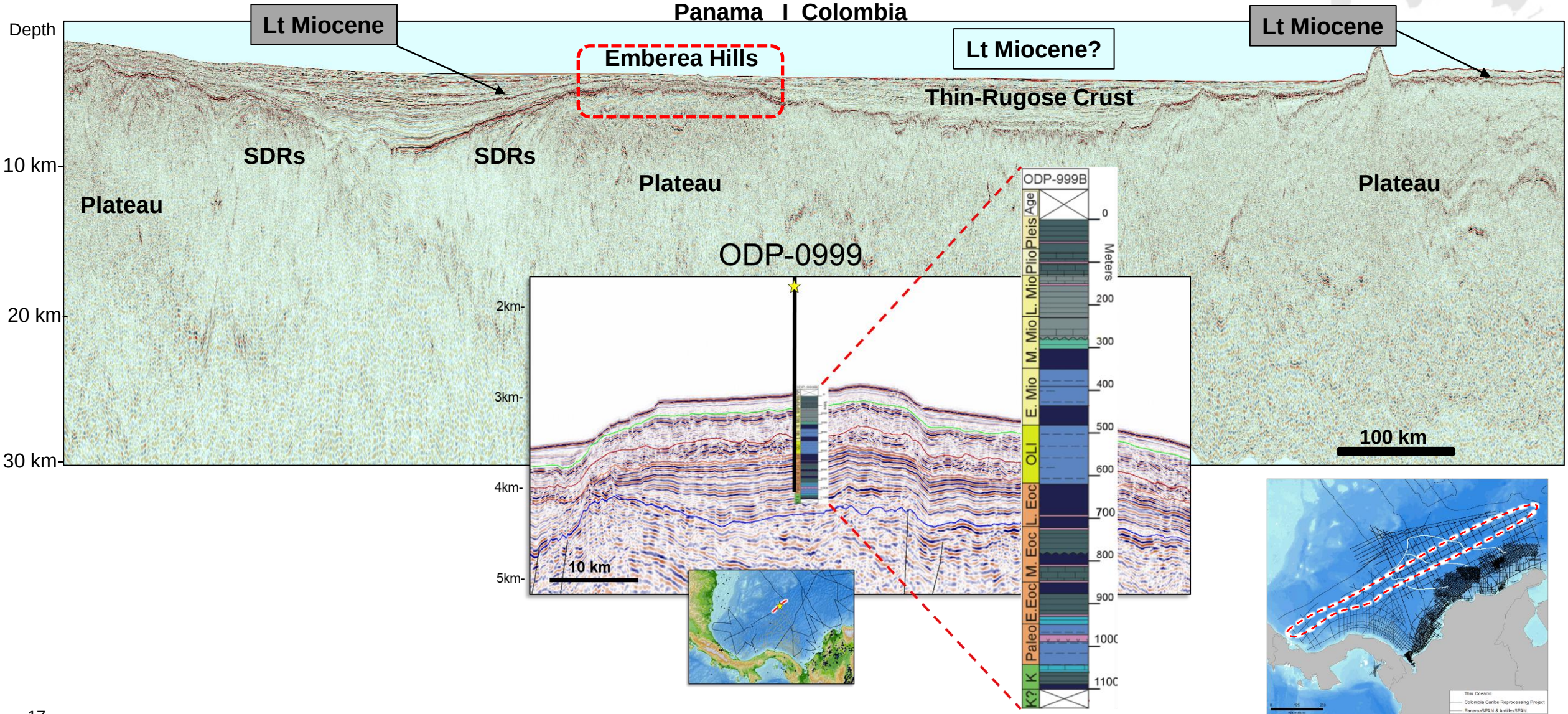
Bronner et al., 2013

Discussion
Age of Spreading

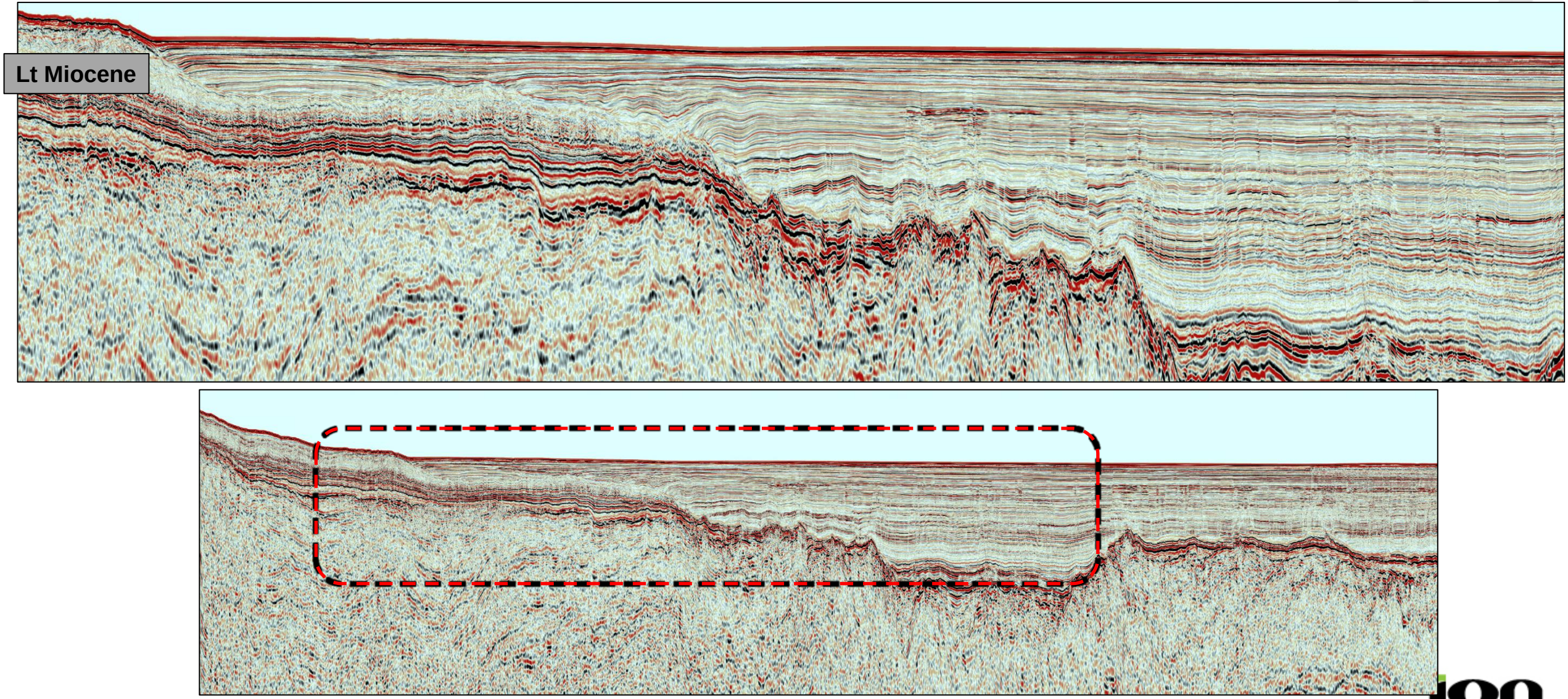




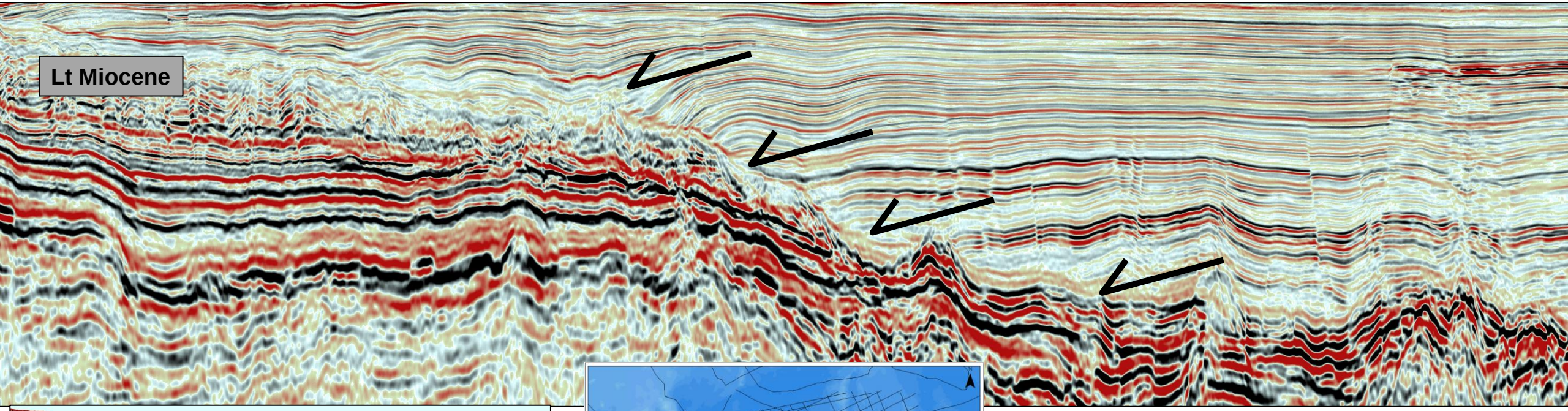
Discussion
Age of Spreading

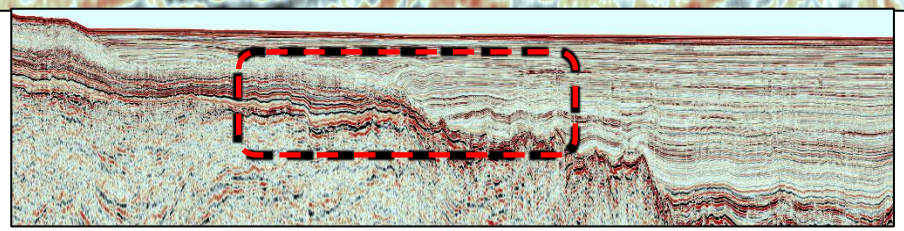


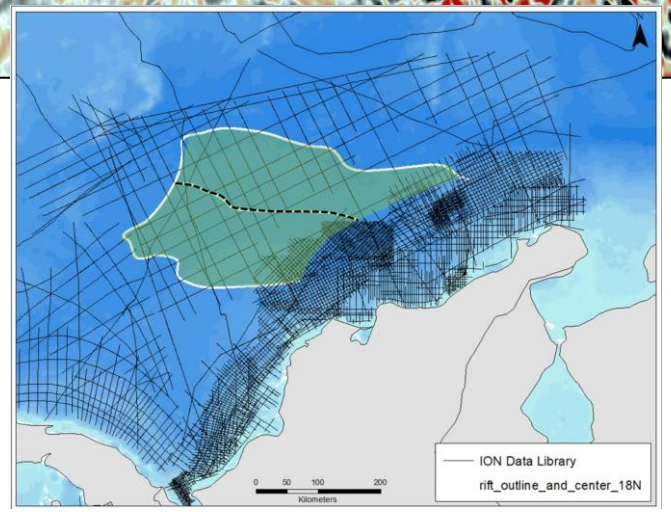
Discussion
Age of Spreading



Discussion
Age of Spreading

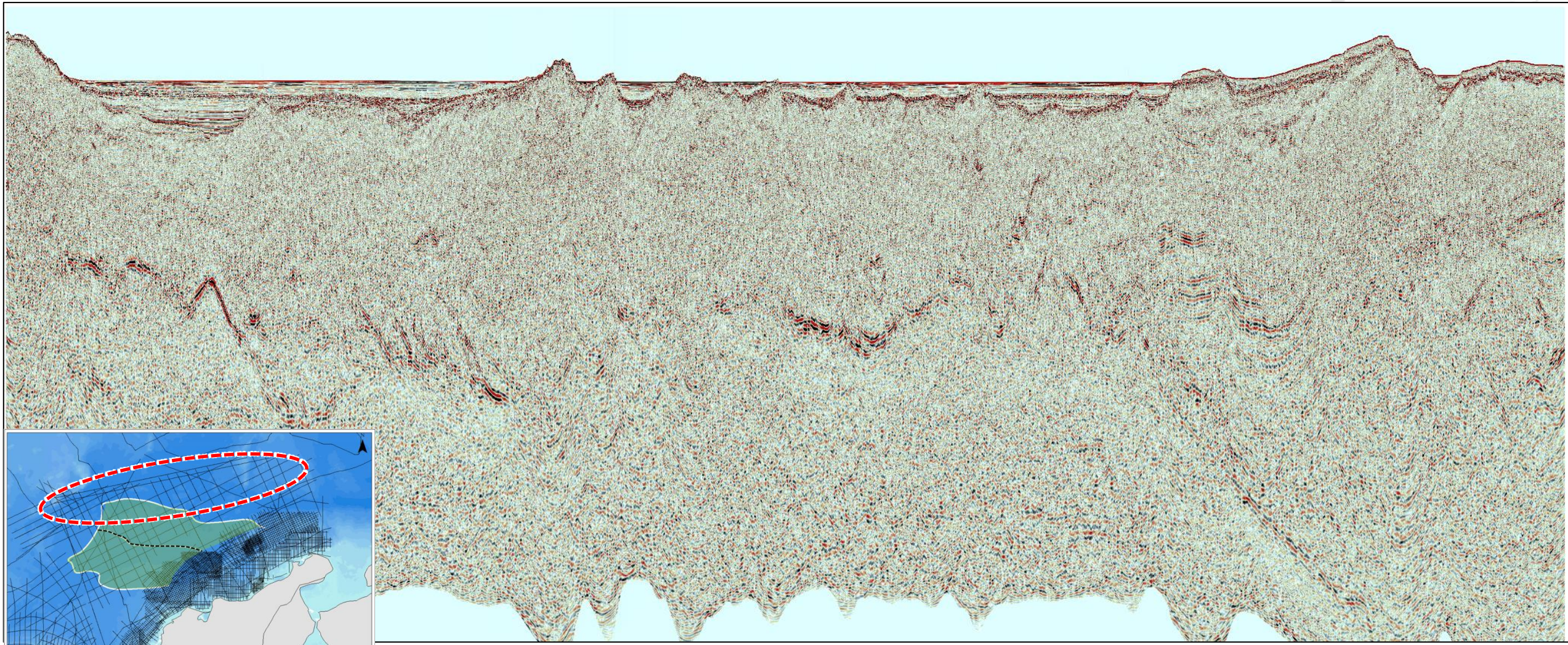






- Yellow area is Absent of Lt Miocene – older units
- …..Still fitting it into the regional context.

Discussion
How do you add ~80,000 sqkm inside a “rigid” plate?



