

Turonian Sill Complexes in the Offshore Morondava Basin, Madagascar: Trap Formation by Compound Forced Folding*

Gabor Tari¹, Katie Hannke¹, Gordon Wilmot¹, Isabell Schretter¹, Gregory Rock¹, and Tim Allan²

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Abstract

Hundreds of seismically imaged igneous sills were analyzed on modern large 3D seismic data sets in the undrilled deepwater segment of the Morondava Basin, Madagascar. The age of these sills is assumed to be Turonian based on well penetrations on the shelf and in the nearby onshore part of the basin. The sills are typically saucer-shaped, but other types, such tabular and transgressive sills were also documented. Besides the large number of sub-volcanic intrusive complexes, a relatively small number of submarine paleo-volcanoes with associated lava flows and hydrothermal vents were also mapped corresponding to an inferred Turonian unconformity. Like many other volcanic basins, where the geometry of the sills has been analyzed in great detail, the vertical magnitude of the 4-way structural closures observed in the forced folds above the sills is a function of the emplacement depth below the paleo-seafloor. Whereas individual sills may not provide very large forced folds above them, a vertical stacking of several sills clearly provide large, compound structural traps with considerable vertical closure (up to 300 m) and moderately large areal extent (up to 75 km²).

Although the intrusive sills and associated hydrothermal vents may locally compromise the reservoir quality of pre-Turonian reservoirs in the deepwater Morondava Basin, their positive impact for hydrocarbon trapping is far more significant. As the Cretaceous to Cenozoic deepwater strata of the margin has a moderately uniform monoclinical dip to the west, with lots of stratigraphic trapping potential, the numerous complex forced folds above the sills provide almost all the structural traps in this frontier basin. In addition to the 4-way closures within the Pre-Turonian strata, differential compaction above the sill-related forced folds influenced the map-view geometry of deepwater sediment dispersal on the margin, including Senonian-Paleocene turbidite fan systems.

References Cited

Jackson, M.P.A, and C.J. Talbot, 1991, A Glossary of Salt Tectonics: Bureau Economic Geology, Texas.

Magee, Craig, D. Muirhead, Alex Karvelas, Simon Holford, Christopher Jackson, Ian Bastow, Nick Schofield, Carl Stevenson, Charlotte Mclean, William McCarthy, and Olga Shtukert, 2016, Lateral magma flow in mafic sill complexes: *Geosphere*, v. 12.

Roig J.-Y., R. Tucker, S. Peters, C. Delor, and H. Théveniaut, 2012, Carte géologique de la République de Madagascar à 1/1 000 000: Ministère des Mines, Antananarivo, République de Madagascar (in French).

Tari, Gabor, Haddou Jabour, Jim Molnar, David Valasek, and Mahmoud Zizi, 2012, Deep-water exploration in Atlantic Morocco: Where are the reservoirs?: Tectonics and sedimentation: Implications for petroleum systems, *AAPG Memoir* 100, p. 337-355.

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OMV Upstream

Outline

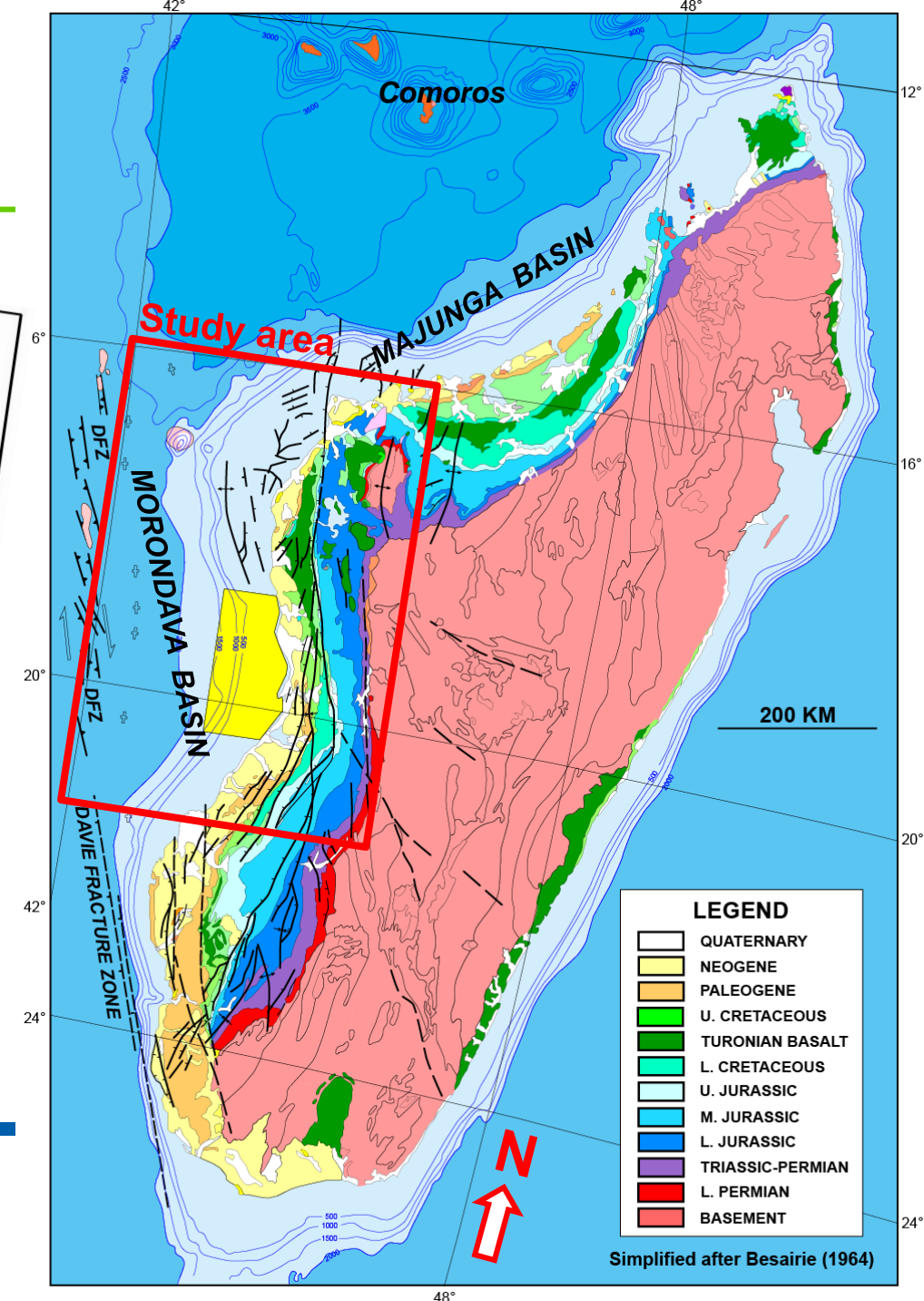
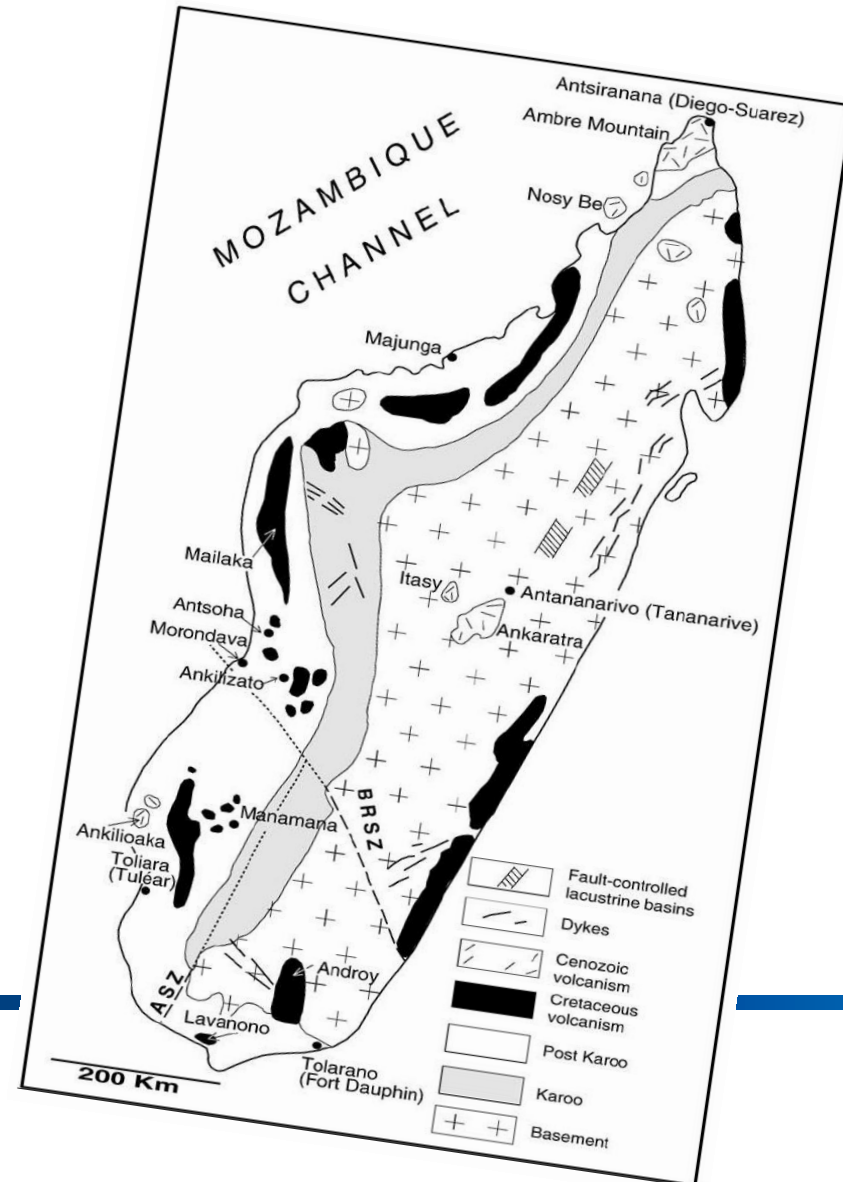
- ▶ Regional context, wells, seismic database
- ▶ Cretaceous (Turonian) magmatism in Madagascar
- ▶ Turonian intrusions reflected in the onshore geology
- ▶ 3D reflections seismic observations of effusives and intrusives
- ▶ Lack of regional impact on maturation by Turonian magmatism
- ▶ Impact of Turonian sills on petroleum plays
- ▶ Analogy with salt tectonics, i.e. salt versus sill tongues/sheets?
- ▶ Conclusions

Cretaceous magmatism in Madagascar

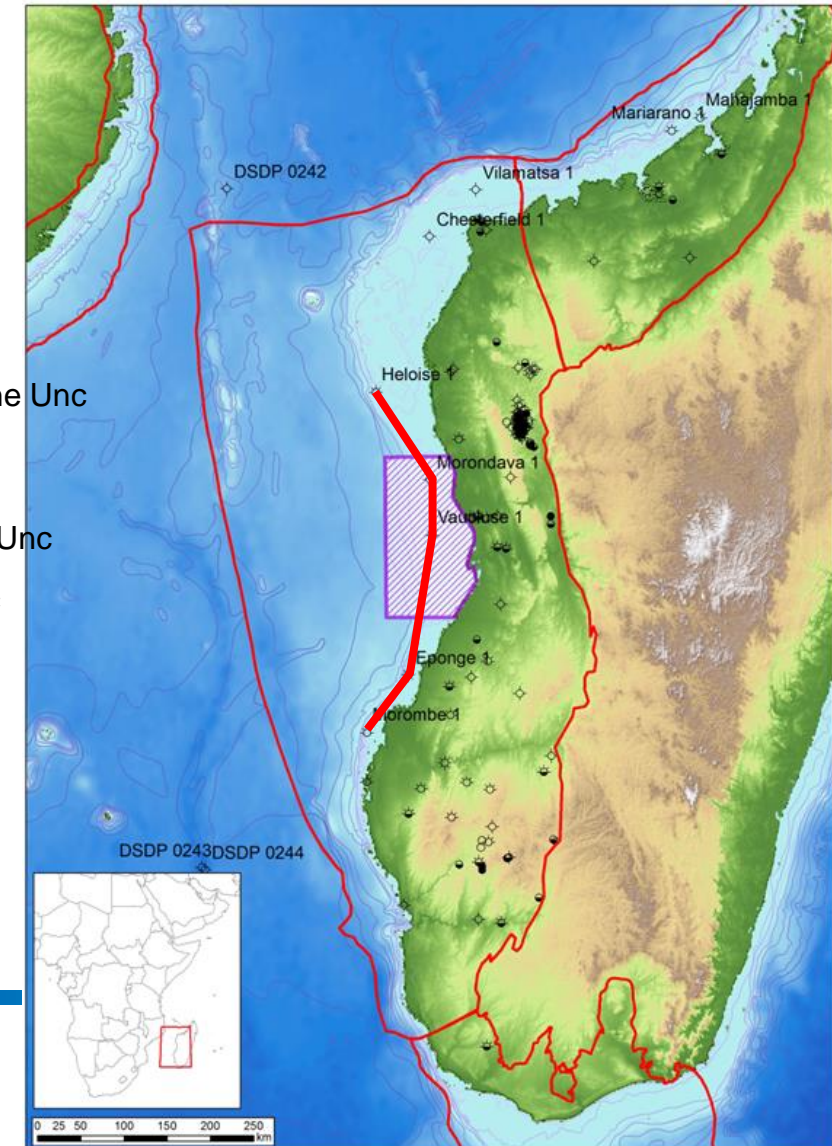
There are several Cretaceous volcanic provinces in Madagascar (in black and dark green). The Morondava flood basalt (CFB) province was emplaced ca. 91-93 Ma ago, during the Turonian.