Discussion
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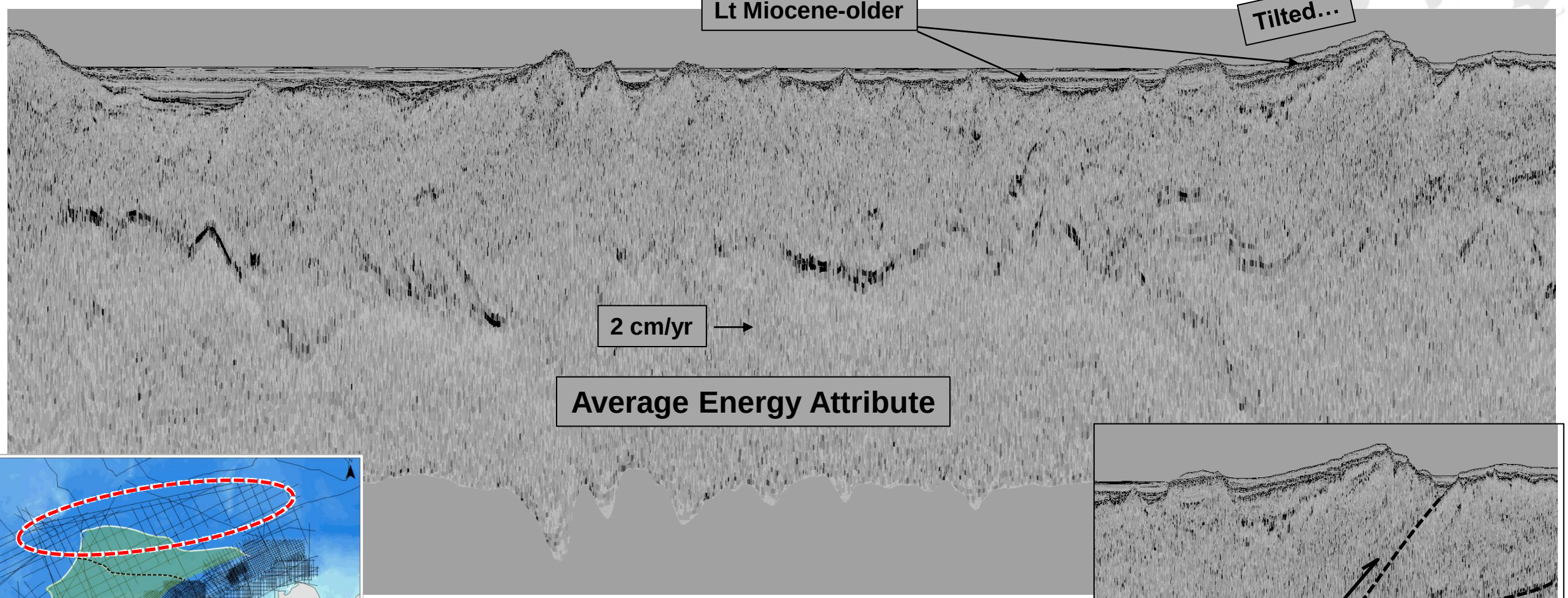
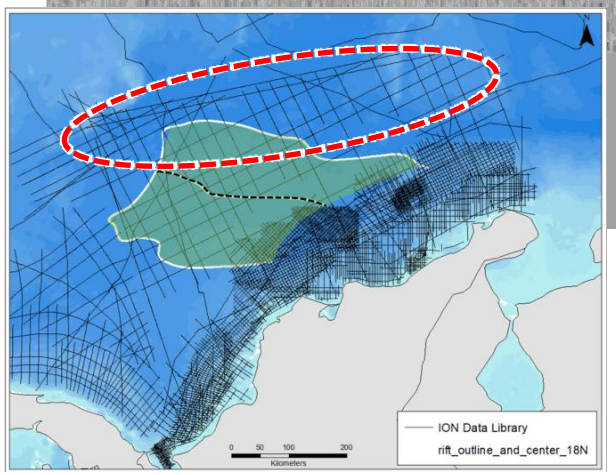
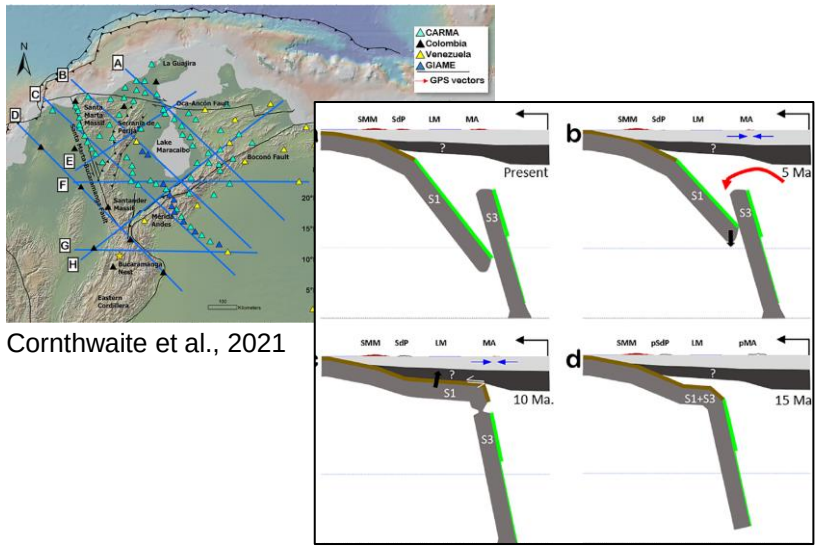




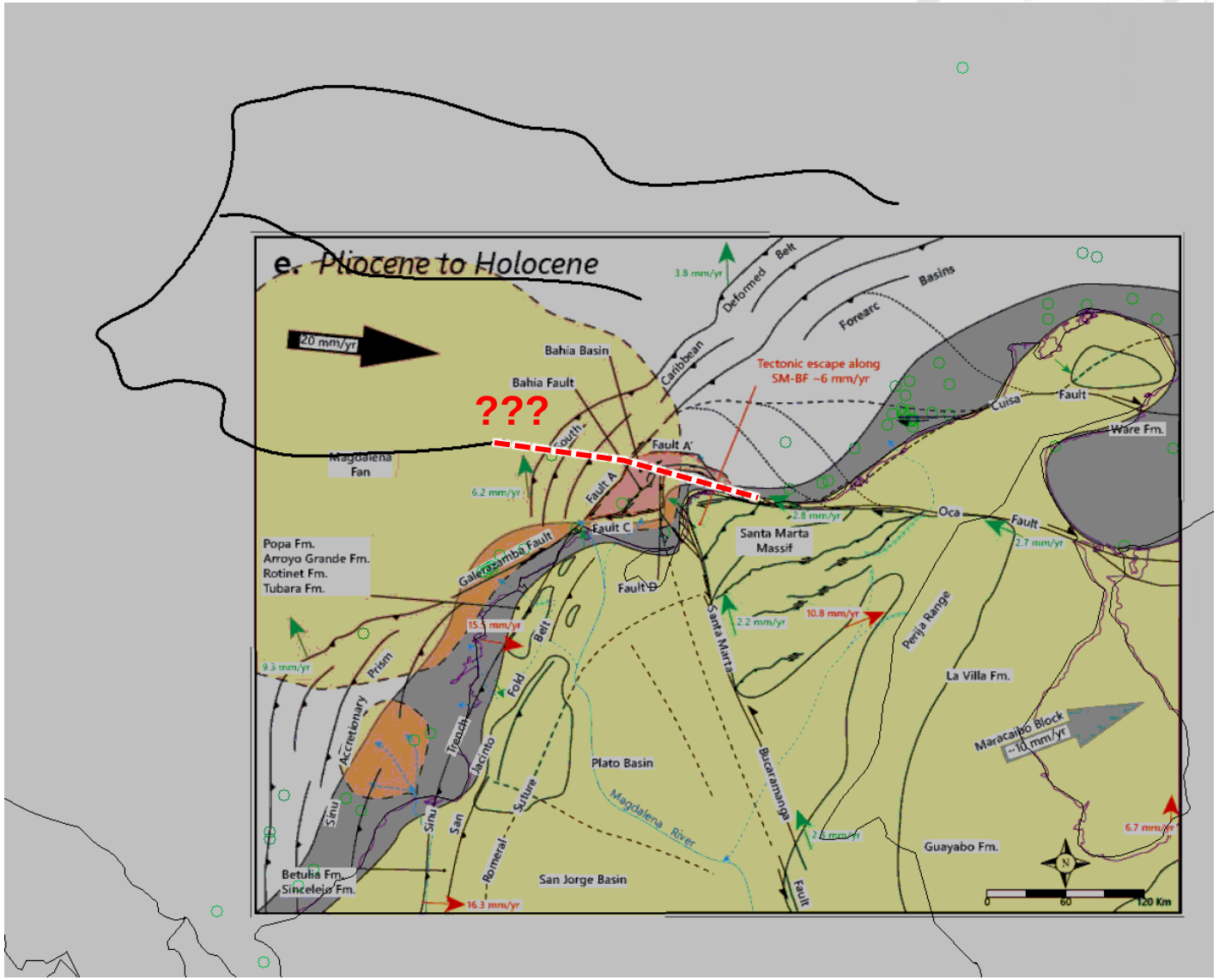
Post-Miocene shortening at the Beata Ridge
~100 km – “ish”

Discussion
How do you add ~80,000 sqkm inside a “rigid” plate?



Cornthwaite et al., 2021

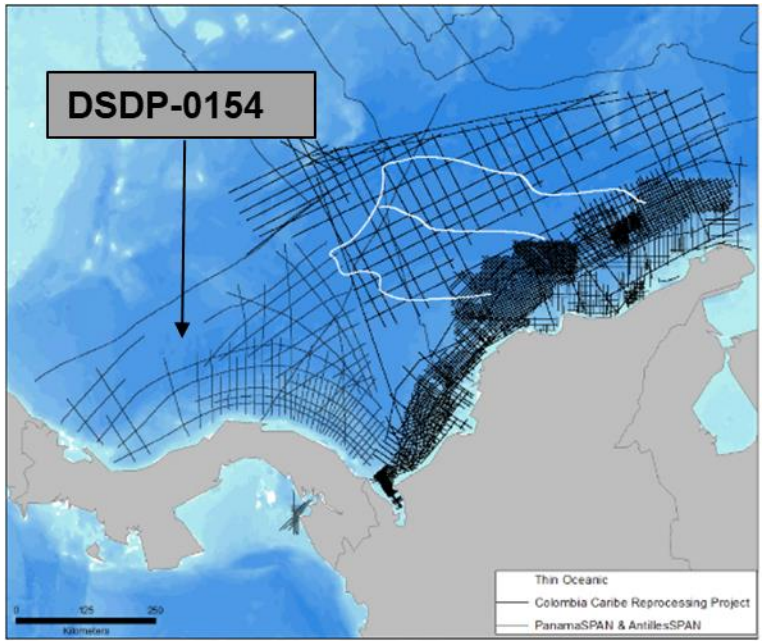
- Cornthwaite
  - Cites location of tear in subducting slab at a weak point in CLIP (east of Santa Marta)
    - Aligns with SW limit of thin oceanic crust (Timing: Coeval)
- Also in position where angle of subduction changes to oblique (w.r.t.- S Am Plate)
- Southwestern limit of thin crust appears to align with the Oca Fault (onshore, South American Plate….)



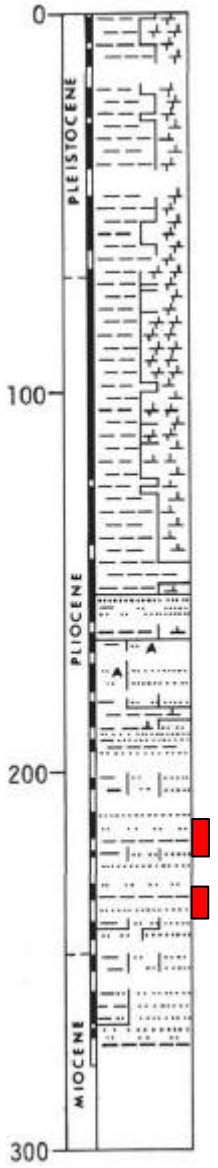
Modified from Galindo and Lonergan, 2020

Impact on Prospectivity?

- Site 154
  - Spot cored to 164 meters and continuously cored to 277 meters. The presence of hydrocarbons, the abundance of coarse sand, and the discovery of a very high sedimentation rate all forced the decision to abandon the hole.
- Offset hole 154A
  - Cored continuously from the surface to 172 meters
  - High TOC intervals in Early Pliocene units.



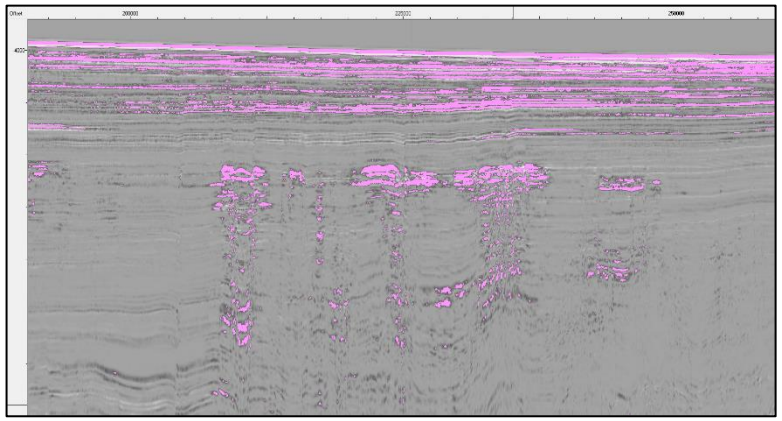
From Initial Rpts. DSDP Leg 15 (1973)

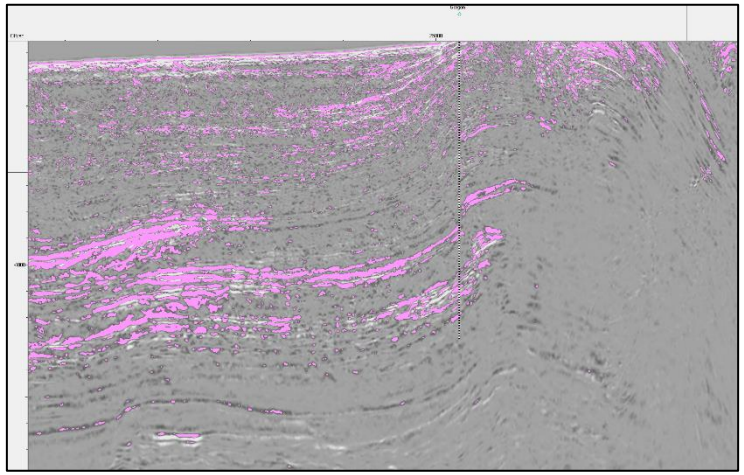


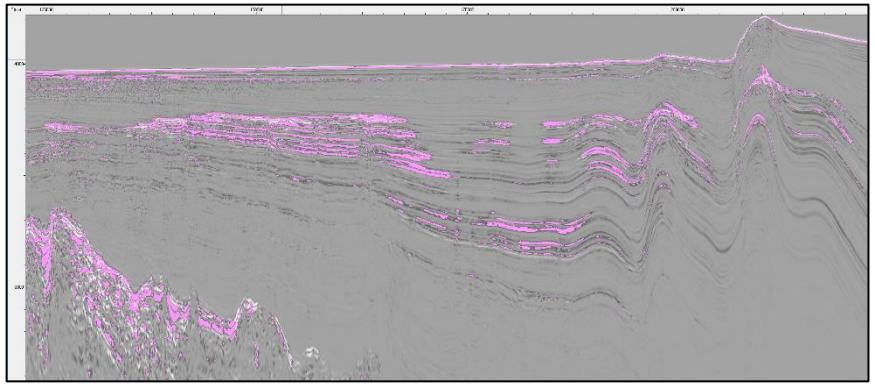
Core, Section Top of Interval (cm)	Depth in Hole (m)	Carbon Total (%)	Organic Carbon (%)	$CaCO_3$ (%)
1-1, 74.00	52.74	2.5	0.2	20
1-2, 15.00	53.65	2.8	0.2	22
1-3, 74.00	55.74	4.2	0.1	34
1-4, 76.00	57.26	4.9	0.1	40
1-5, 133.00	59.33	4.8	0.2	38
1-6, 90.00	60.40	4.6	0.1	37
2-2, 109.00	110.59	3.9	0.2	31
2-3, 58.00	111.58	4.3	0.0	36
2-5, 62.00	114.62	4.4	0.2	35
2-6, 18.50	115.69	4.4	0.2	35
2-7, 32.00	117.32	3.0	0.1	24
3-2, 4.00	165.54	2.3	0.3	17
3-3, 71.00	167.71	0.3	0.1	1
4-2, 96.00	175.46	0.1	0.0	1
4-3, 9.50	176.09	0.4	0.1	3
5-1, 5.00	182.05	1.6	0.3	11
5-2, 71.00	184.21	0.1	0.0	1
5-3, 21.00	185.21	1.5	0.2	11
5-6, 79.00	190.29	0.1	0.0	0
6-1, 18.00	192.18	0.6	0.3	2
8-1, 71.50	211.71	2.8	1.8	8
8-2, 111.00	213.61	1.4	0.9	4
8-3, 30.50	214.30	2.0	1.3	6
8-4, 120.00	216.70	1.1	0.6	4
8-5, 110.00	218.10	1.5	1.0	5
8-6, 136.00	219.86	3.1	2.7	3
9-1, 109.00	222.09	0.1	0.0	1
10-1, 142.00	231.42	0.4	0.2	2
10-2, 103.00	232.53	0.4	0.2	2
10-3, 20.00	233.20	5.4	3.5	16
11-1, 138.00	241.38	6.0	5.9	1
11-2, 88.00	242.38	0.1	0.0	0
11-3, 60.00	243.60	1.4	0.7	6
12-1, 75.00	249.75	0.6	0.2	3
12-2, 146.00	251.96	0.8	0.4	4
13-1, 124.00	259.24	2.6	1.5	9
13-3, 50.00	261.50	0.2	0.1	1
13-5, 127.00	265.27	0.2	0.1	1
13-6, 74.00	266.24	0.2	0.1	1
14-1, 50.00	268.50	0.1	0.0	0