Several lines of evidence dismiss the mantle plume model proposed in the 1990s for these volcanics relating them to the Marion hot spot.

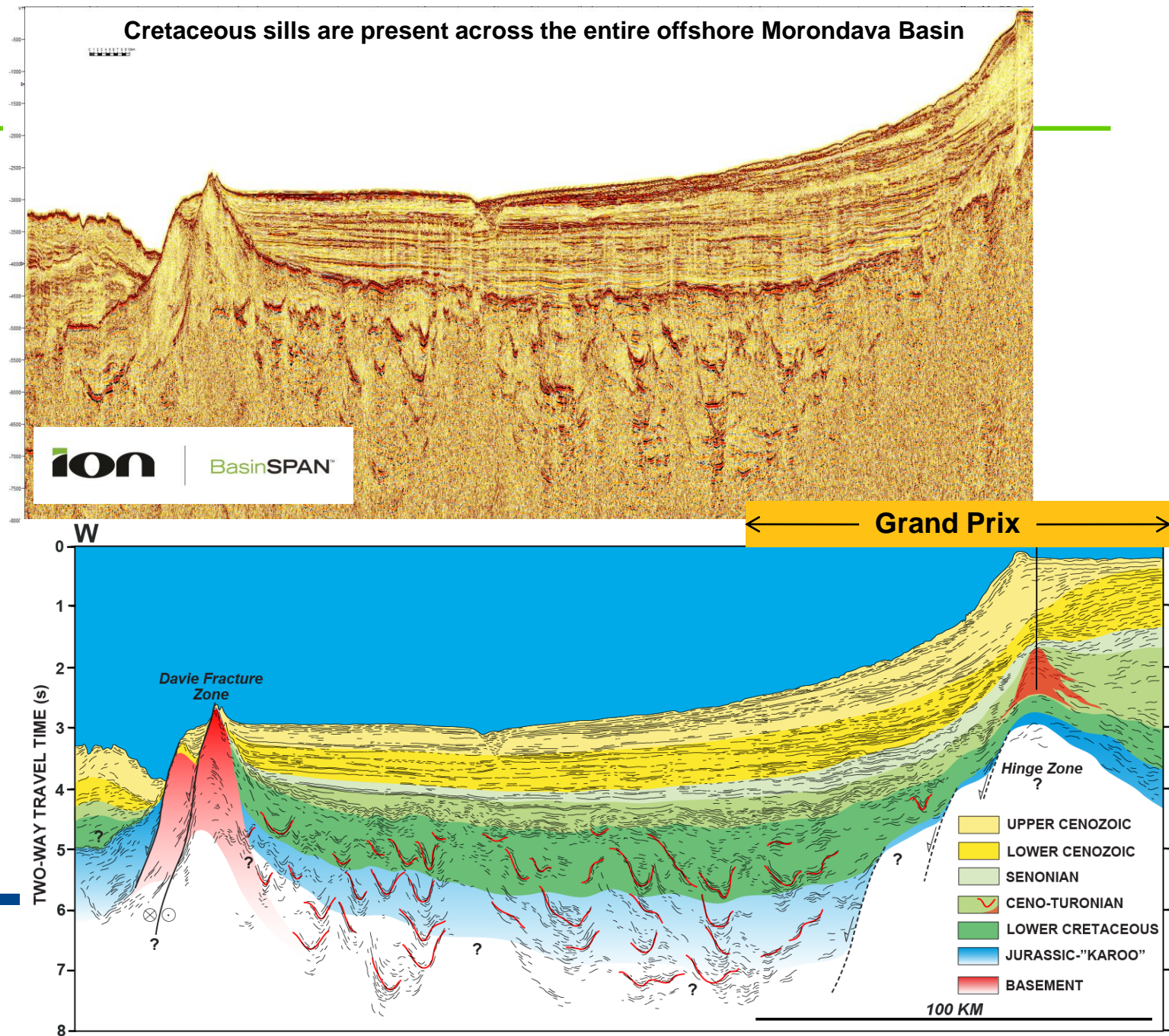
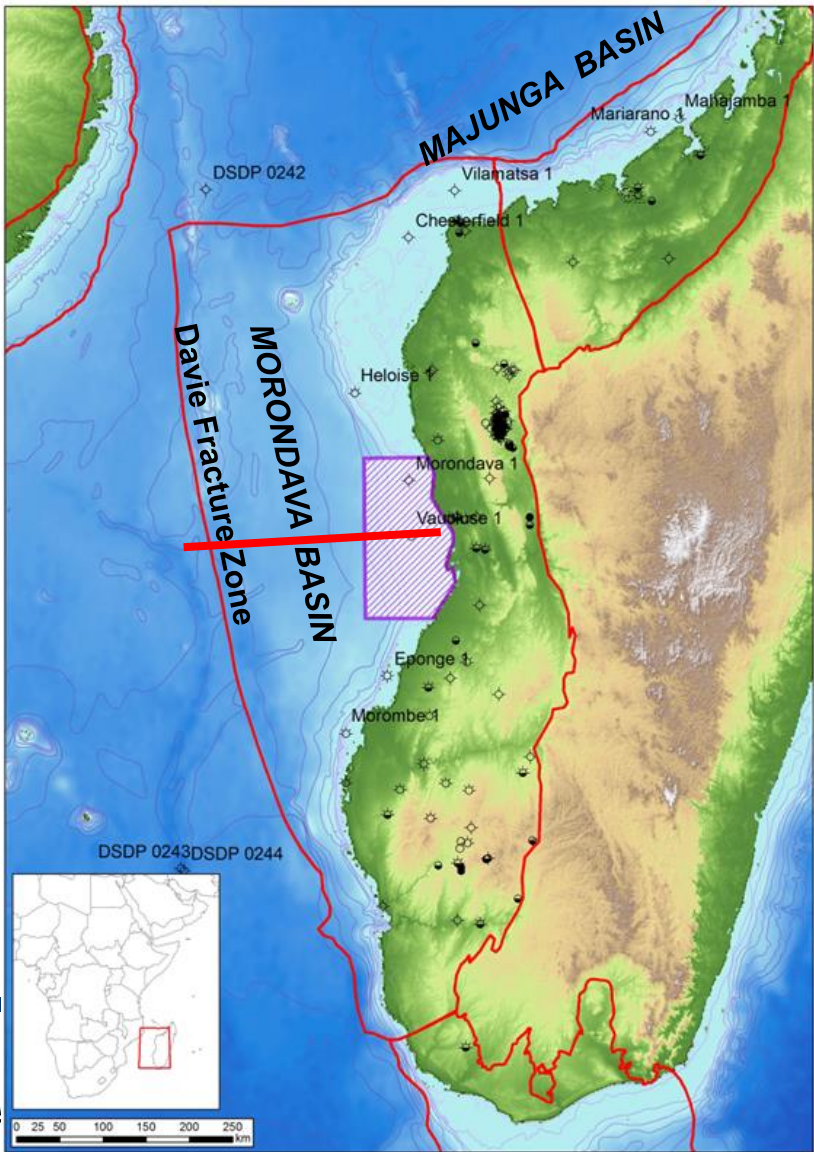
The latest interpretations suggest that Cretaceous volcanism resulted from reactivation of a lithospheric scale shear zone due to plate reorganisation that eventually led to the break-up between Madagascar and Greater India (e.g. Bardintzeff et al., 2010)



Drilled on poor quality 2D seismic, invalid traps, updip of reservoir fairway

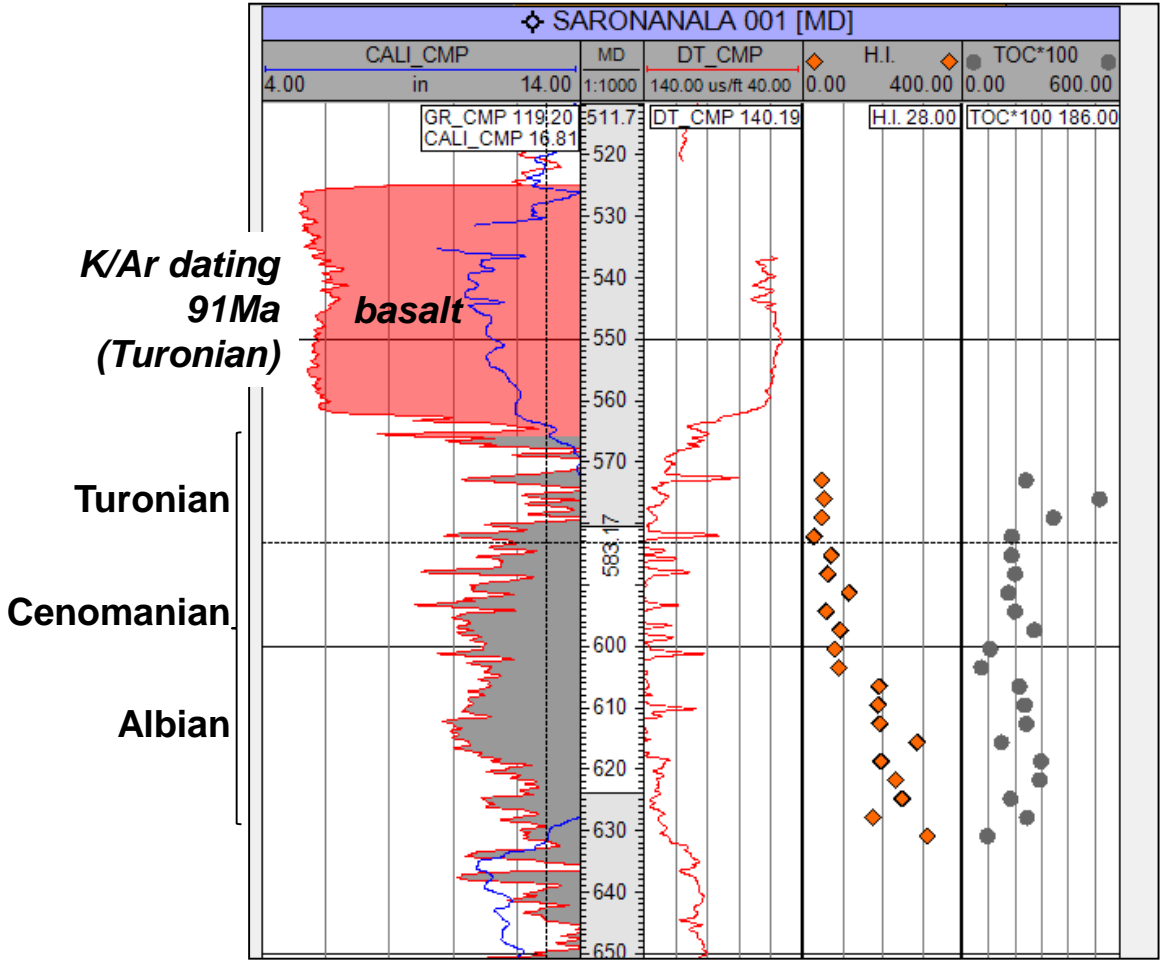
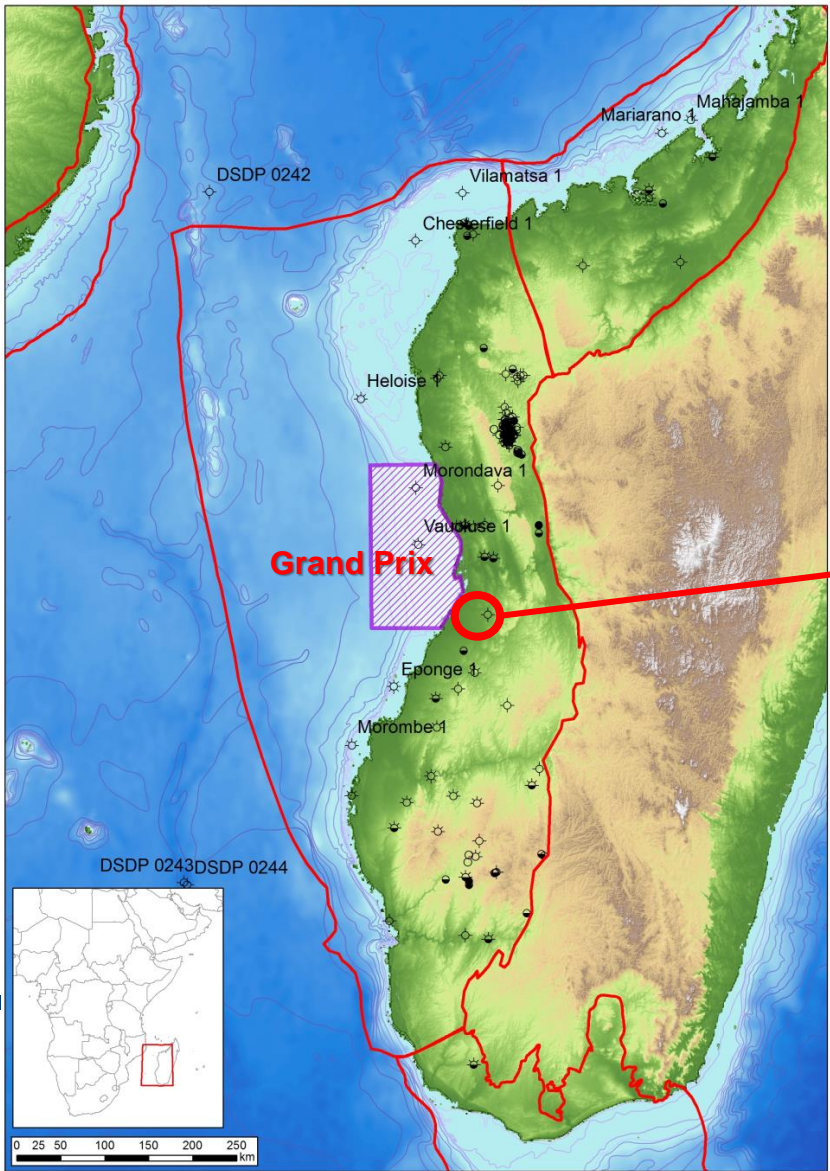


ION BasinSPAN seismic in the Morondava Basin



Turonian basalt in onshore well

Saronanala-1
Amoco 1985
dry, with shows

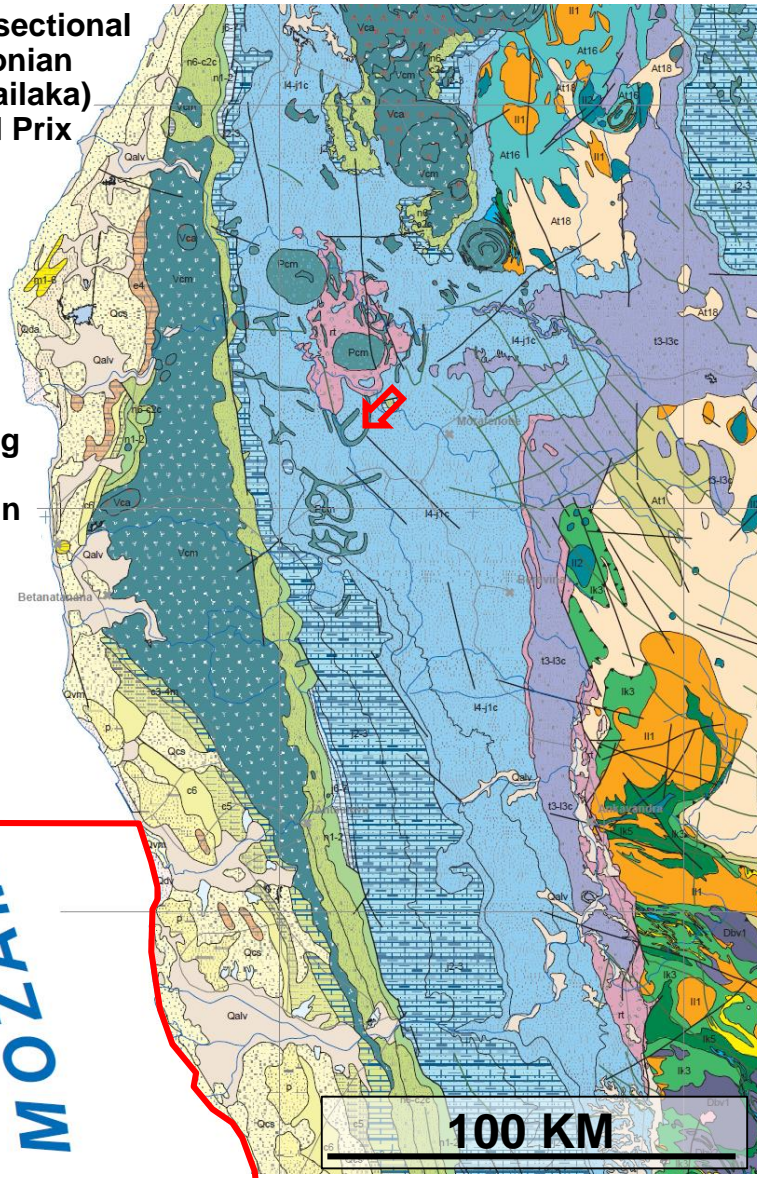


Exlog report notes that the lower HI values immediately below the basalt may be related to local thermal degradation

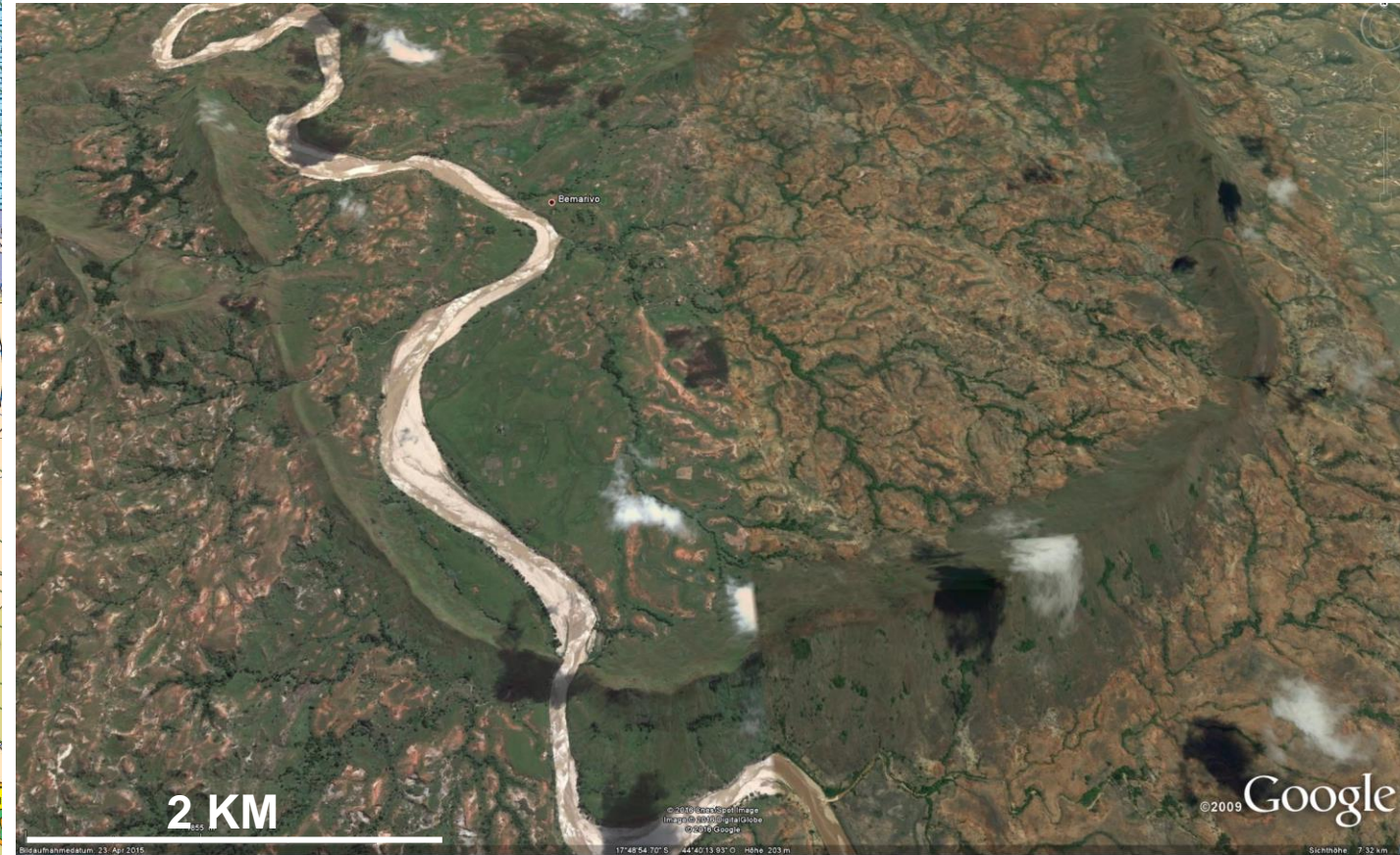
Onshore „classic“ sills, described previously as „dyke swarms“

Note the semi-cross sectional view of the large Turonian volcanic complex (Mailaka) to the NE from Grand Prix (oblique view due to the regional westerly tilt of the margin)

Also note outcropping sills and other sub-volcanic bodies within the Jurassic



Note the thickness of the outcropping Turonian sill (tens of meters) within the host Jurassic sediments



NE part of
Grand Prix

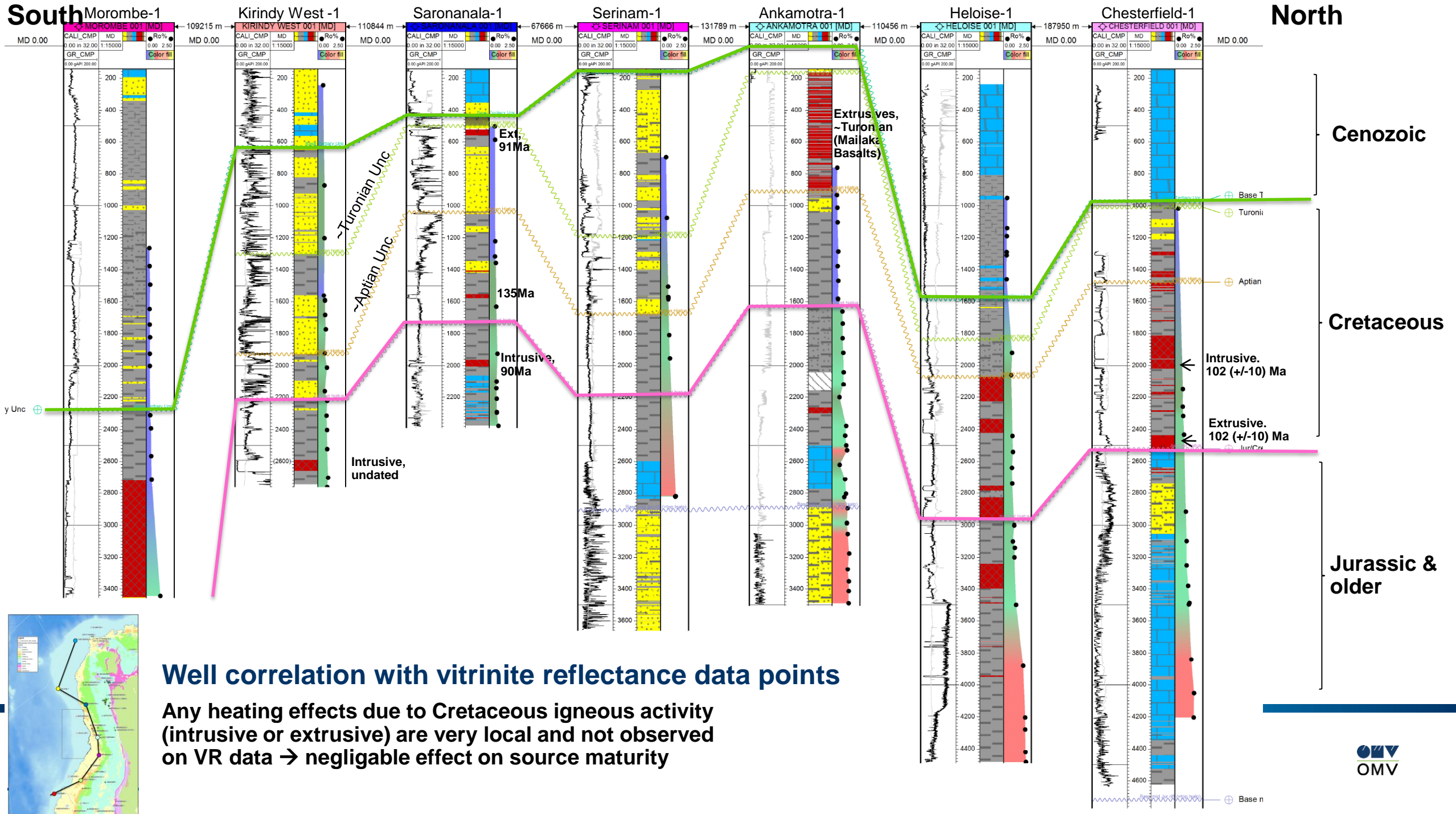
MOZAMBIQUE



De Roig et al. (2012)