AVO Gradient estimate

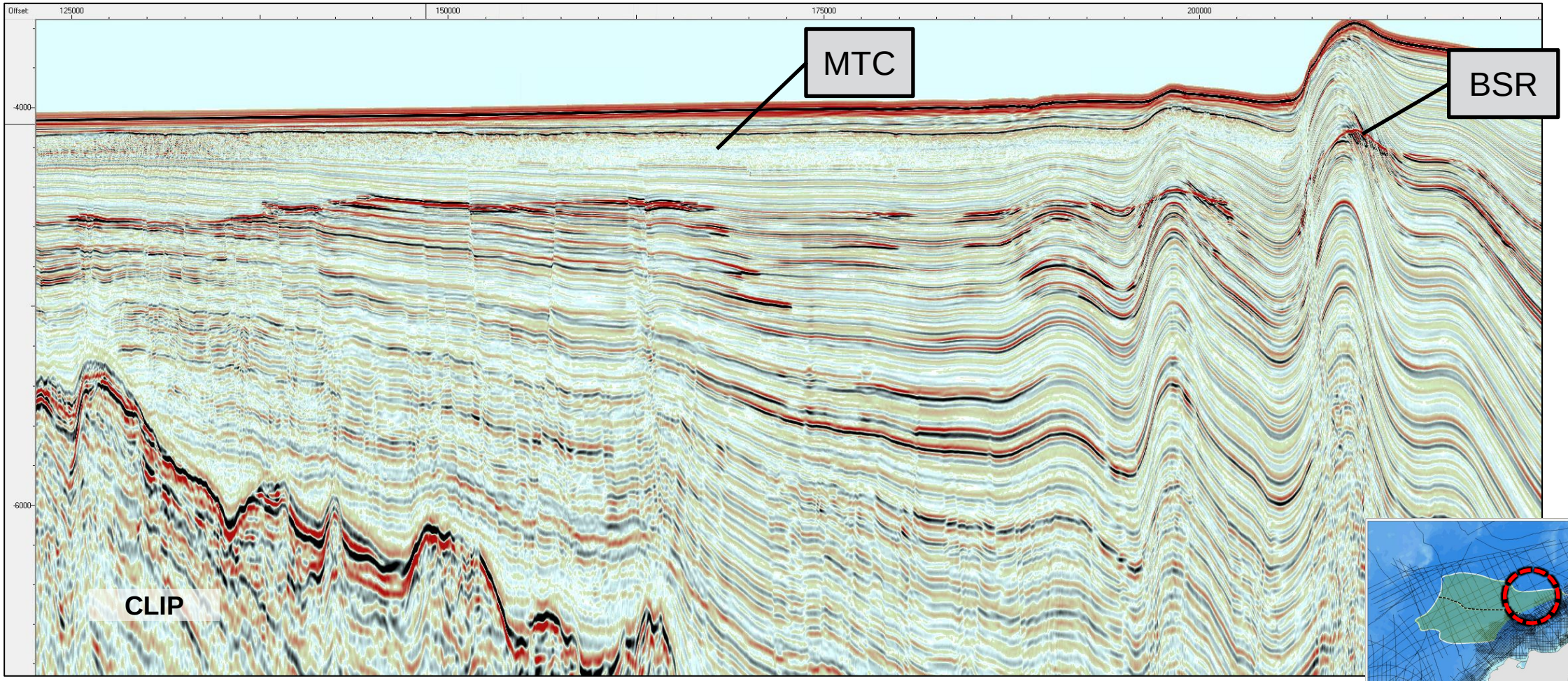
(Far stack – Near stack) * Far stack



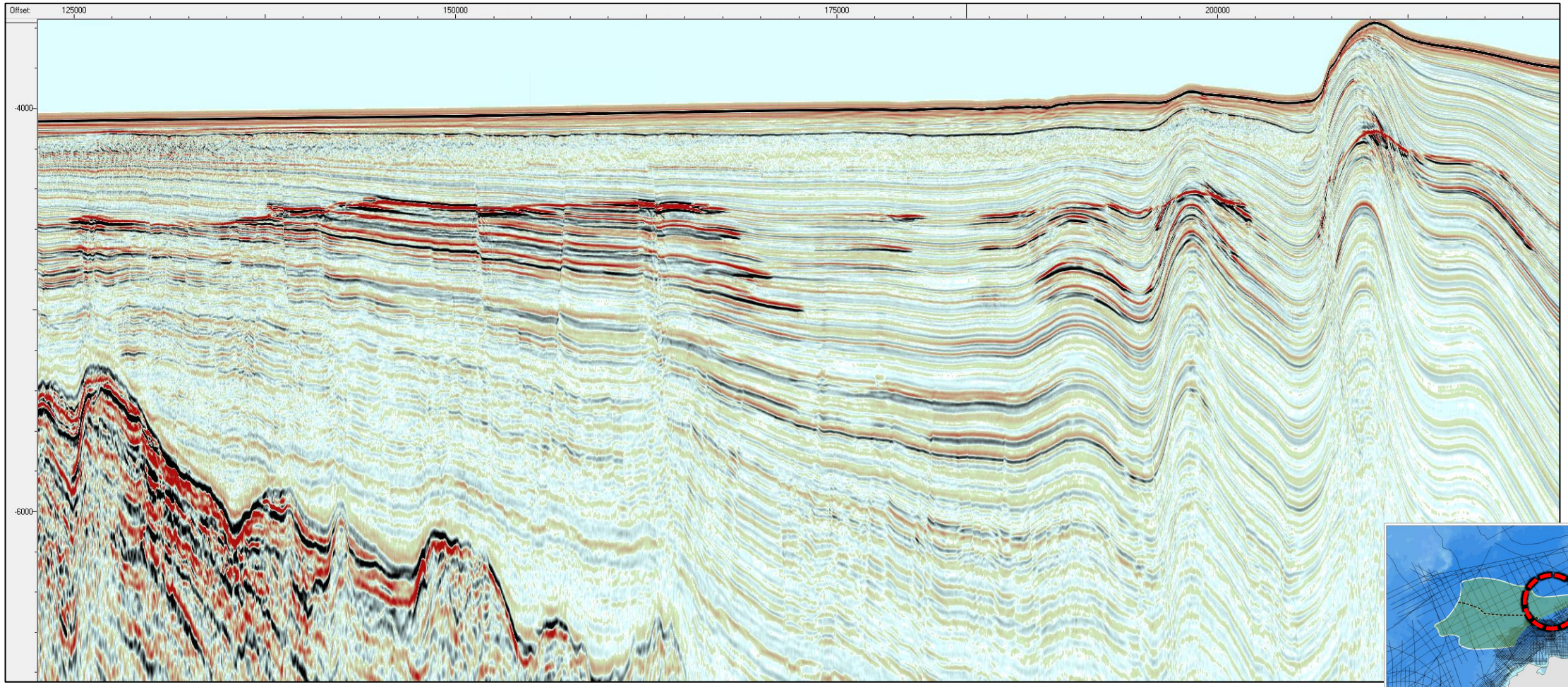


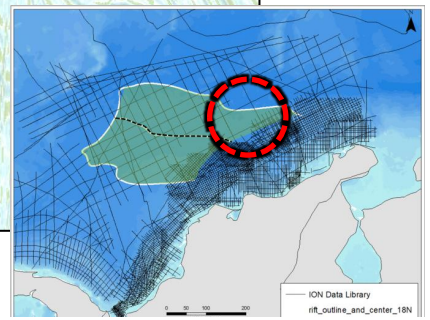


Esmerelda Area- PSDM

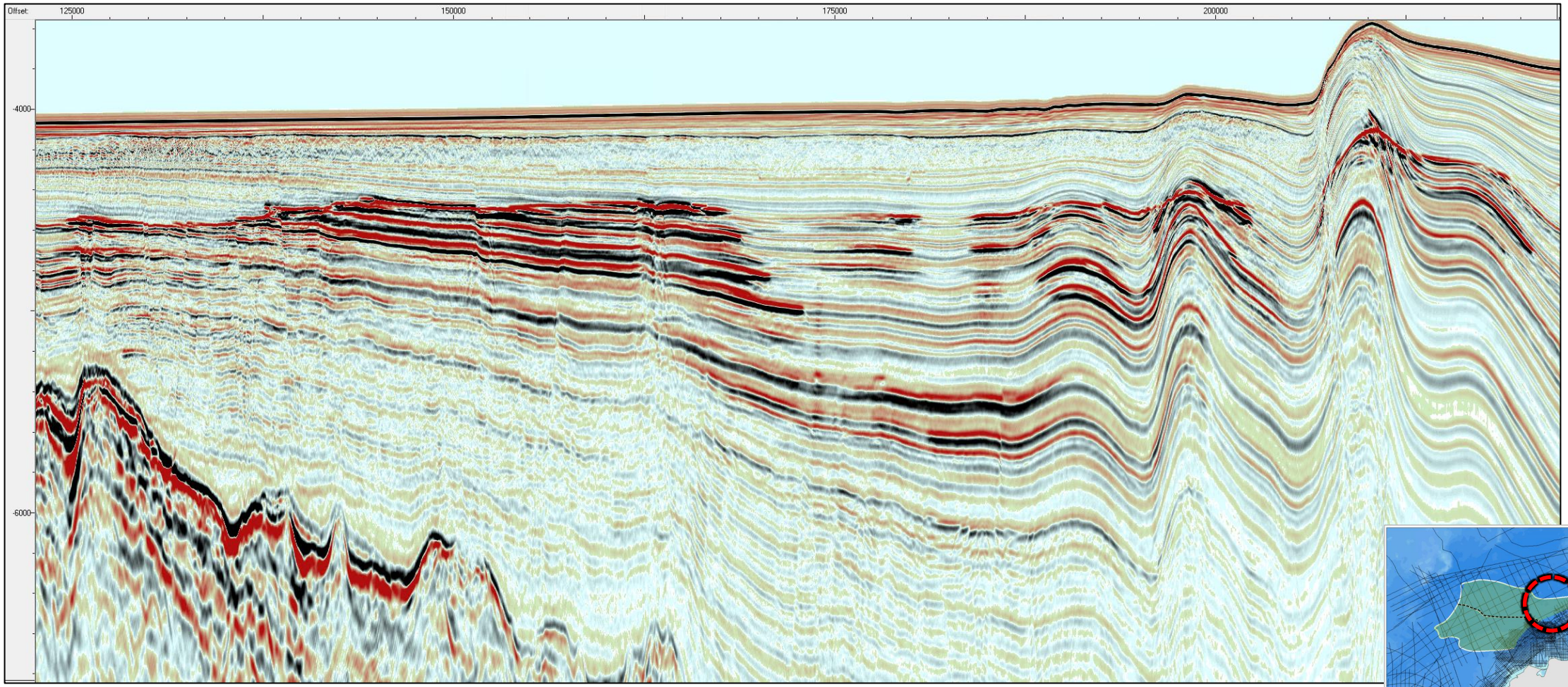


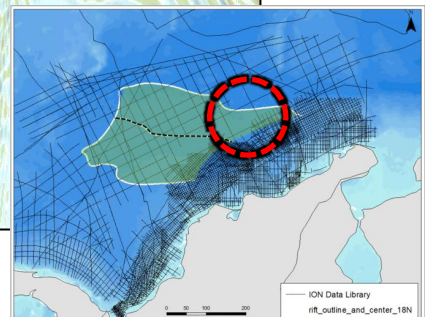
Esmerelda Area (Nears)



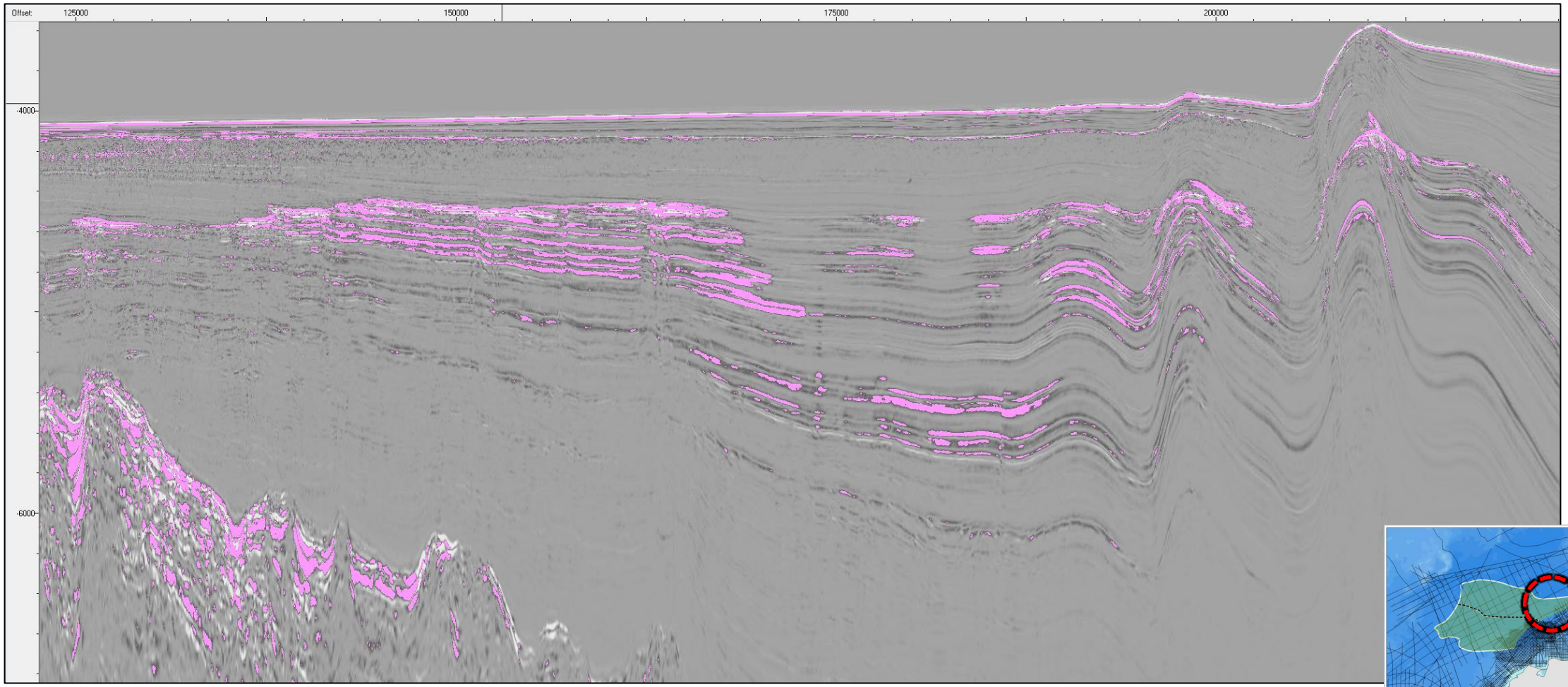


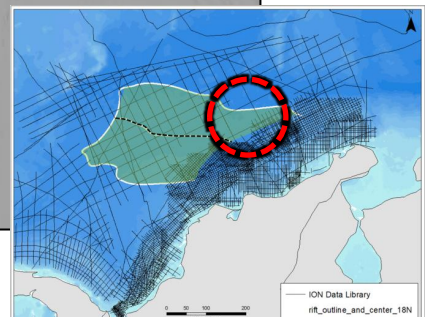
Esmerelda Area (Fars)



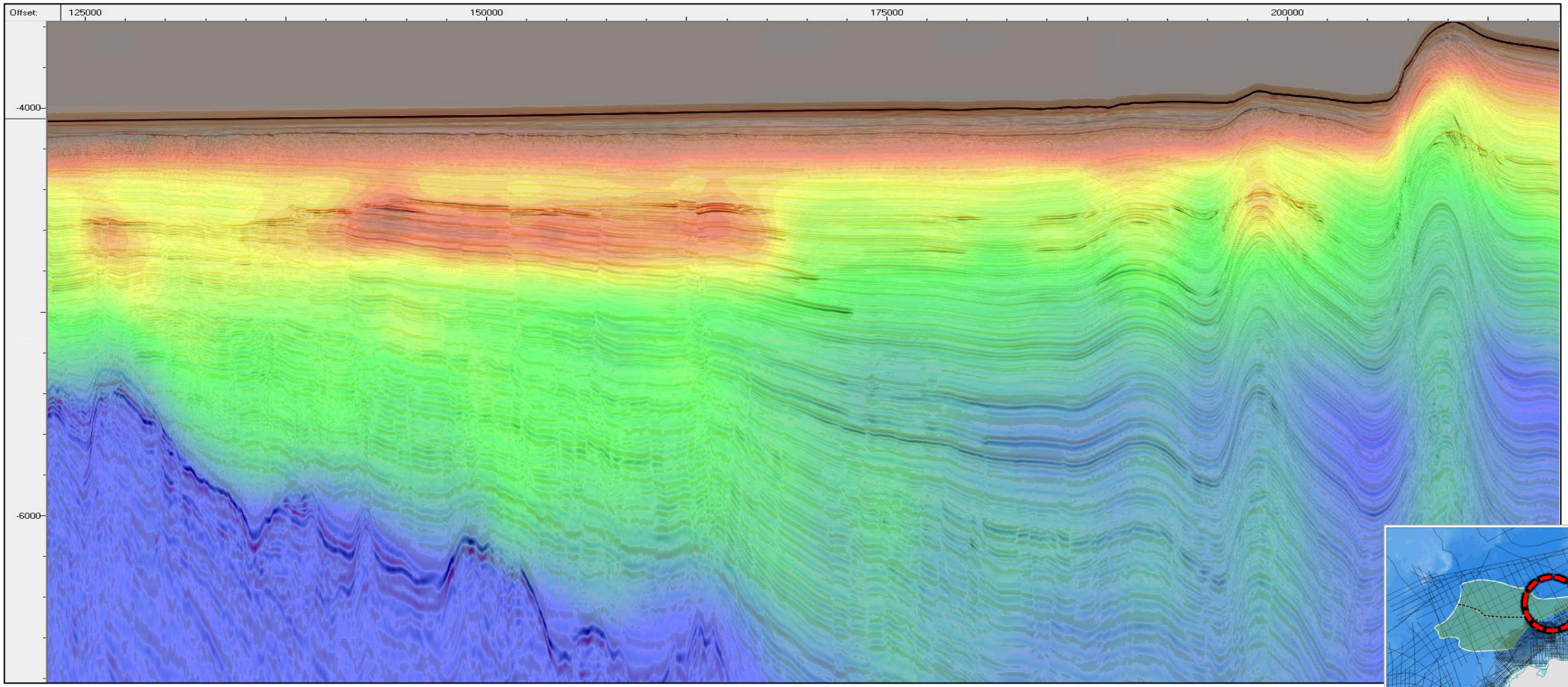


Esmerelda Area (AVO Attribute)

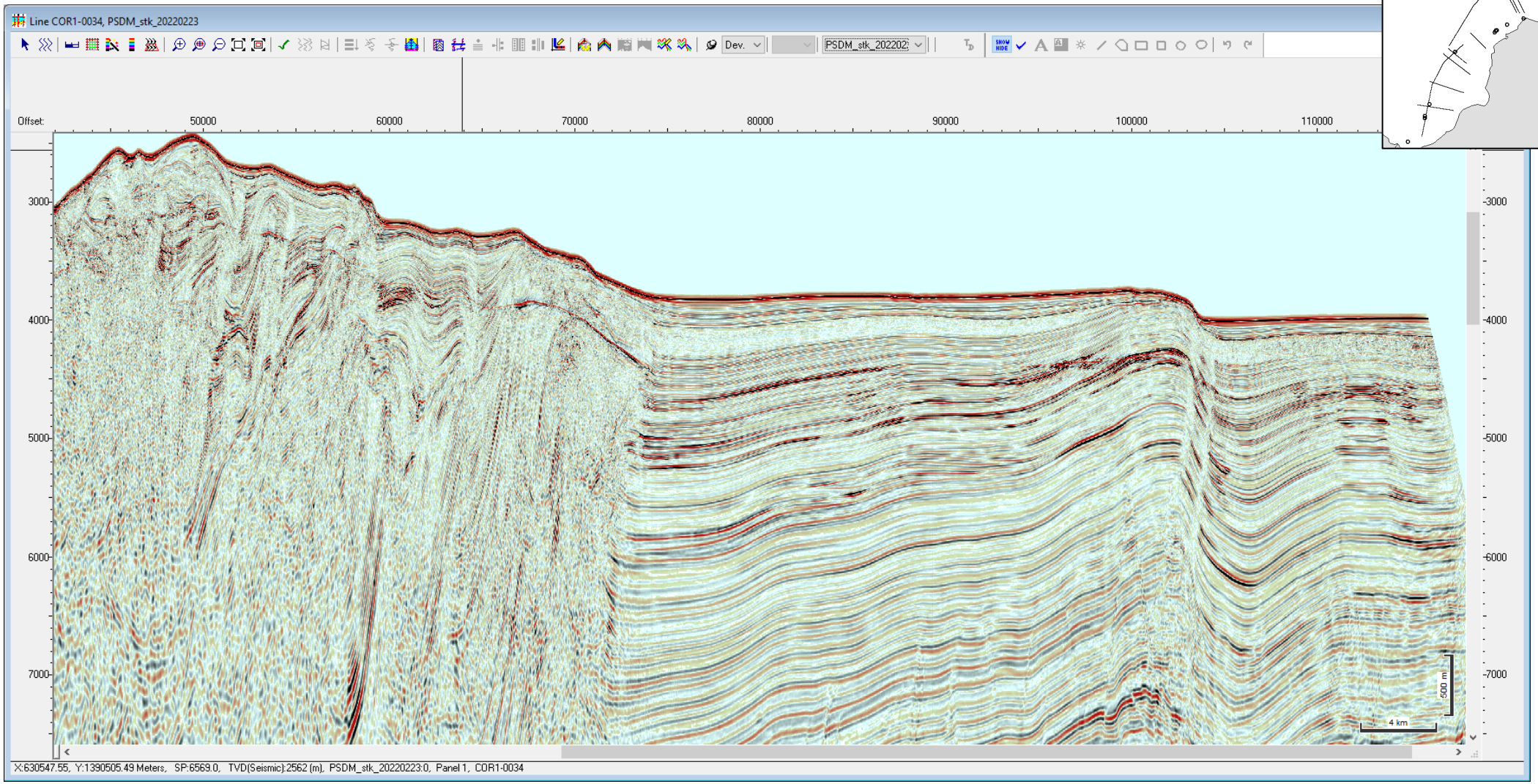


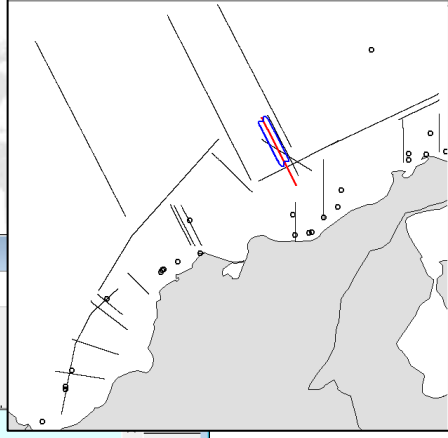


Esmerelda Area- PSDM Velocity

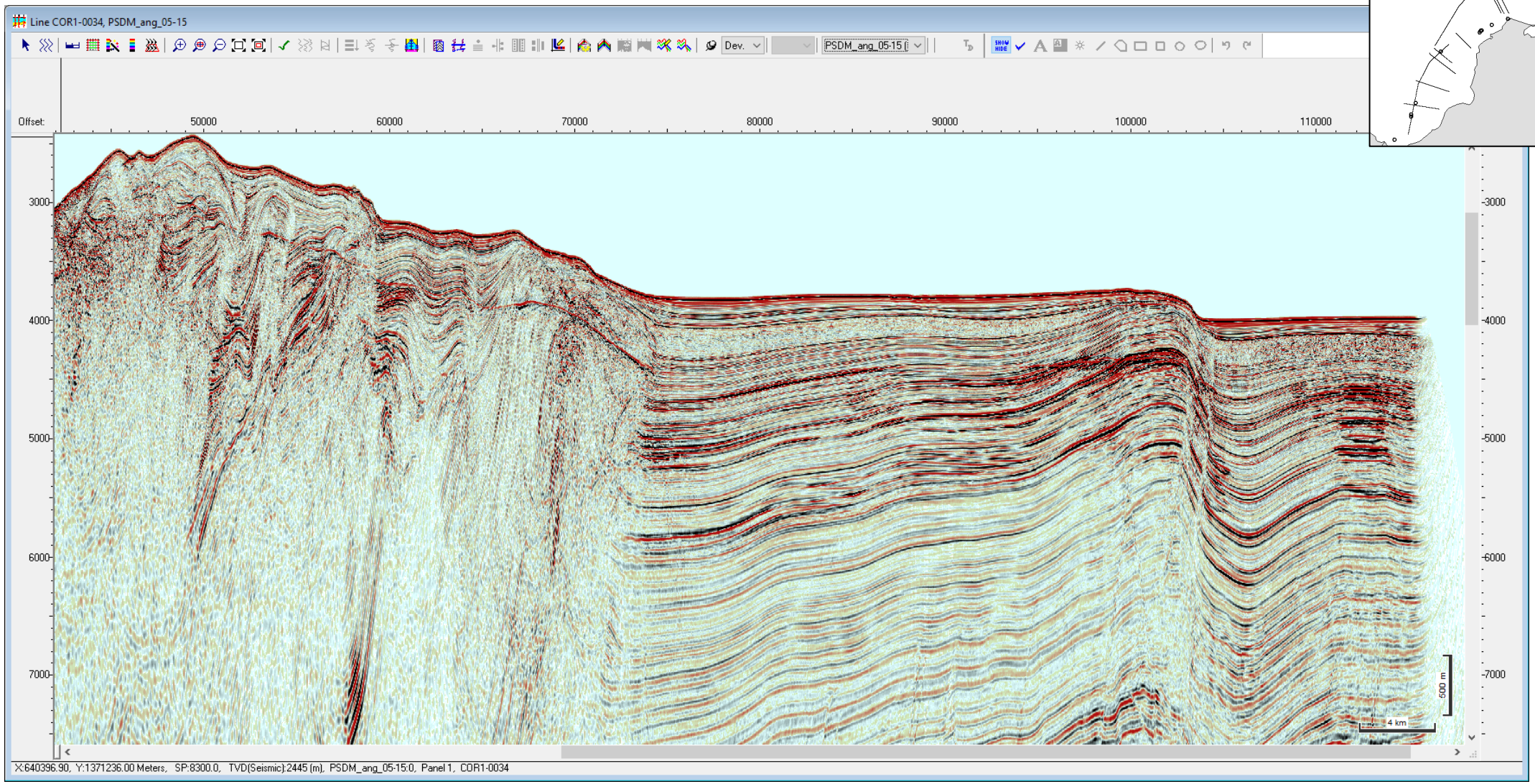


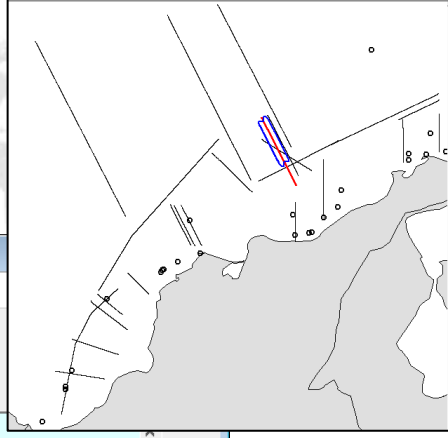
COR1-34 PSDM Stack



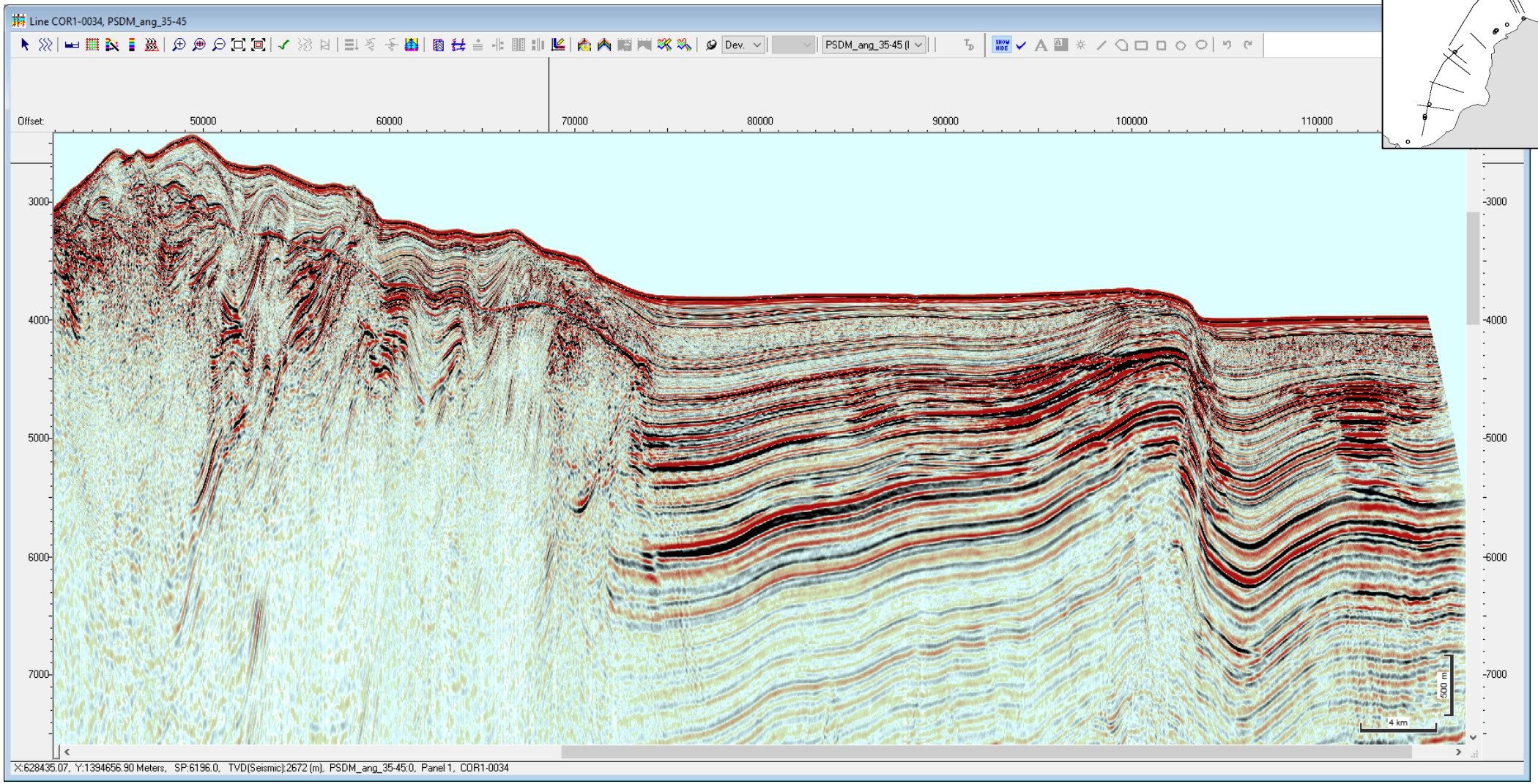


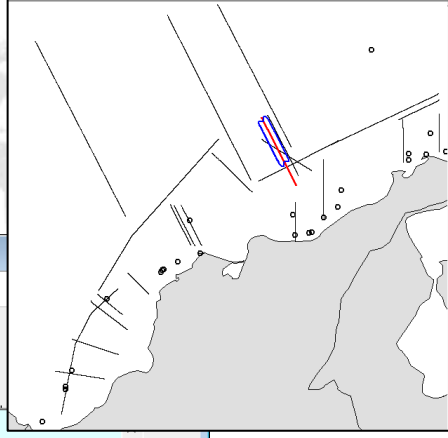
COR1-34 PSDM 5-15 Ang



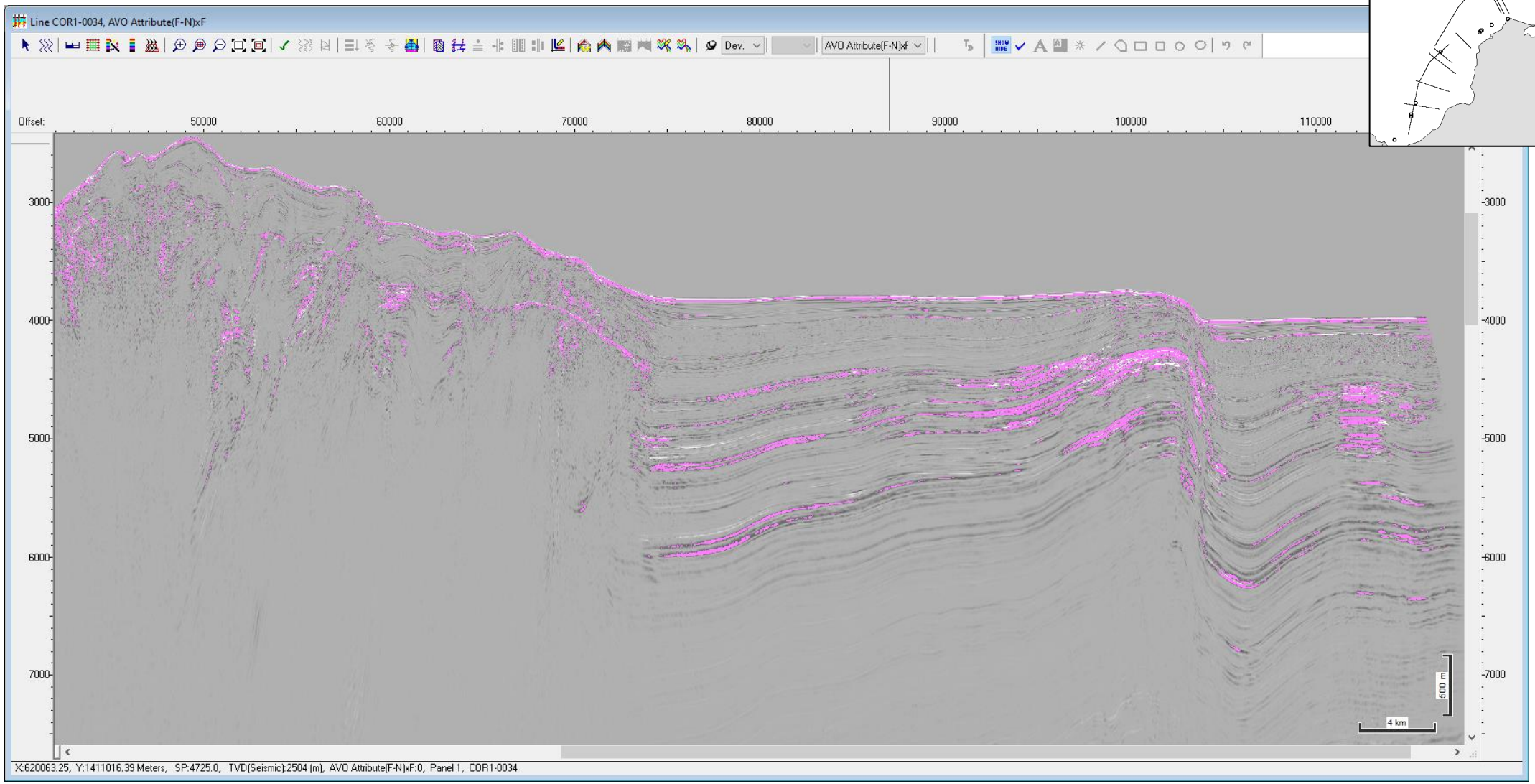