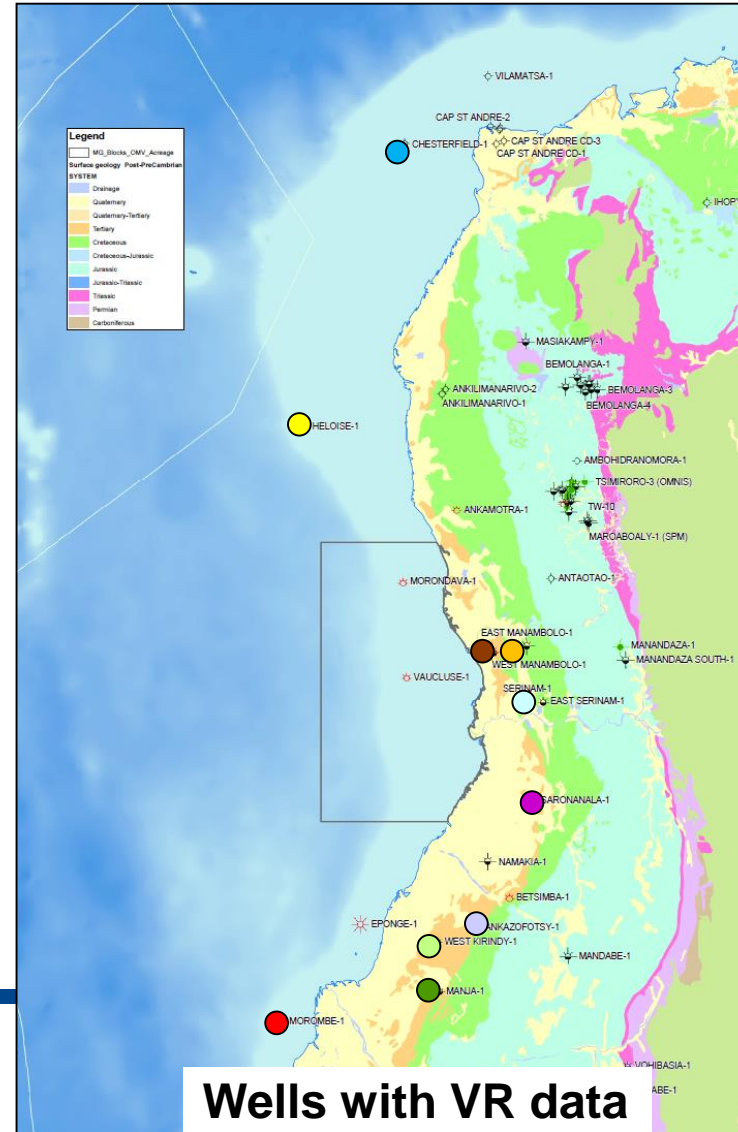
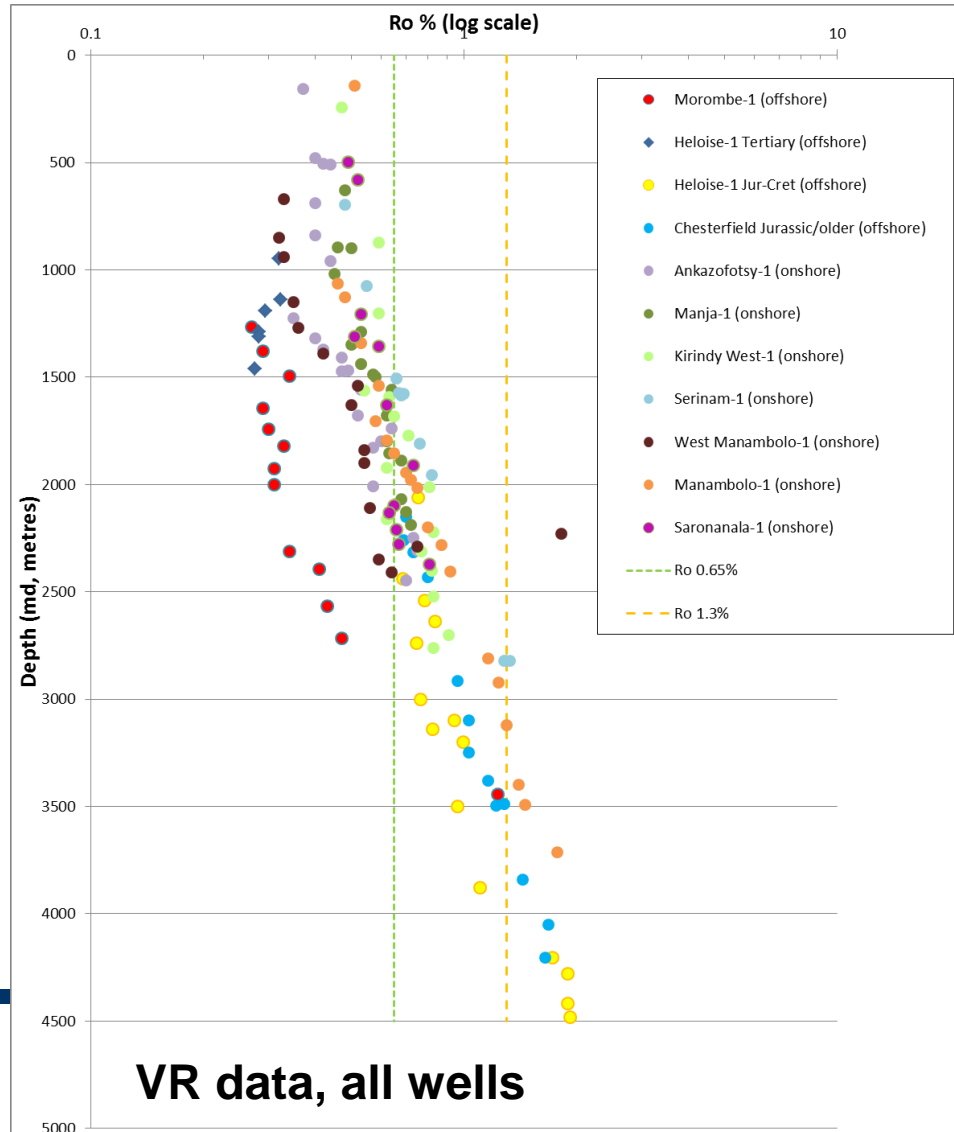
- Vca - Rhyolite, trachyte, phonolite
- Vcm - Basalte, basanite, sakalavite
- Pcm - Gabbro, microgabbro, dolérite
- Pca - Syénite
- Pcum - Péridotite, dunite, pyroxénite

Santonien
Coniacien
Turonien
Cénomanién
Albien



Vitrinite reflectance data (onshore and offshore)

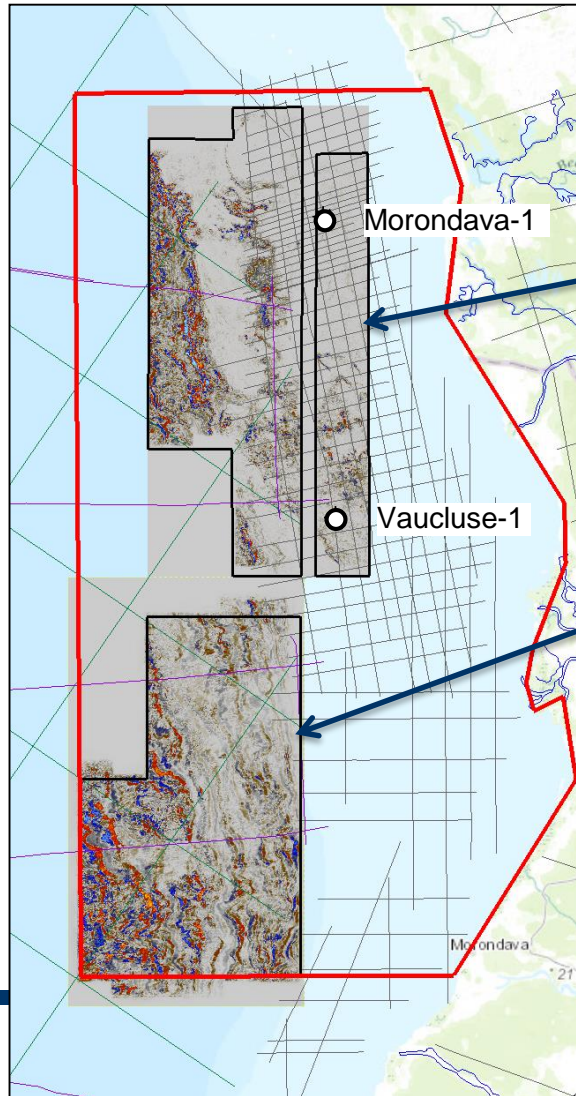
No evidence for noticeably higher heat flow during the Cretaceous igneous activity



► Gradients of both onshore and offshore trends are similar, implying fairly stable paleo-heat flow

► The VR data does not indicate noticeably higher heat flow during the Cretaceous igneous activity

Seismic data sets, Grand Prix Block, offshore Morondava Basin



2D data – regional TGS dataset from 2005 (35 km line spacing); + older (mid 70s) SEAGAP survey; shelfal 2d data, mostly from 1970s-80s

2010 3D Survey – 3200 km²

2015 3D Survey – 3014 km² full fold area, acquired July-Sept 2015.

Datasets useful for interpretation

On-board processing fast-track cube: October 27th 2015

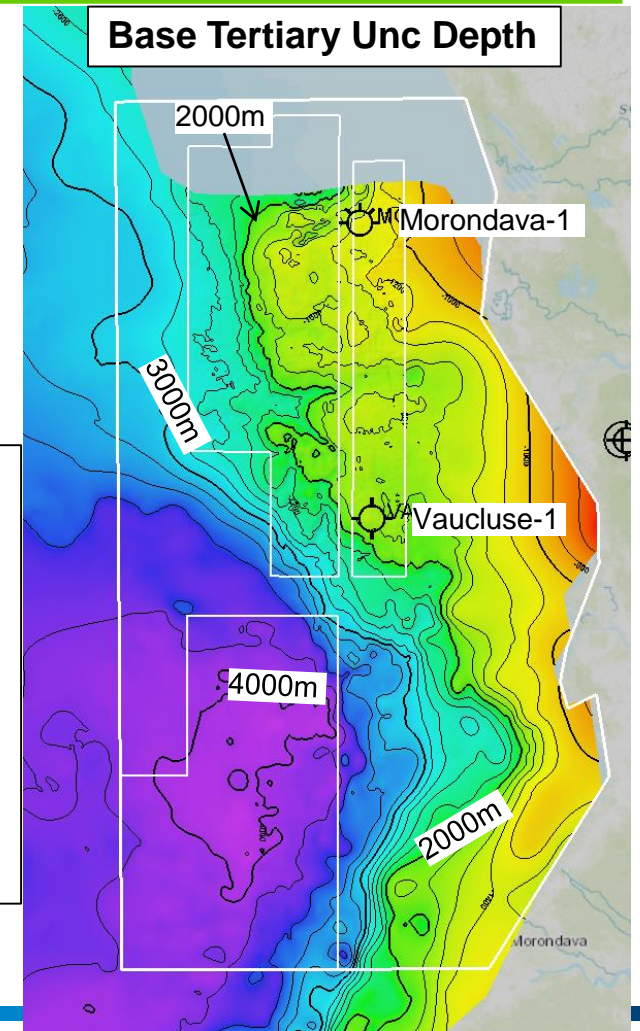
Intermediate PSTM: 29th August 2016

Intermediate PSDM (Iteration 2) – 22nd August 2016

PSTM cubes using OMV pre-conditioned gathers (in-house product)