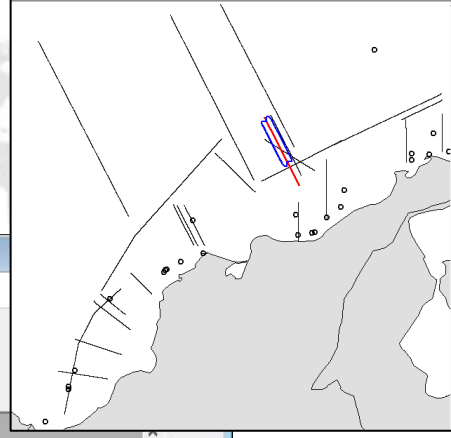
COR1-34 PSDM 35-45 Ang



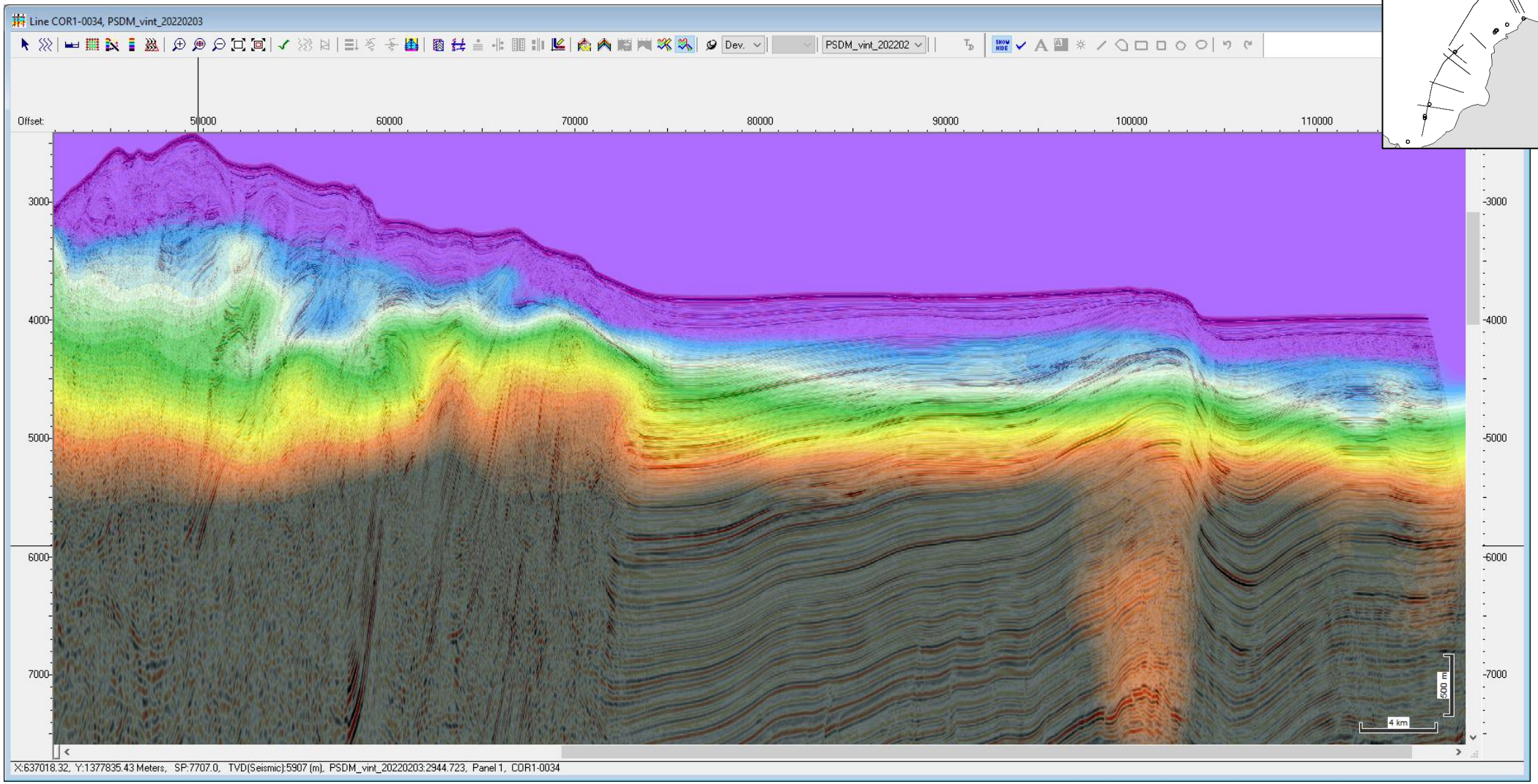


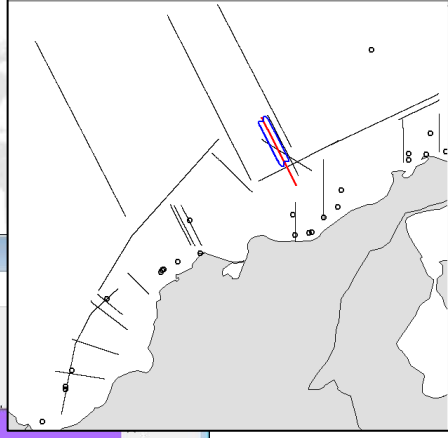
COR1-34 PSDM AVO Attribute

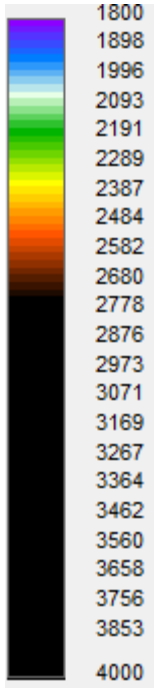




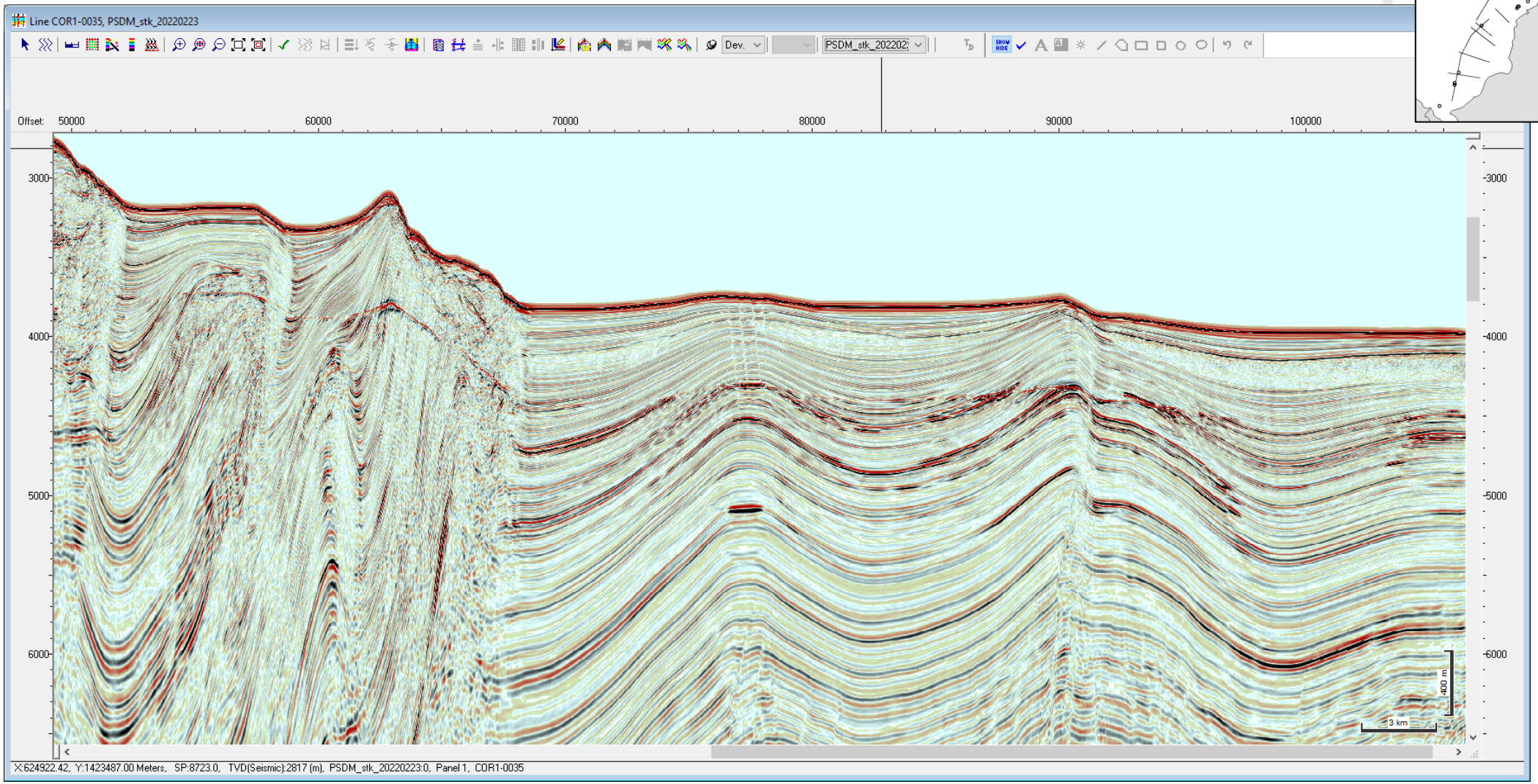
COR1-34 PSDM Velocity

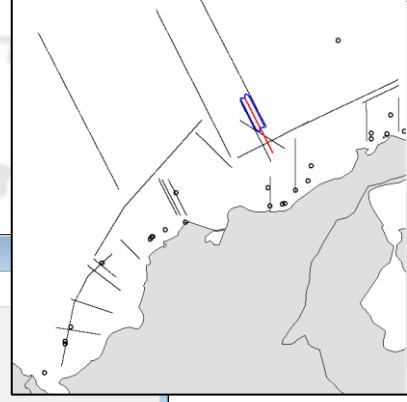




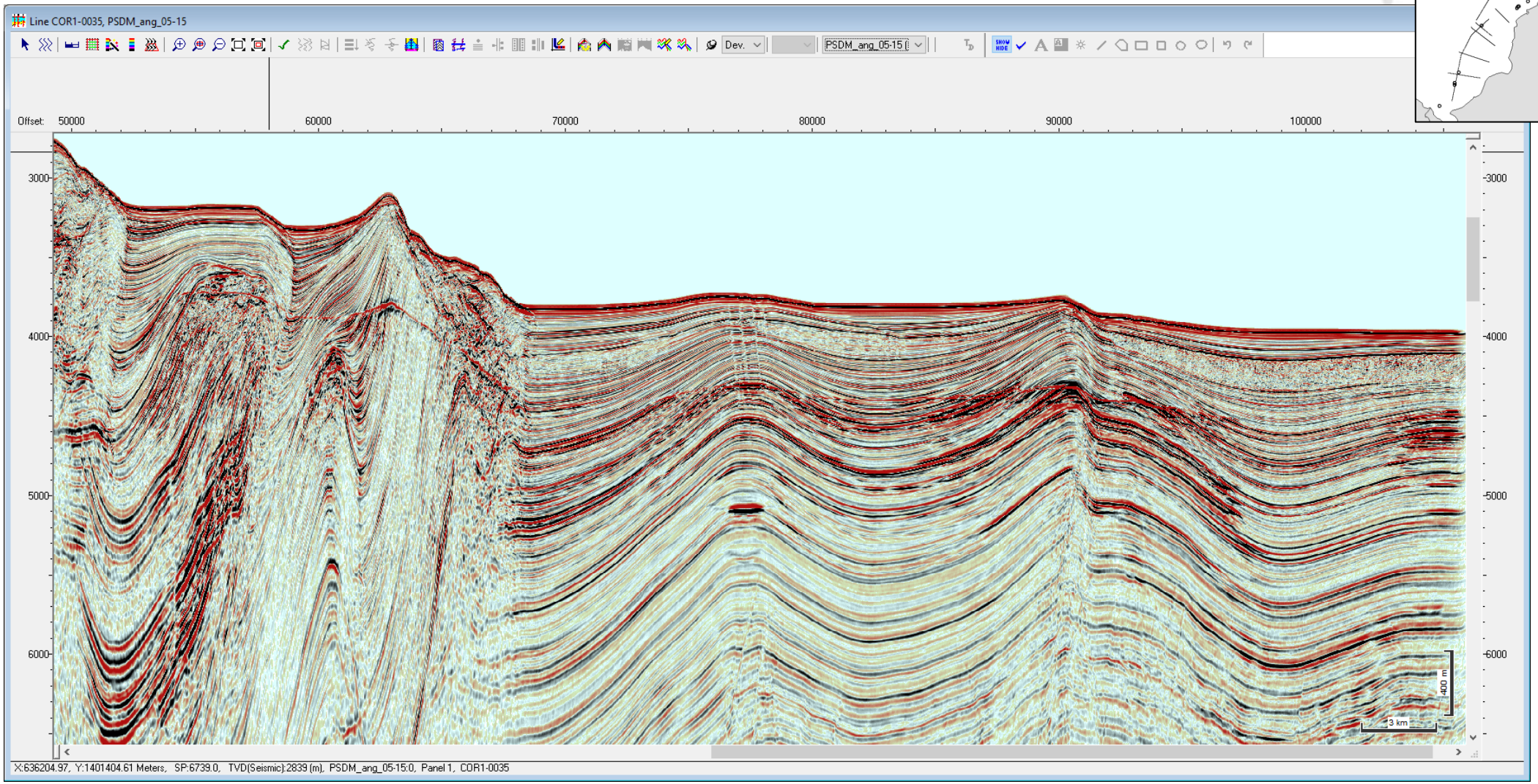


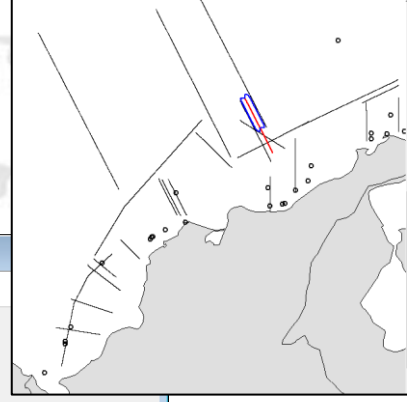