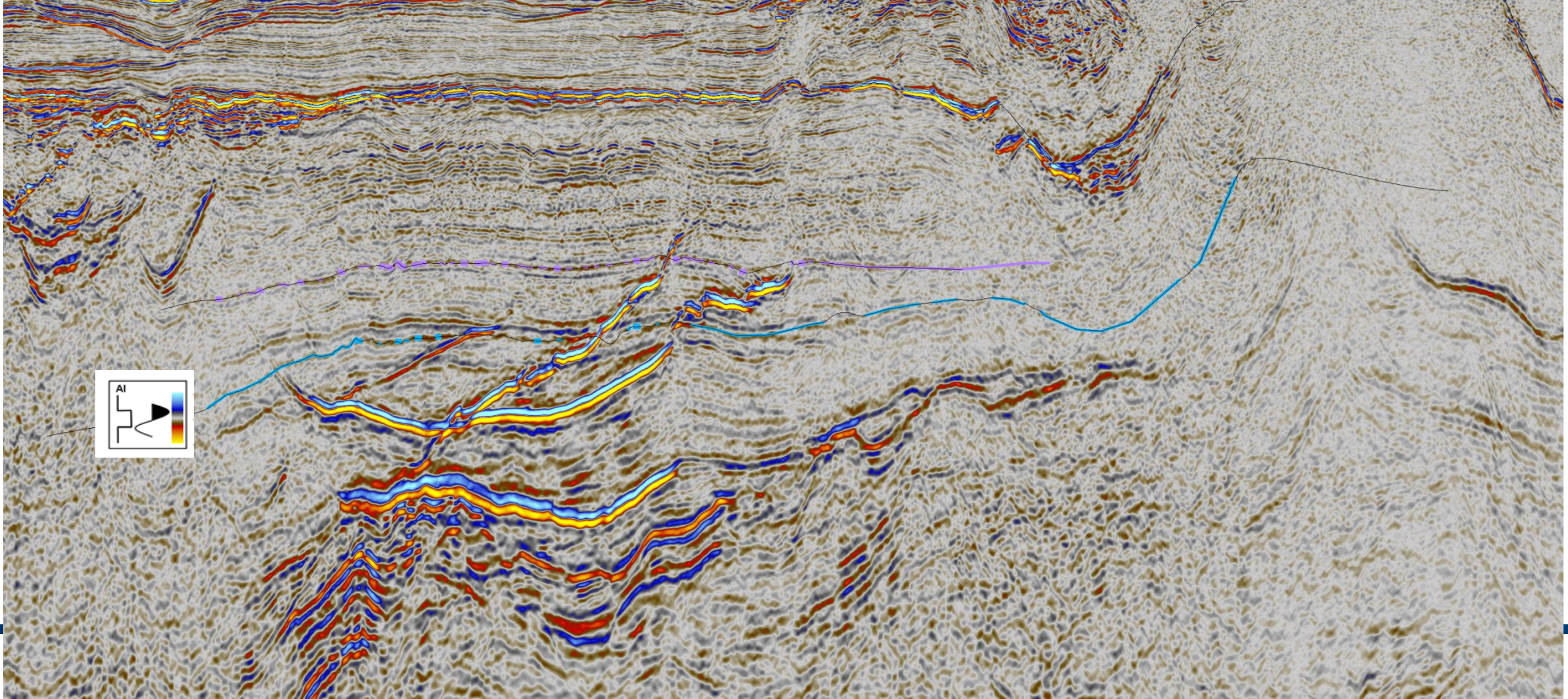
Final PSTM – 21st November 2016

Final PSDM with Q-Tomo (3rd Iteration) – 20th December 2016

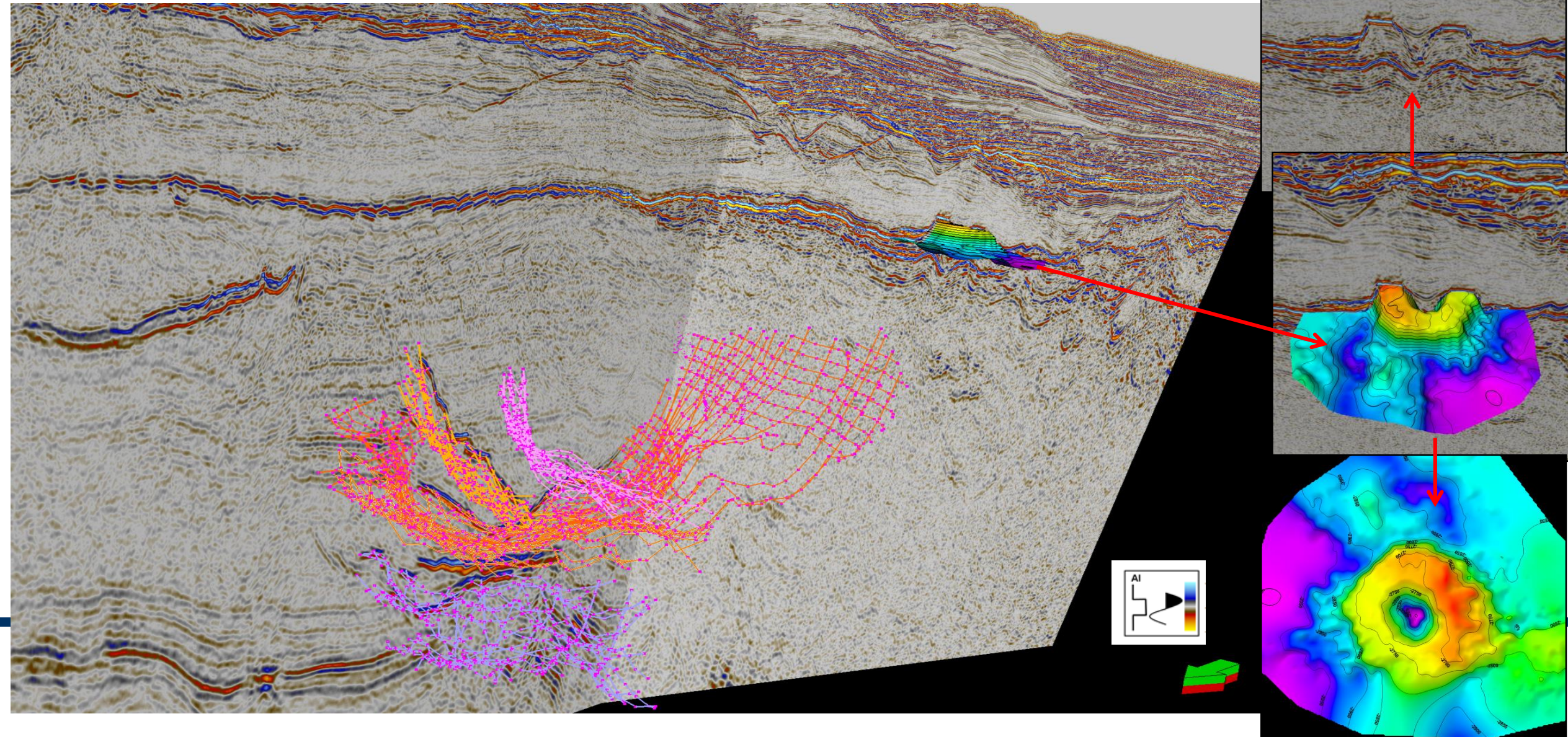


Contour Interval: 200m

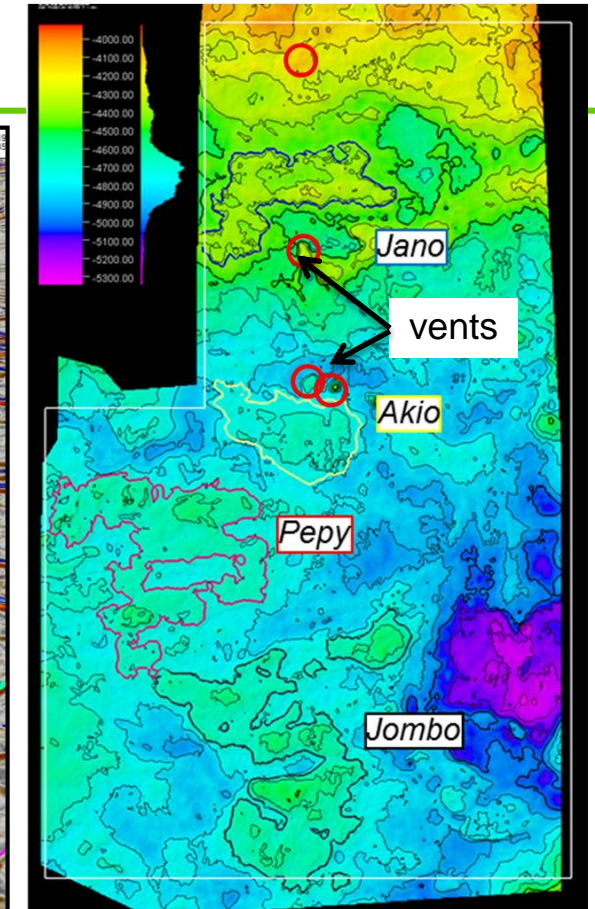
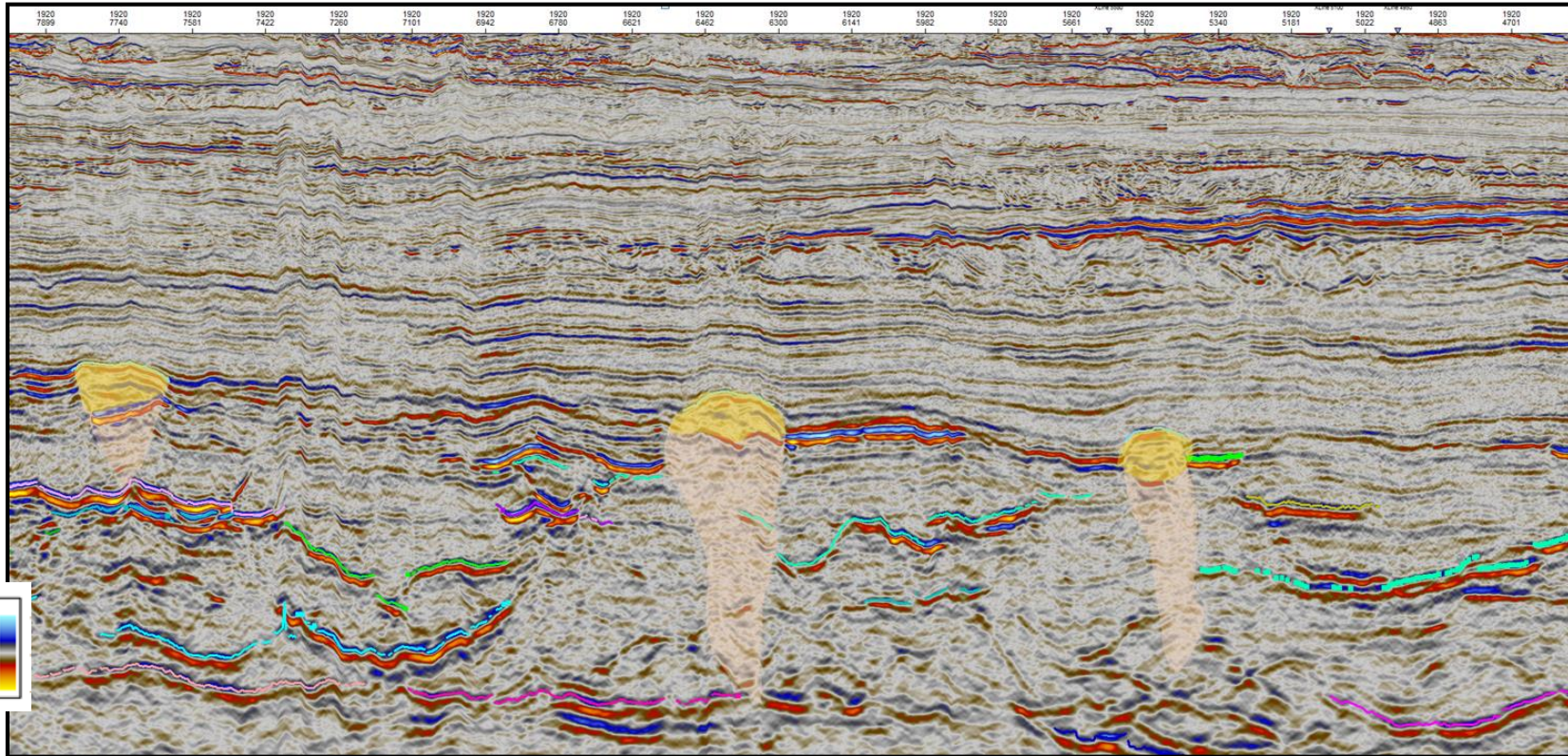
Sills on the 3D northern 3D seismic, offshore Morondava Basin



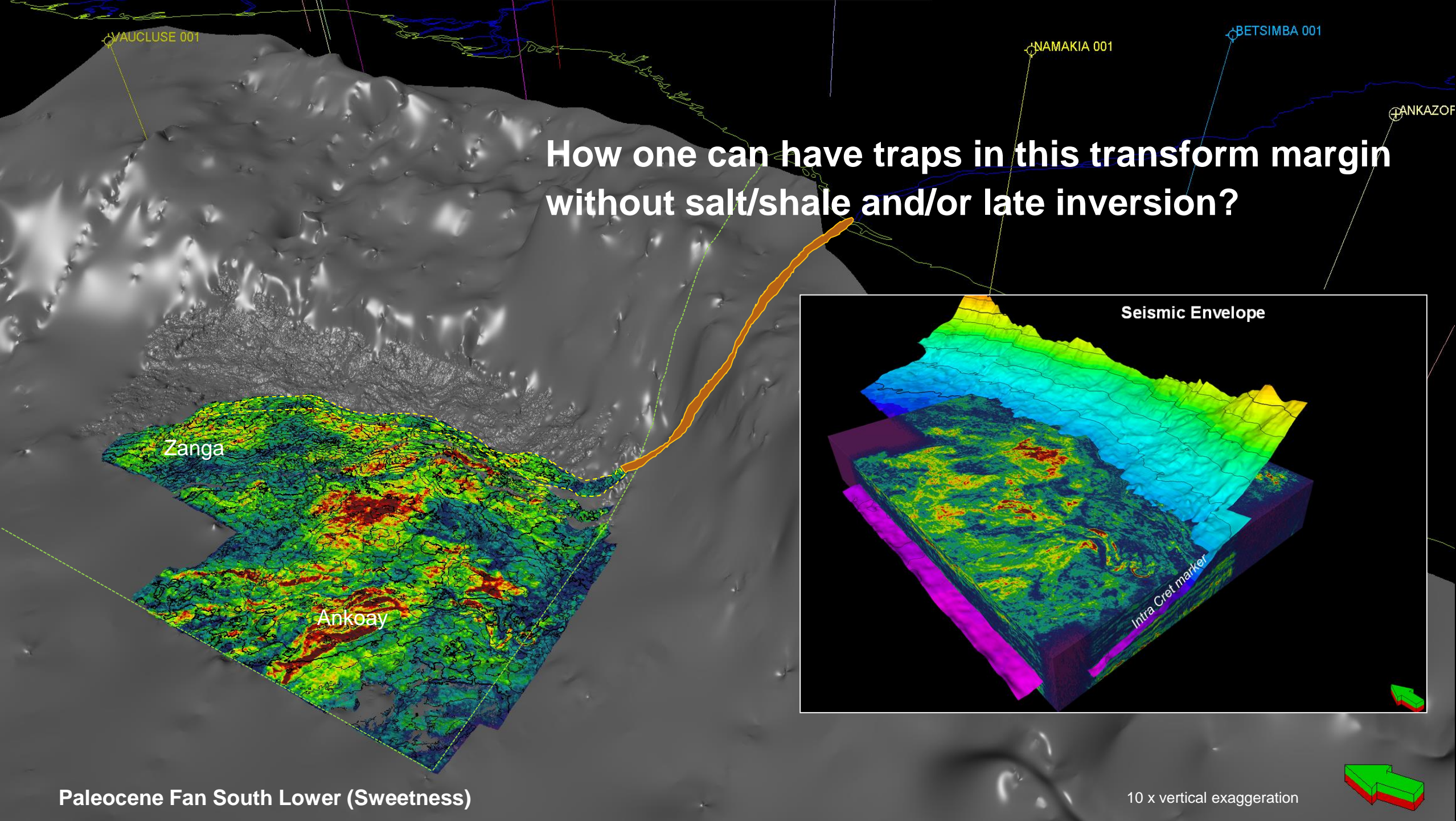
Sills and volcano on 3D seismic, Morondava Basin



Hydrothermal vent complexes confirm timing of intrusive activity (Turonian)



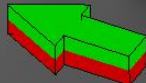
- ▶ Vent complexes are located above sills and formed as a direct consequence of the intrusive event, formed by the explosive eruption of gases, liquids and sediments
- ▶ Just a few vent complexes identified on the southern Grand Prix (2015) data set – all at the Turonian level. As these form at the paleo-seafloor during intrusive episodes, they provide additional support that the intrusives are Turonian in age (and older)
- ▶ Reservoir quality implications – Cenomanian-Turonian reservoirs were close to the sea floor during the intrusive events, therefore the diagenetic effect of the hot mineralising fluids on the reservoirs thought to be limited



How one can have traps in this transform margin without salt/shale and/or late inversion?

Paleocene Fan South Lower (Sweetness)

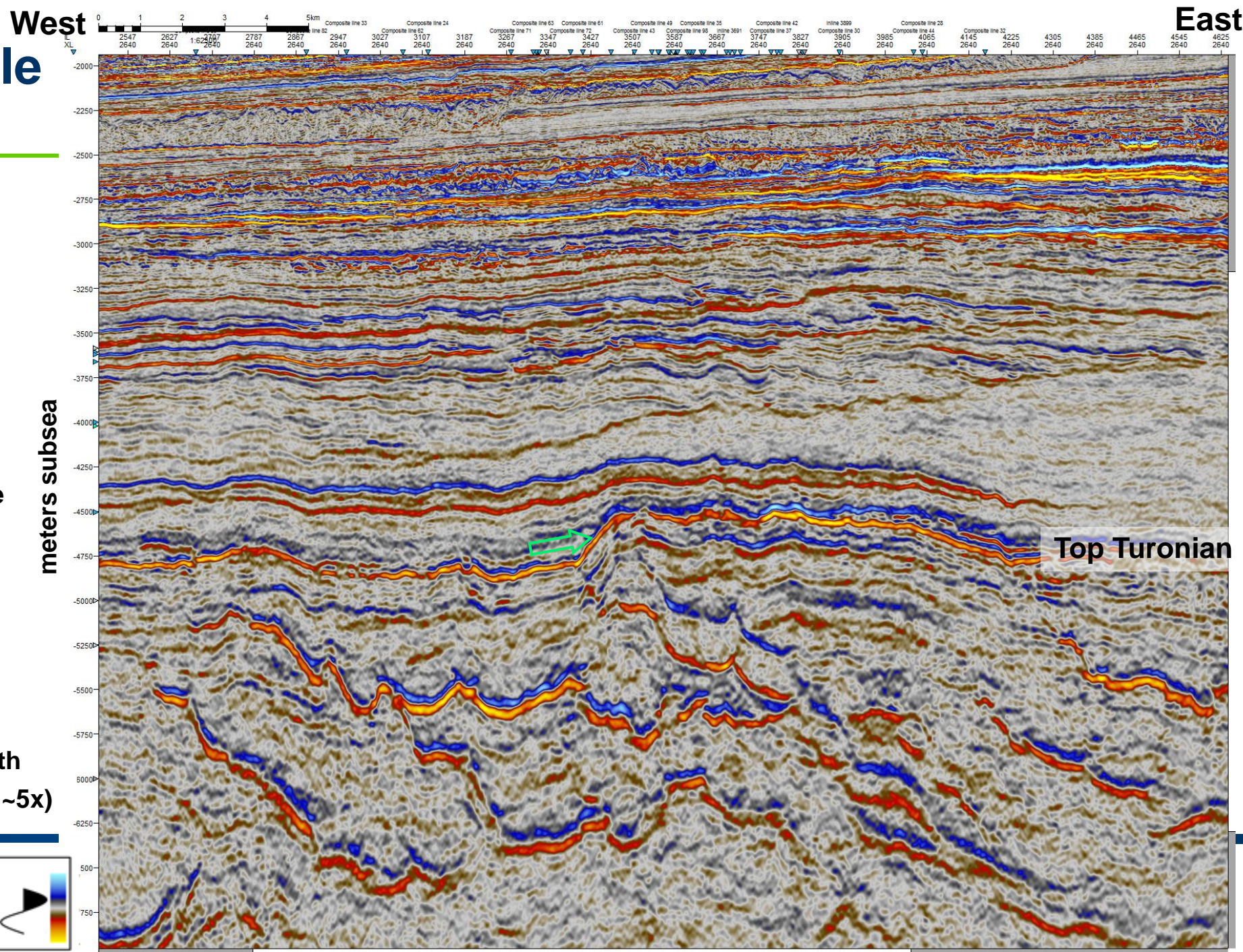
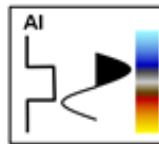
10 x vertical exaggeration



3D PSDM example „southern 3D“

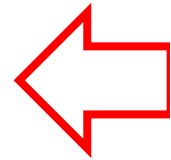
- ▶ Most sills have distinct top (peak) and base (trough) reflectors suggesting thicknesses on the order of tens of meters
- ▶ Some 100 sills were mapped by auto-tracking top sill (peak) horizons
- ▶ Most sills appear to ramp up preferentially basinward, to the west, causing asymmetry
- ▶ Note pronounced onlap (green arrow) on the basinward flank of the forced fold, post-dating the intrusive period

PSDM XL 2640, in depth
(vertical exaggeration ~5x)

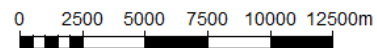
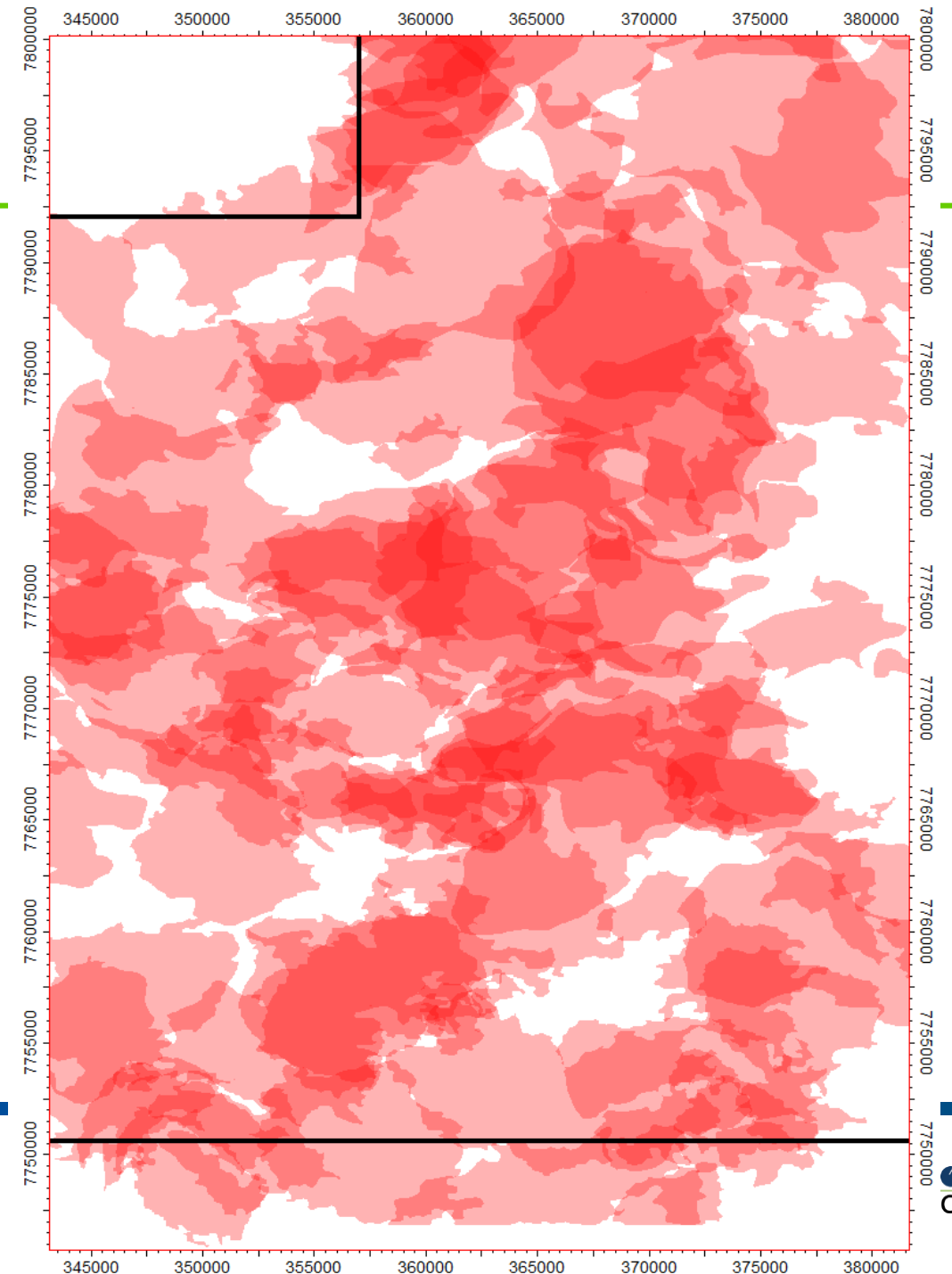