COR1-35 PSDM Stack



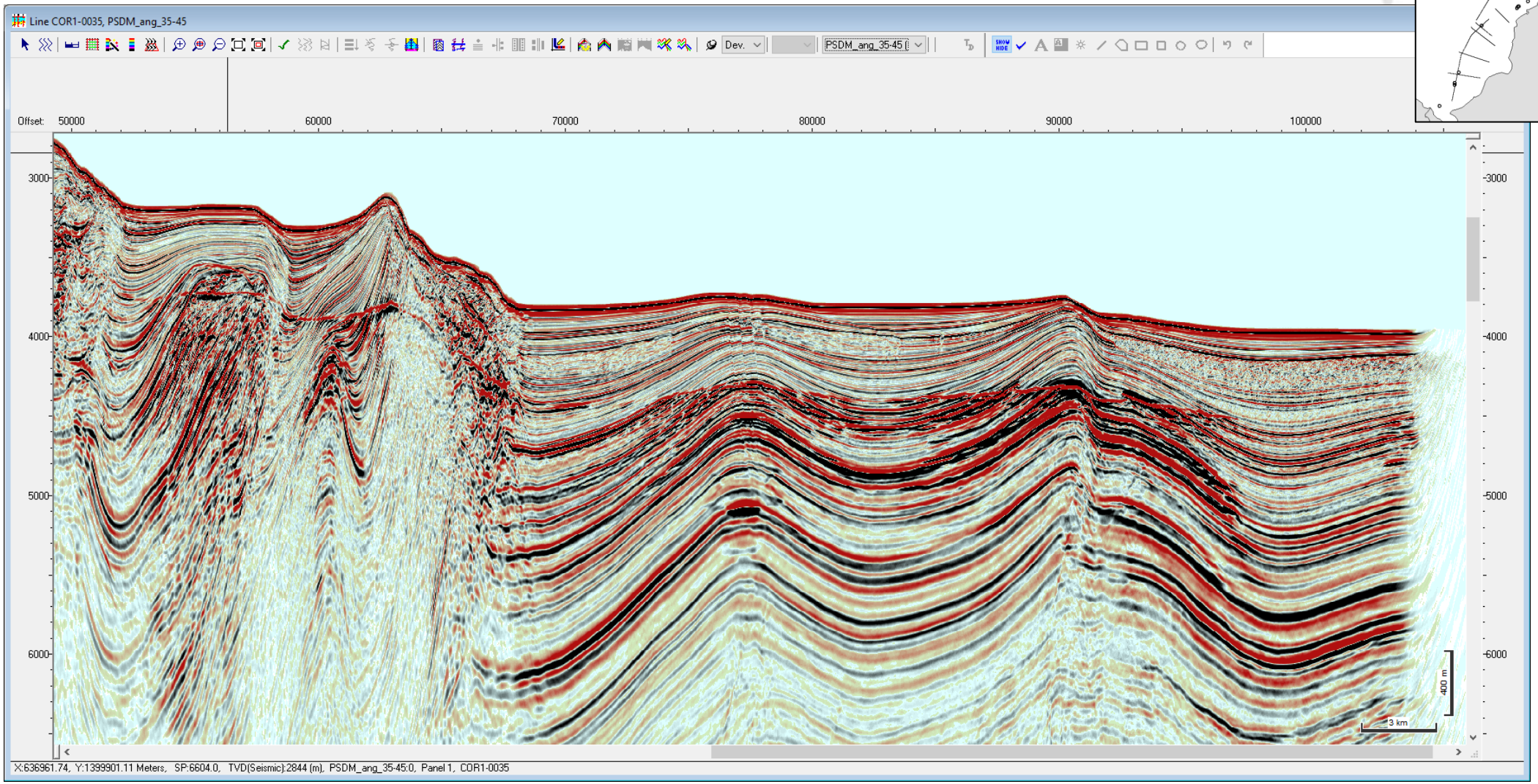


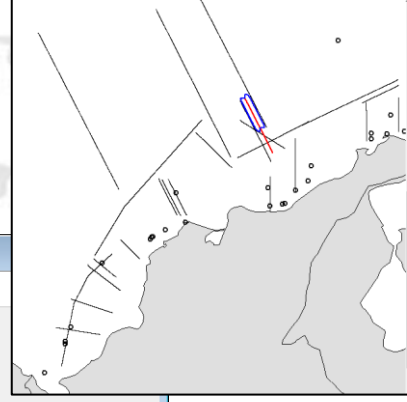
COR1-35 PSDM 5-15 Ang



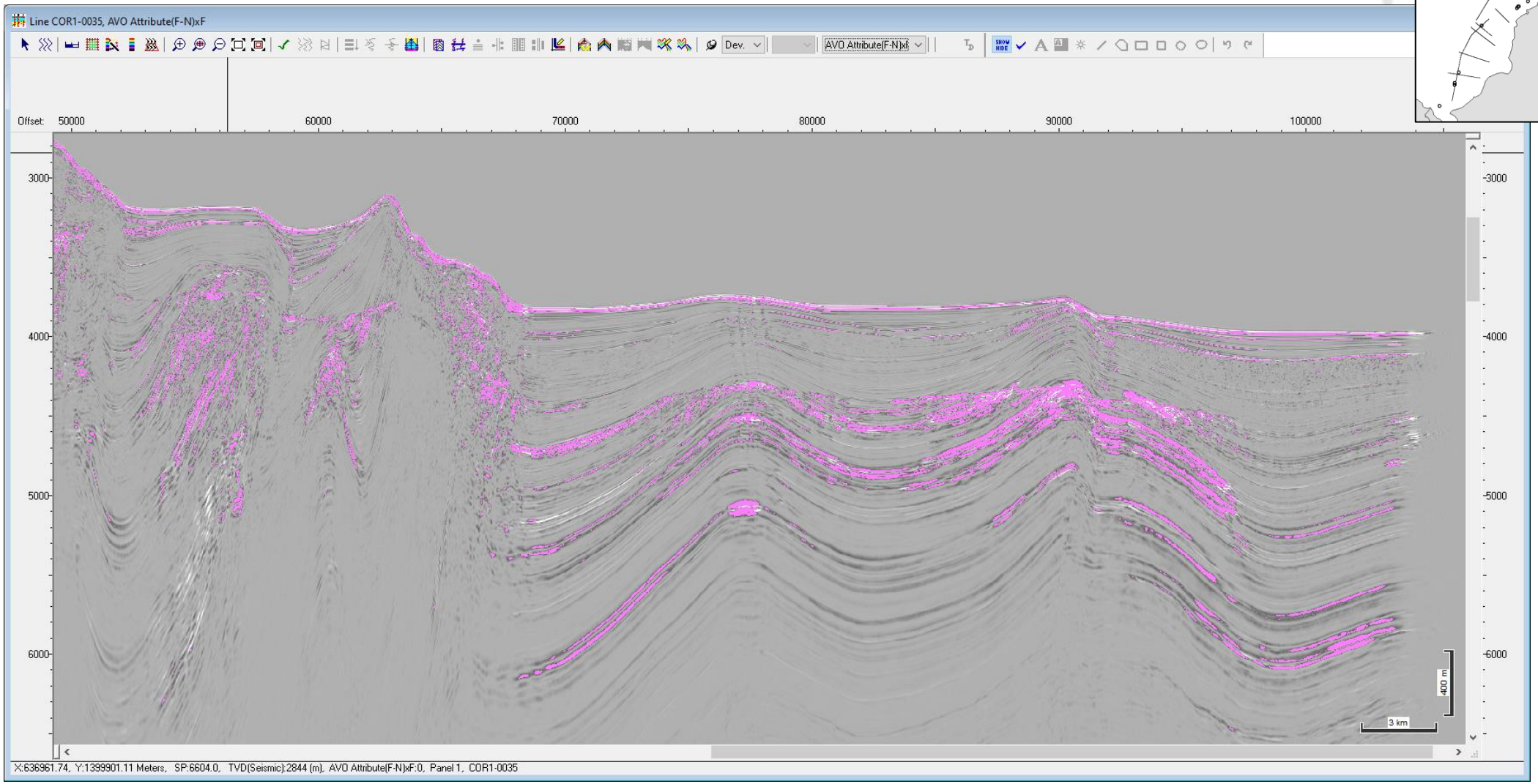


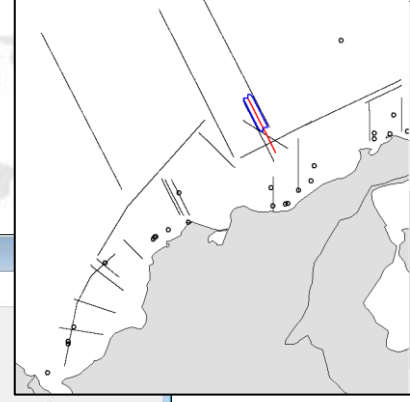
COR1-35 PSDM 35-45 Ang



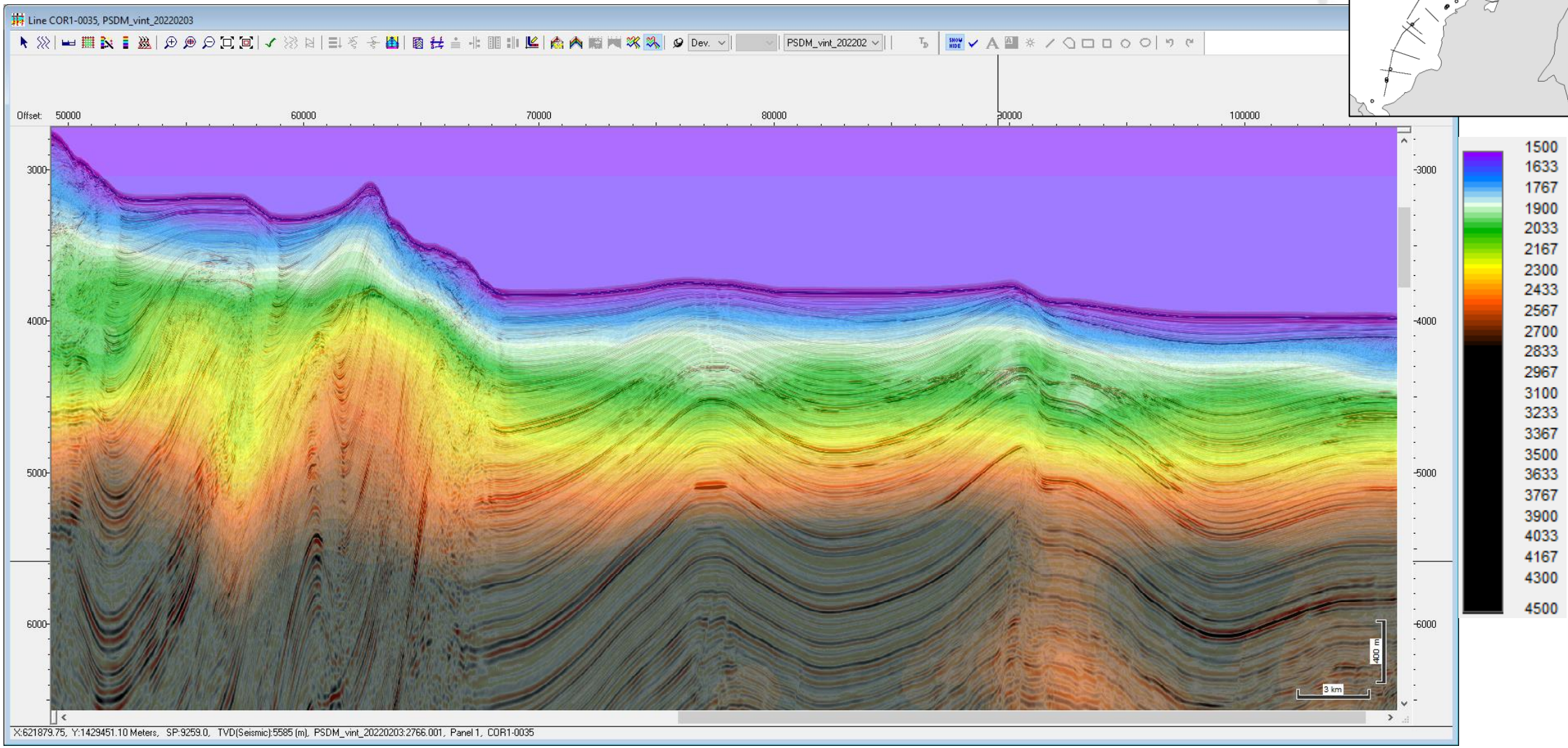


COR1-35 PSDM AVO Attribute

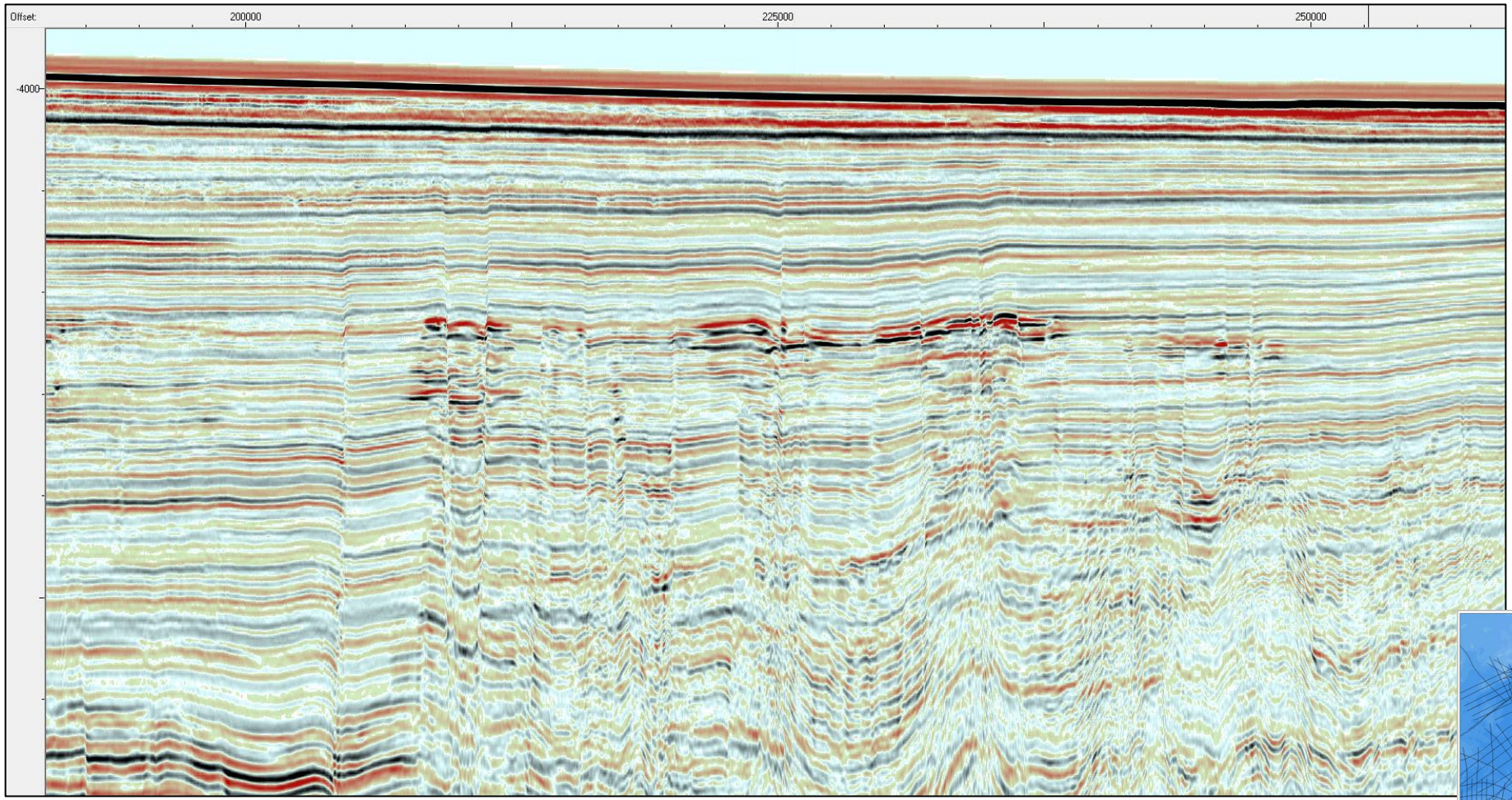