Stacked sills mapped on 3D seismic

- ▶ Some 100 sills were mapped in a circa 3000 km² 3D area by auto-tracking top sill horizons (peaks)
- ▶ Most sills are not isometric and saucer-shaped but rather elongated in an W-E direction, tongue-shaped and ramping up to the W
- ▶ Locally the stacking of up to 5 sills can be observed (sill polygons on the map are displayed with 80% transparency)



Regional basinward tilt



Compound forced folds

- ▶ Multiple intrusive events can cause fairly large four-way closures above sill complexes (Magee et al., 2014)
- ▶ In a deepwater basin, like the Morondava Basin of Madagascar, which would not have any other hydrocarbon traps due to regional monoclinial basinward dip (in the absence of salt, shale or late-stage structural inversion) this trapping style becomes a critical element in the petroleum system

C. Magee et al.

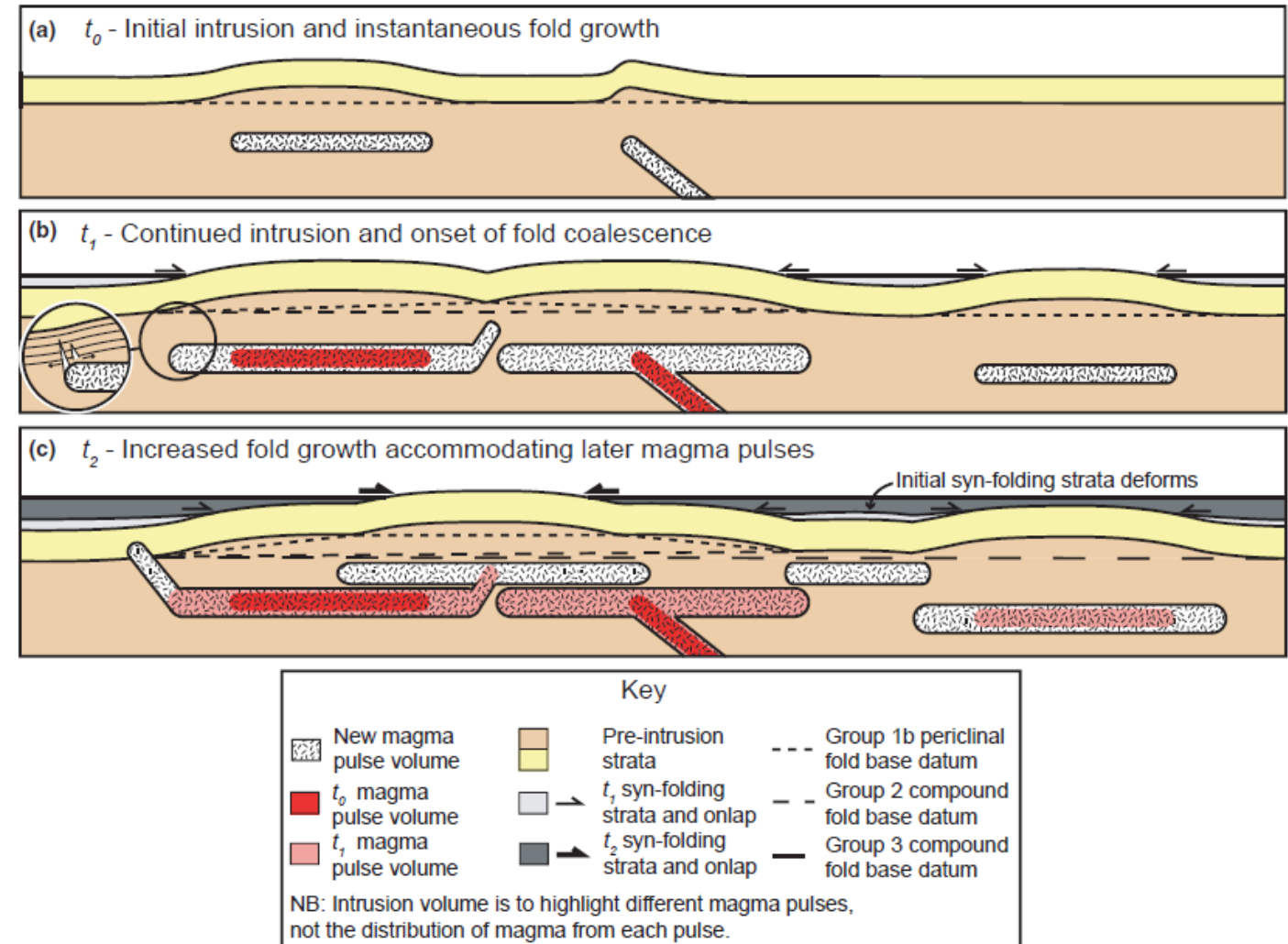
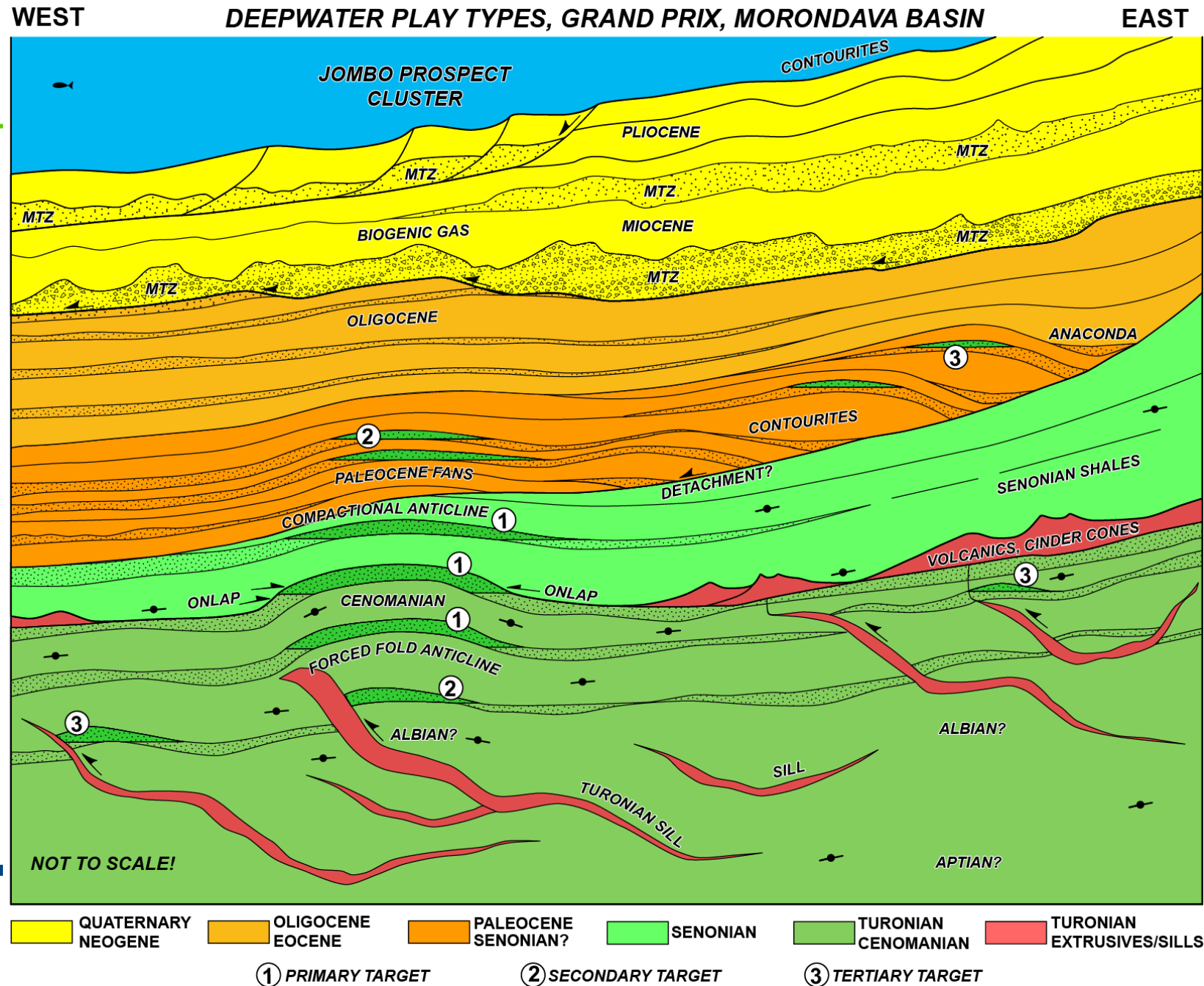


Fig. 13. (a) Initial intrusion of two thin sills generating two laterally adjacent but non-interfering forced folds. (b) Continued magma flow into the two sills induces inflation and instigates a proportional increase in fold amplitude. Where the two folds interfere, their lateral extent becomes pinned and the inflection point between them is uplifted; potentially allowing the two folds to merge into a larger volume compound fold. (c) Further intrusion may increase fold size and deform onlapping sediments deposited during the previous phase of fold growth. Note that the fold amplitude becomes a function of multiple intruded sills and cannot be related to the thickness of an individual intrusion. The length of the fold datum's for each group highlight fold width.

Deepwater play types

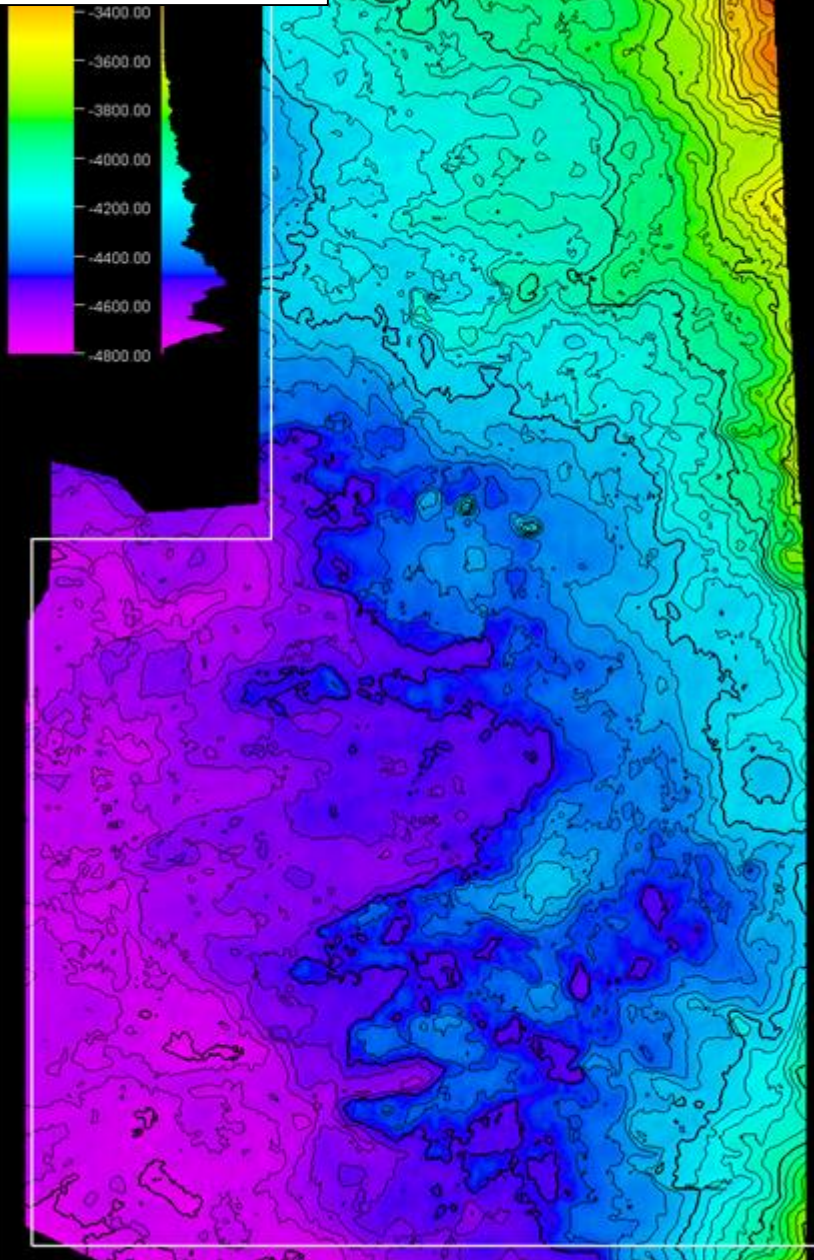
Grand Prix, offshore Morondava

- ▶ Combination traps due to differential compaction within Paleocene, *secondary target*
- ▶ Four-way closure due to differential compaction within Senonian (Santonian?), *primary target*
- ▶ Four-way closures in compound forced folds within Cenomanian-Turonian, *primary target*