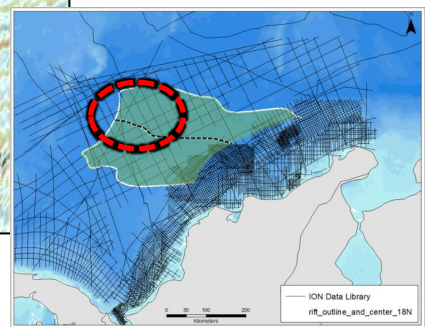


COR1-35 PSDM Velocity

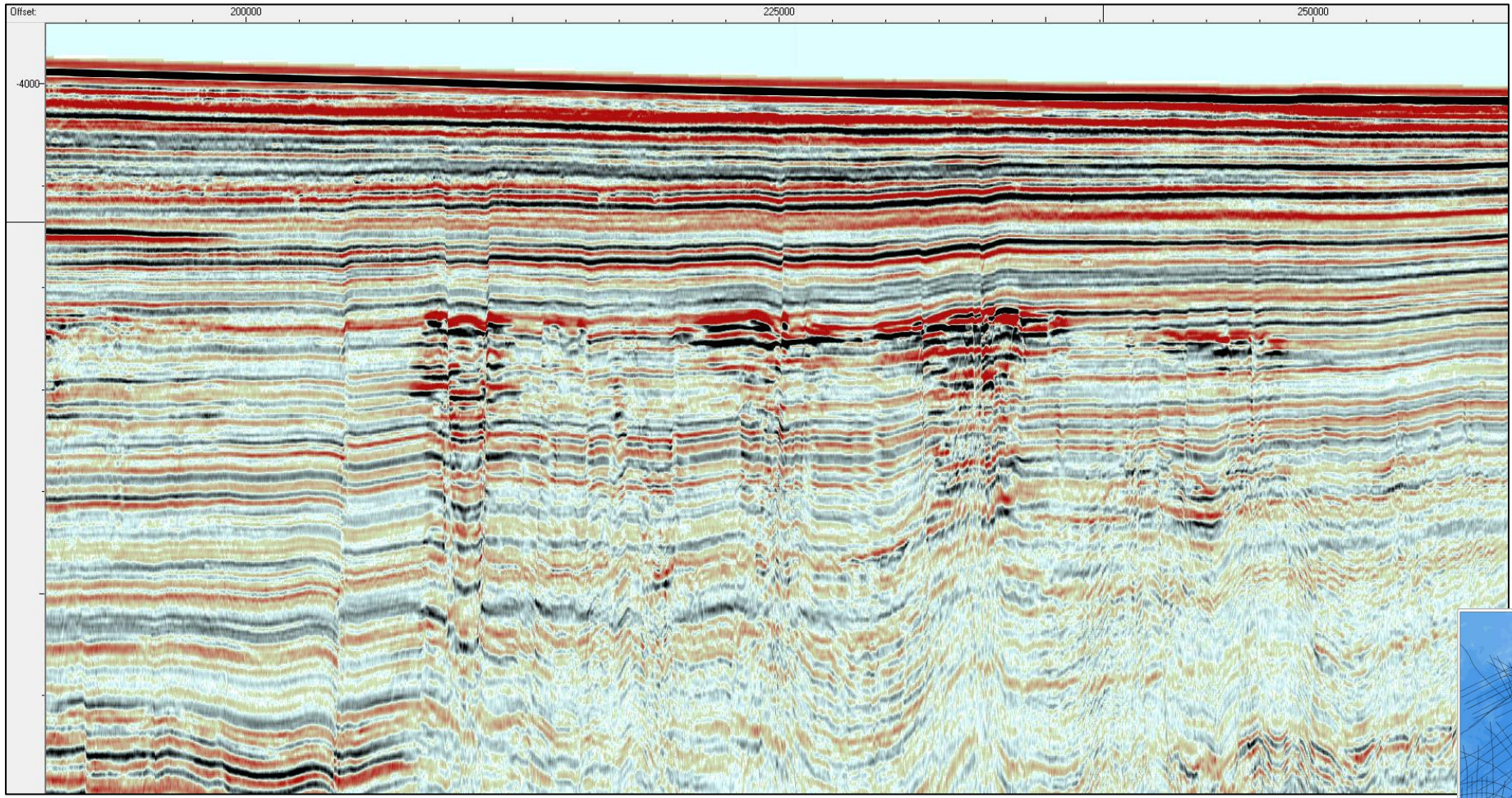


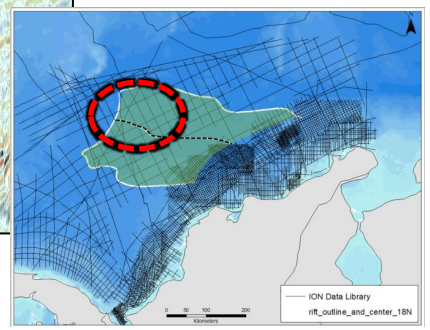
Colombia Deepwater- PSDM



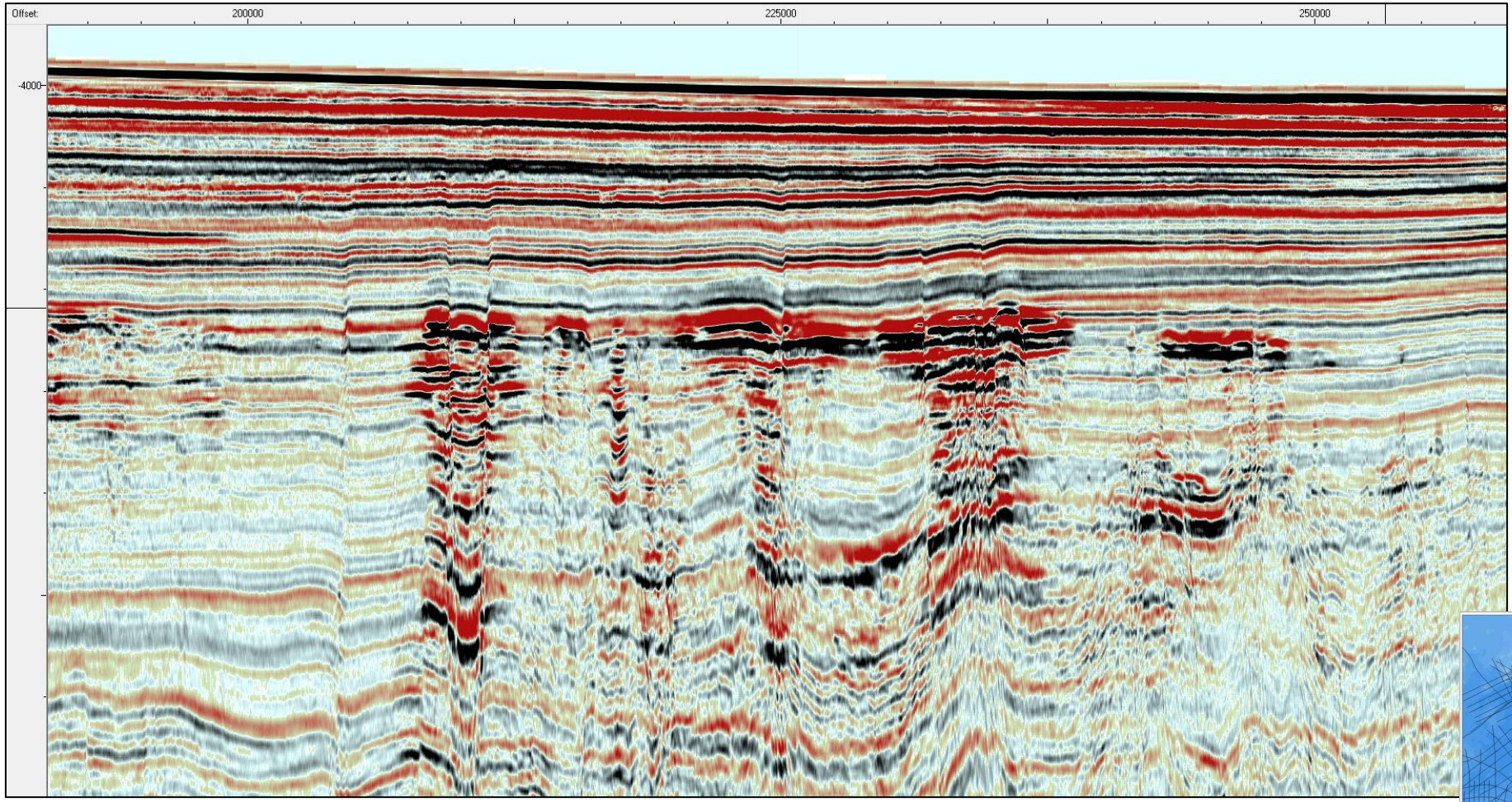


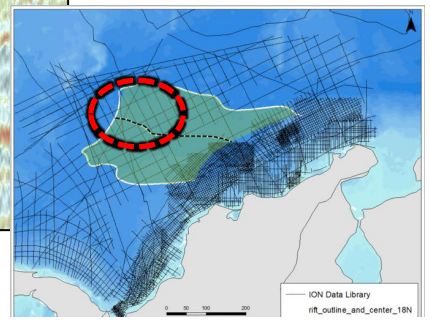
Colombia Deepwater (Nears)



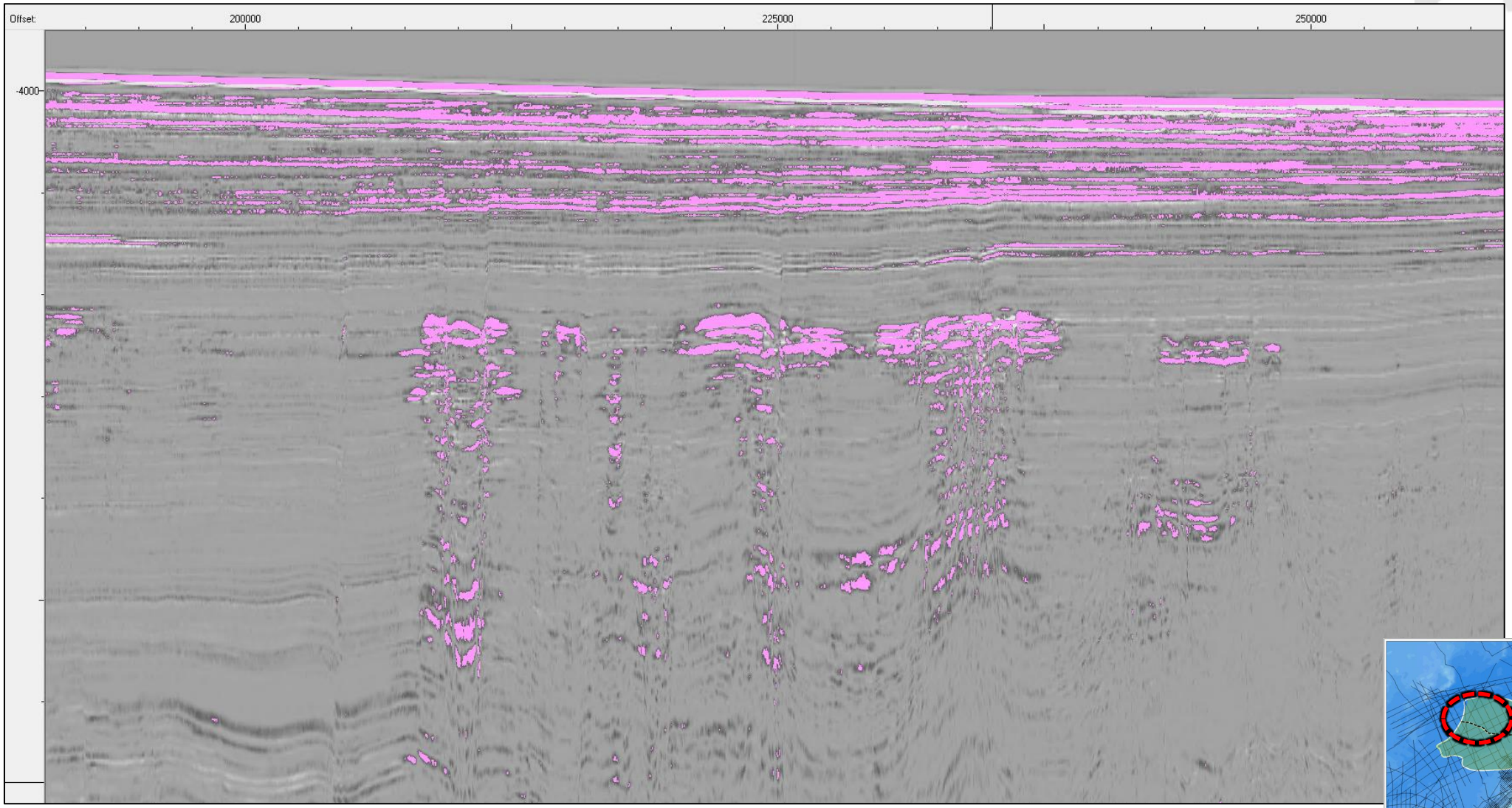


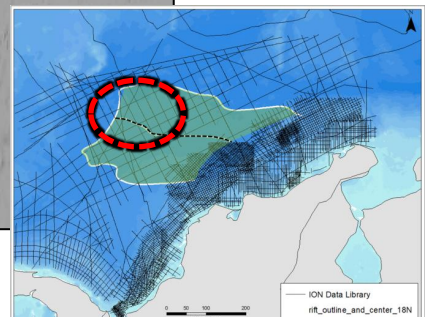
Colombia Deepwater (Fars)



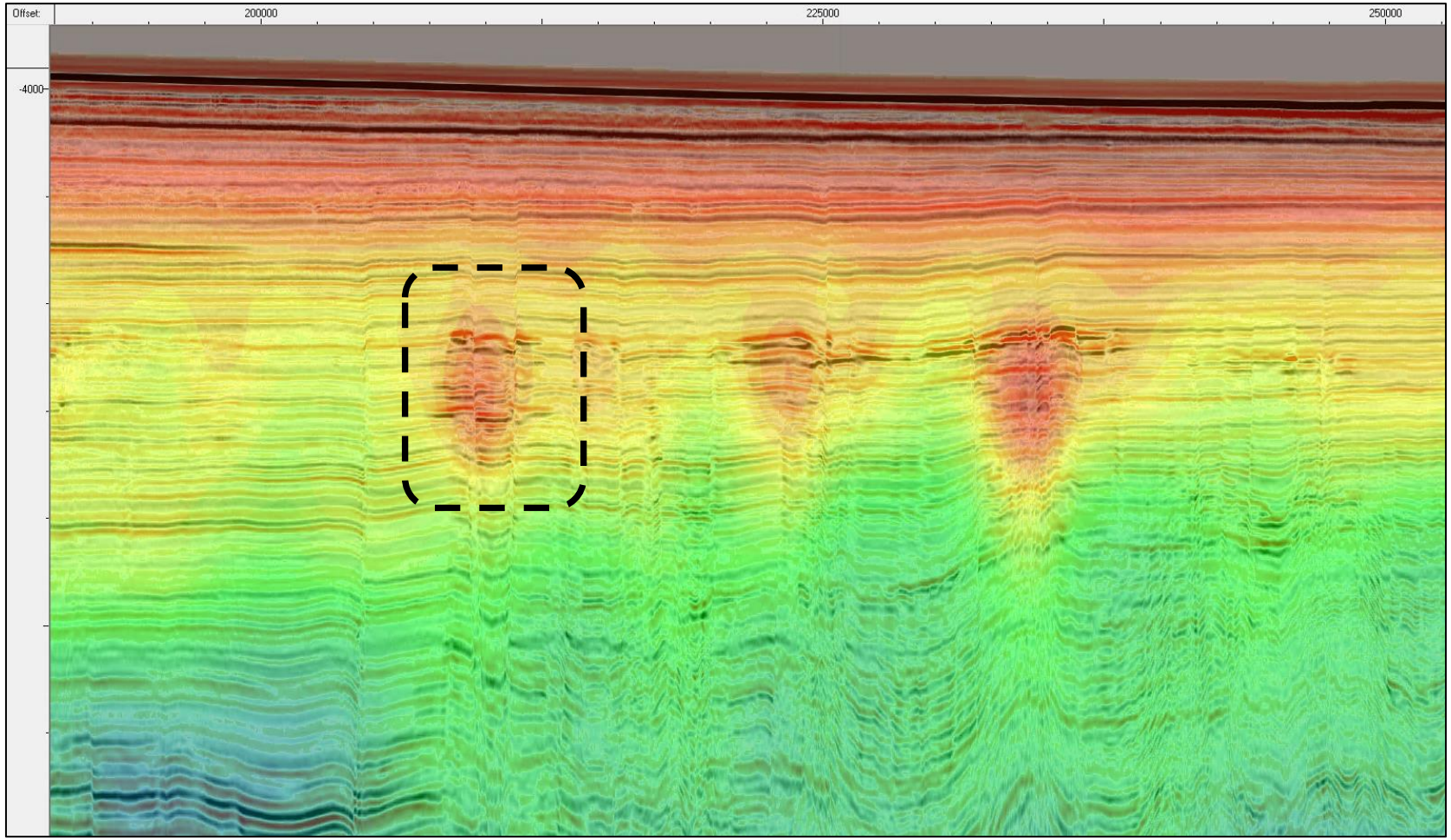


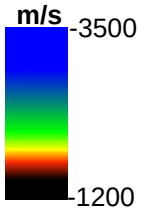
Colombia Deepwater -AVO Attribute

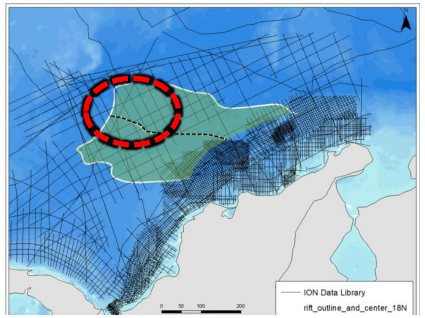




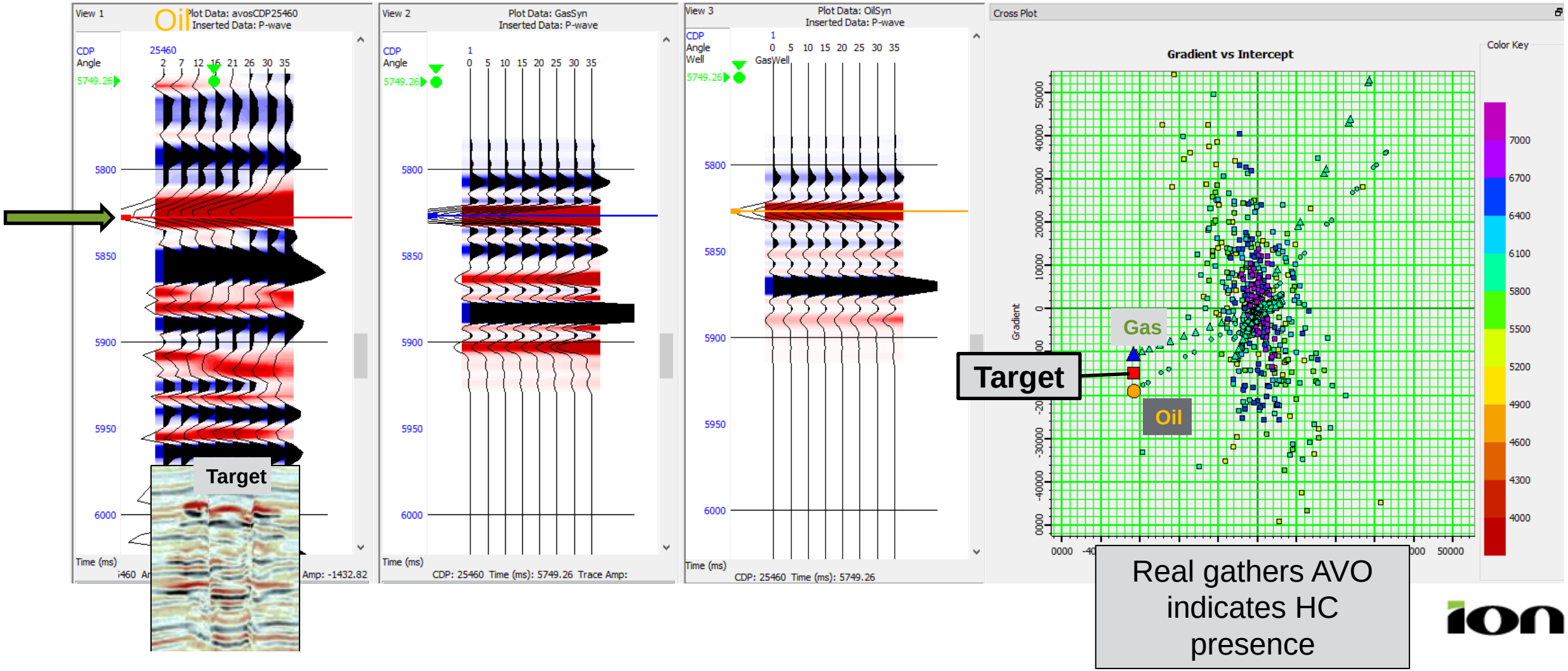
Colombia Deepwater- PSDM Velocity



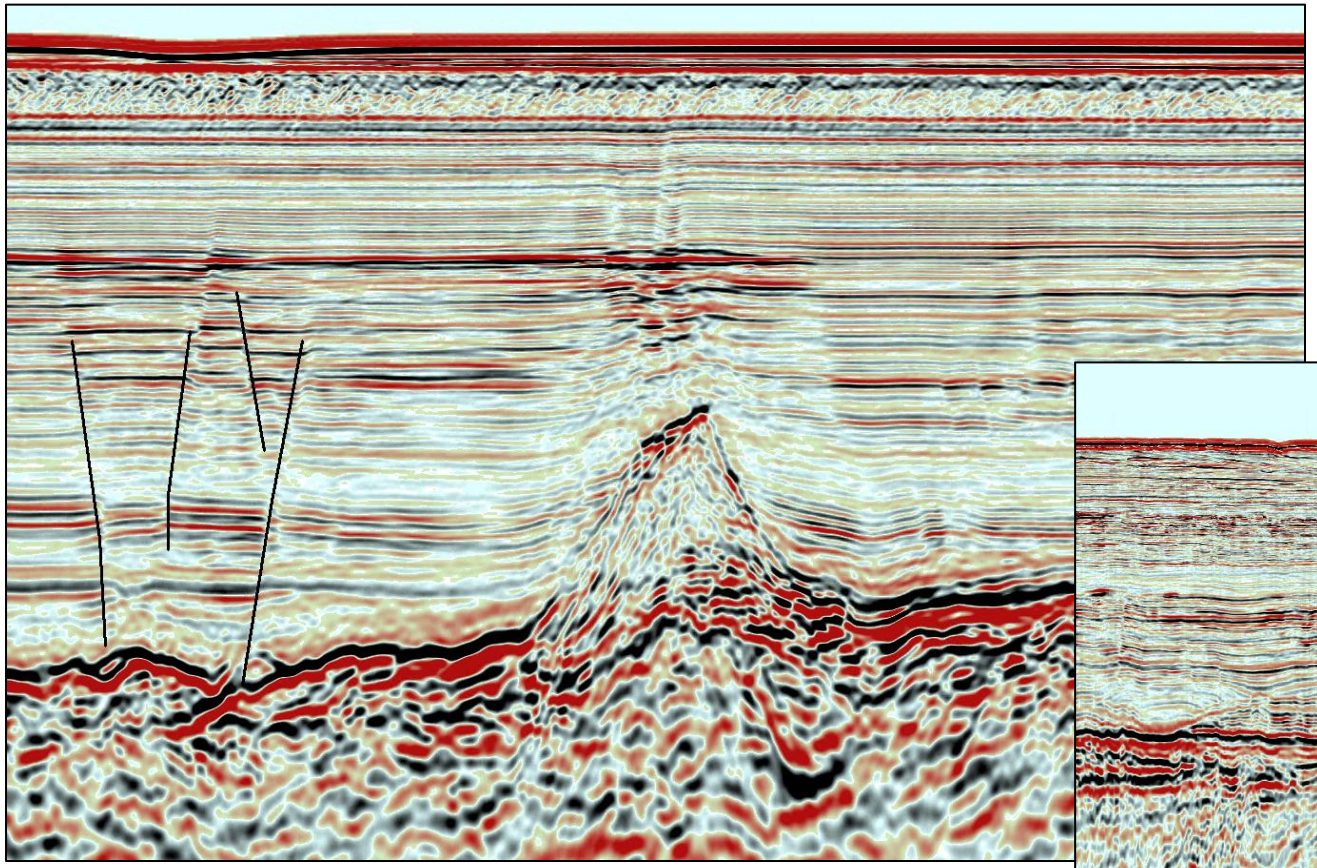


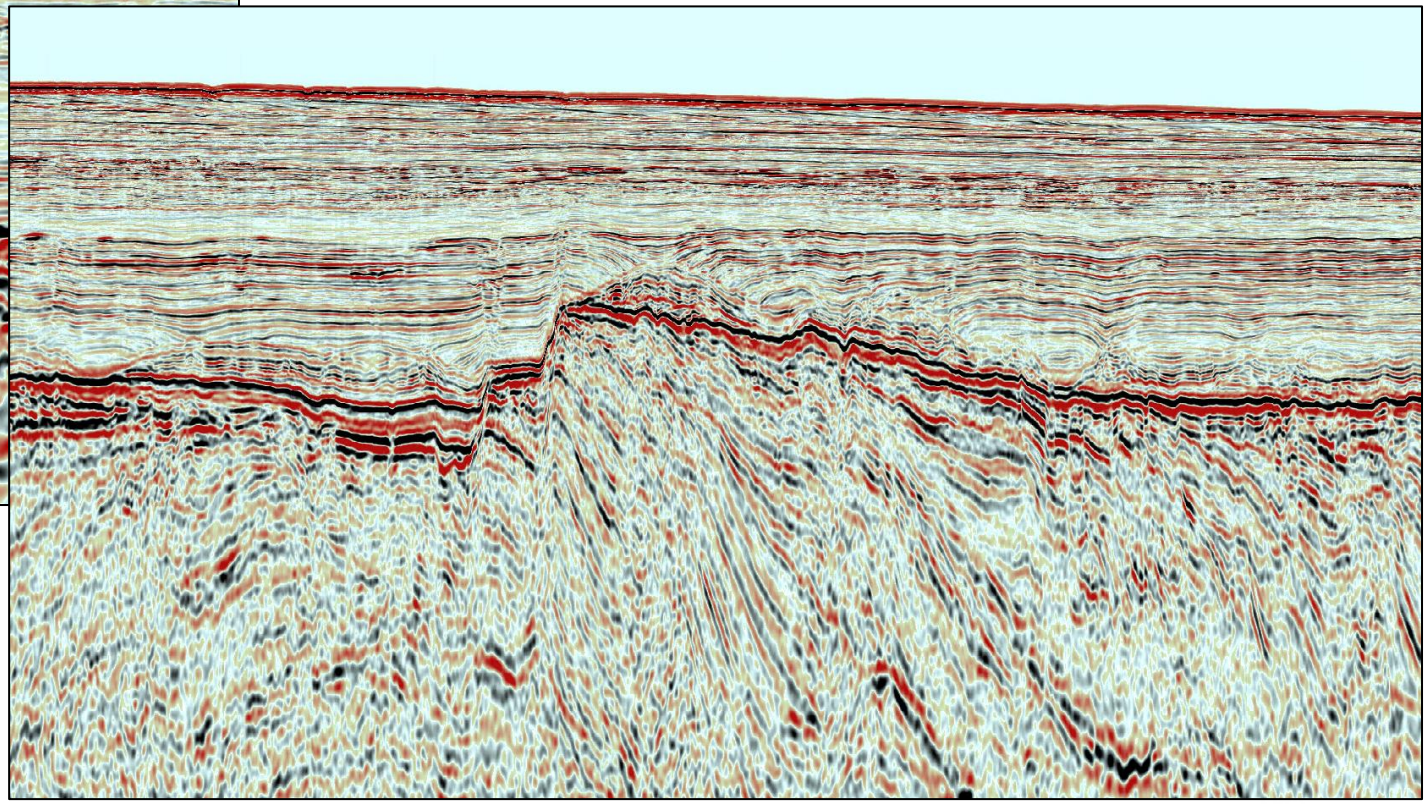


AVO Comparison:
Conditioned vs. Modeled Gathers



Additional deepwater plays?

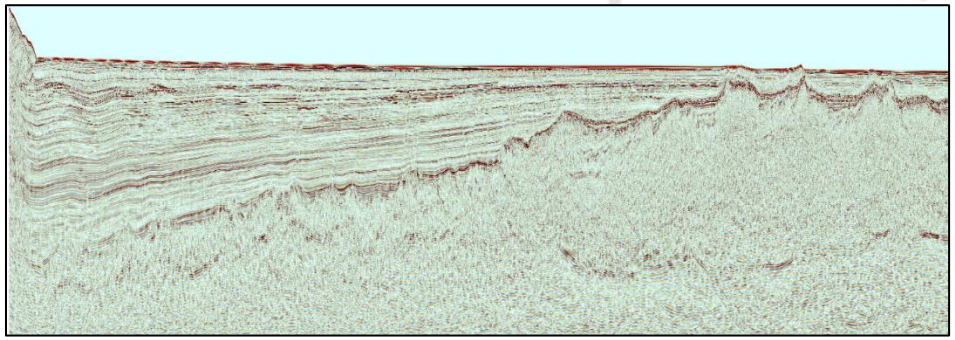


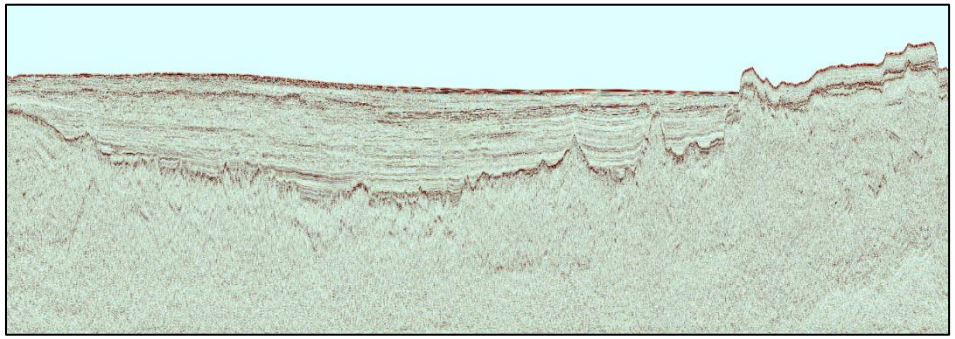


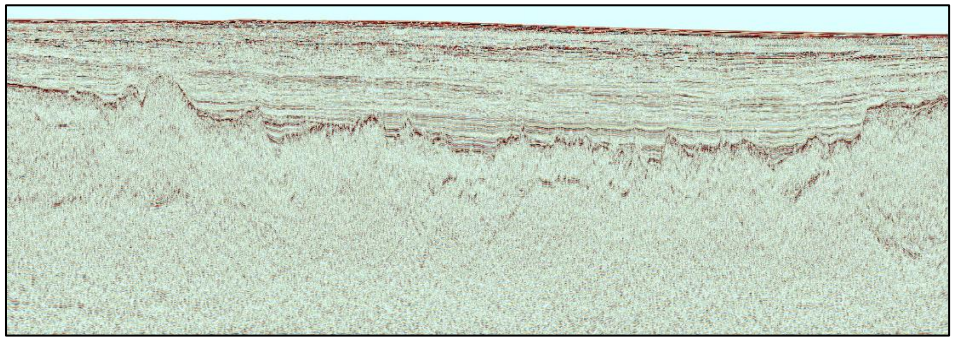
Conclusions
Intra-CLIP Detachment Style Spreading

- Identification of Intra-CLIP Oceanic Spreading
  - Detachment-style spreading
    - Creates large areas of exhumed mantle
      - ~80,000 km^2 in Colombia offshore
    - Wide areas of normal faults bounded by deep, listric detachment faults
    - Magma-poor setting
    - Creates asymmetrical conjugate flanks
    - Magnetization is weak to absent

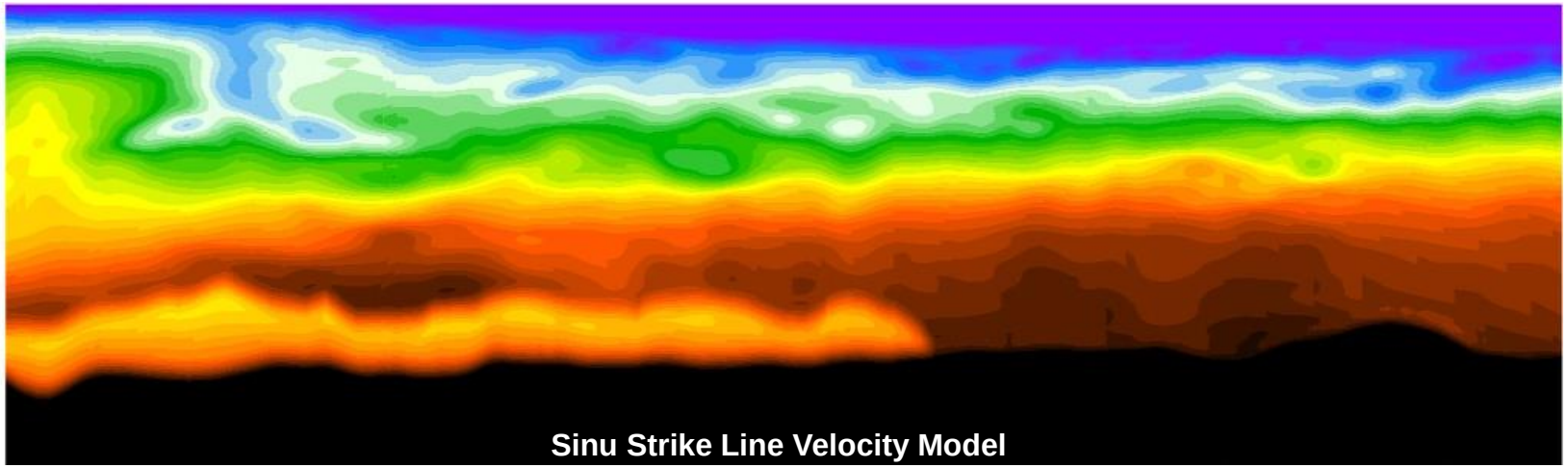
- Timing/Age of spreading?
  - Late Miocene







The newly reprocessed and integrated data set has permitted a fresh look at Offshore Colombia and its exploration potential



Sinu Strike Line Velocity Model

Thank you!