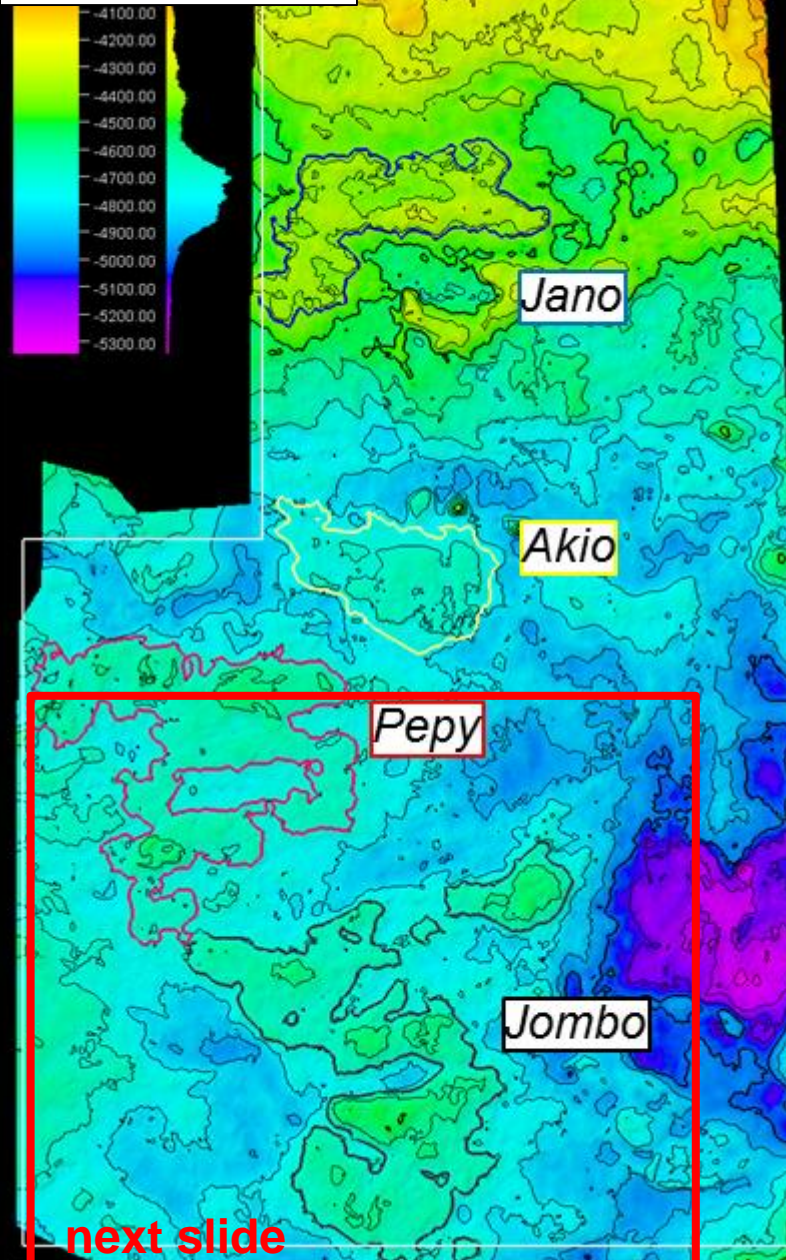
Turonian Green TWT

CI 50ms



Turonian Green Depth

CI 100m



Near top Turonian „Green“ horizon

- ▶ Cenomanian-Turonian forced folds have a pronounced expression in the time domain (left) and are robust closures in depth (right)
- ▶ These closures are large enough to provide economic traps for the deepwater setting (i.e. average water depth of about 1500 m)

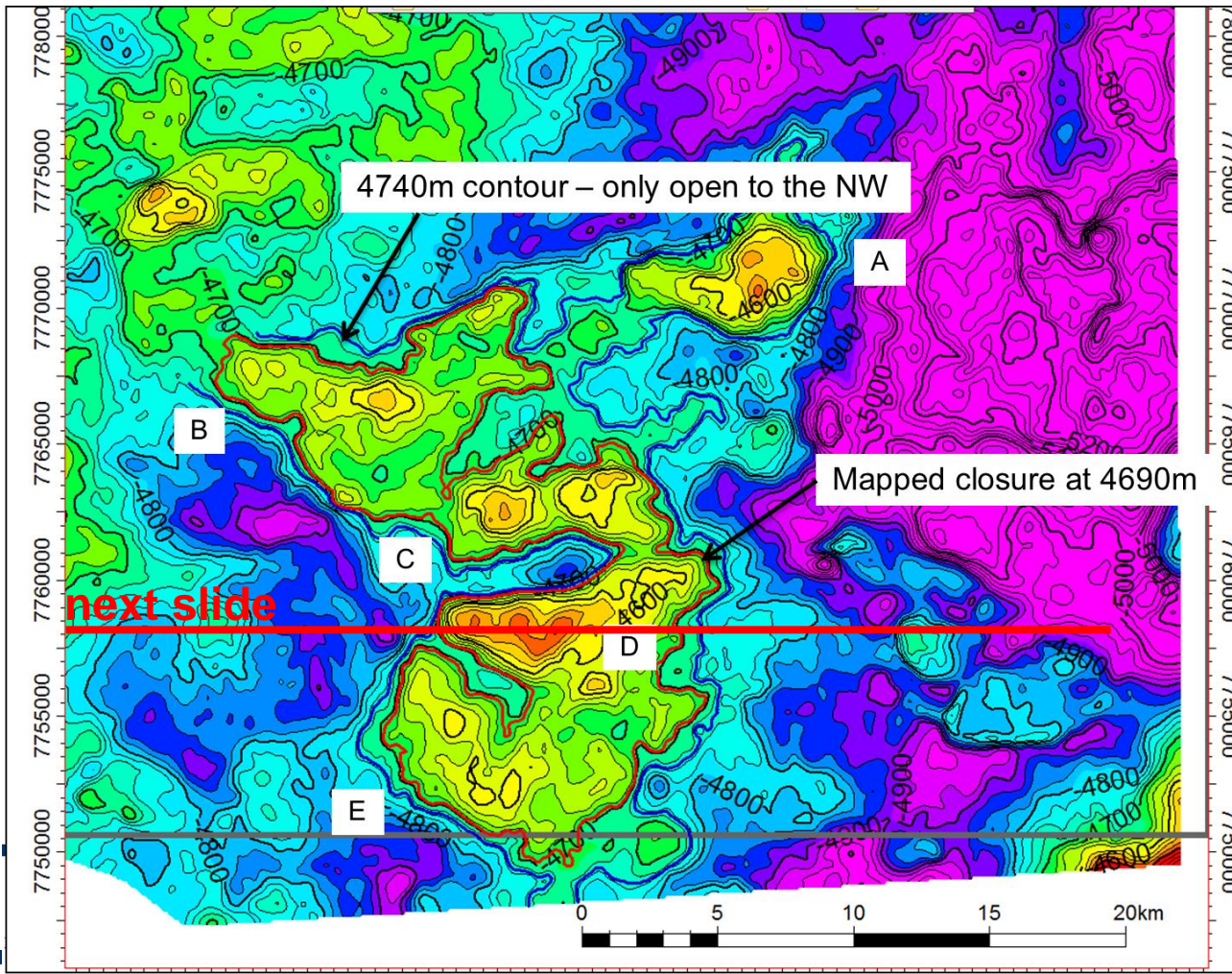
Jano: 80 km²

Akio: 66 km²

Pepy: 151 km²

Jombo: ~250 km²

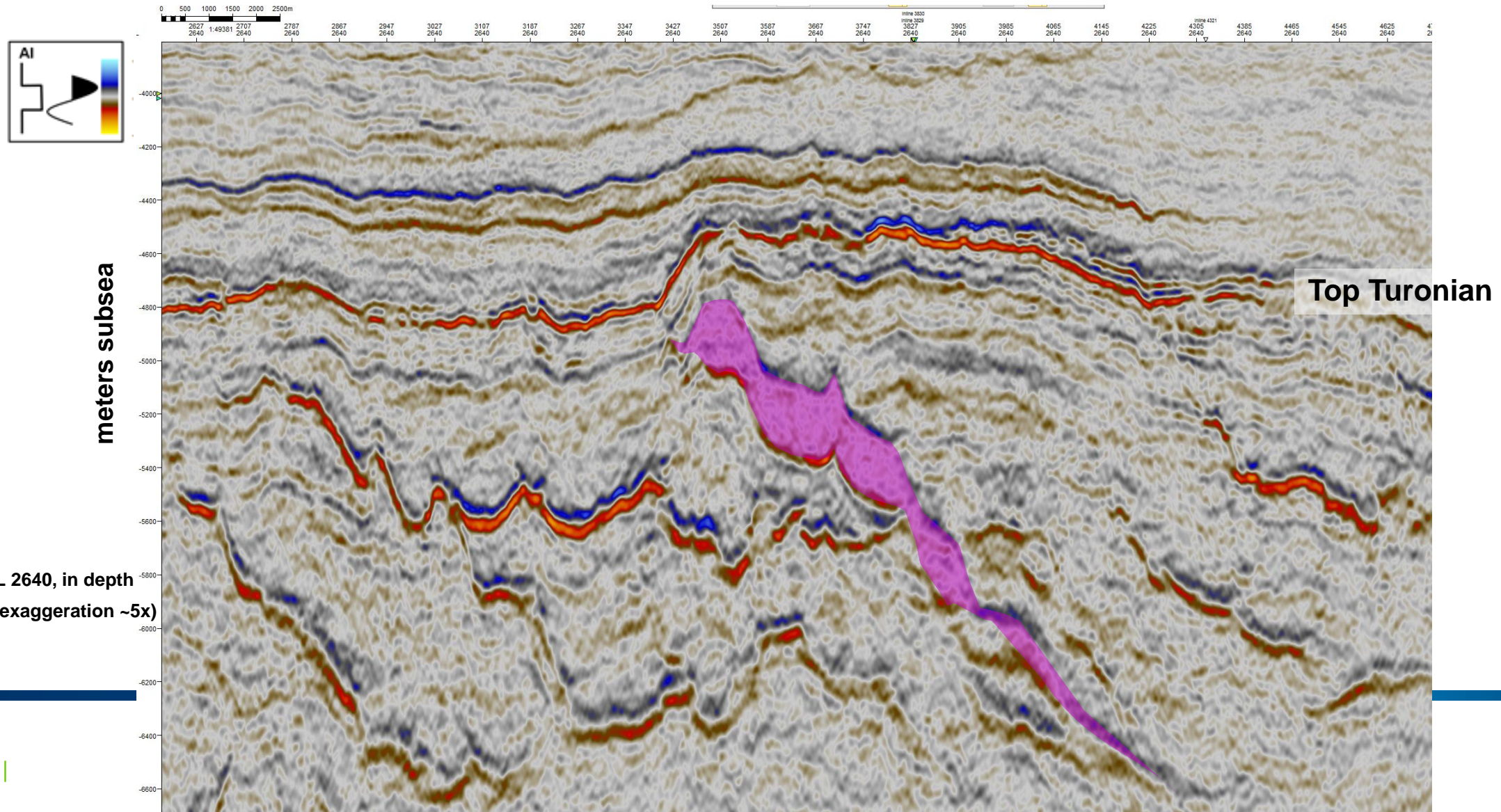
Near top Turonian depth structure, Jombo Prospect cluster



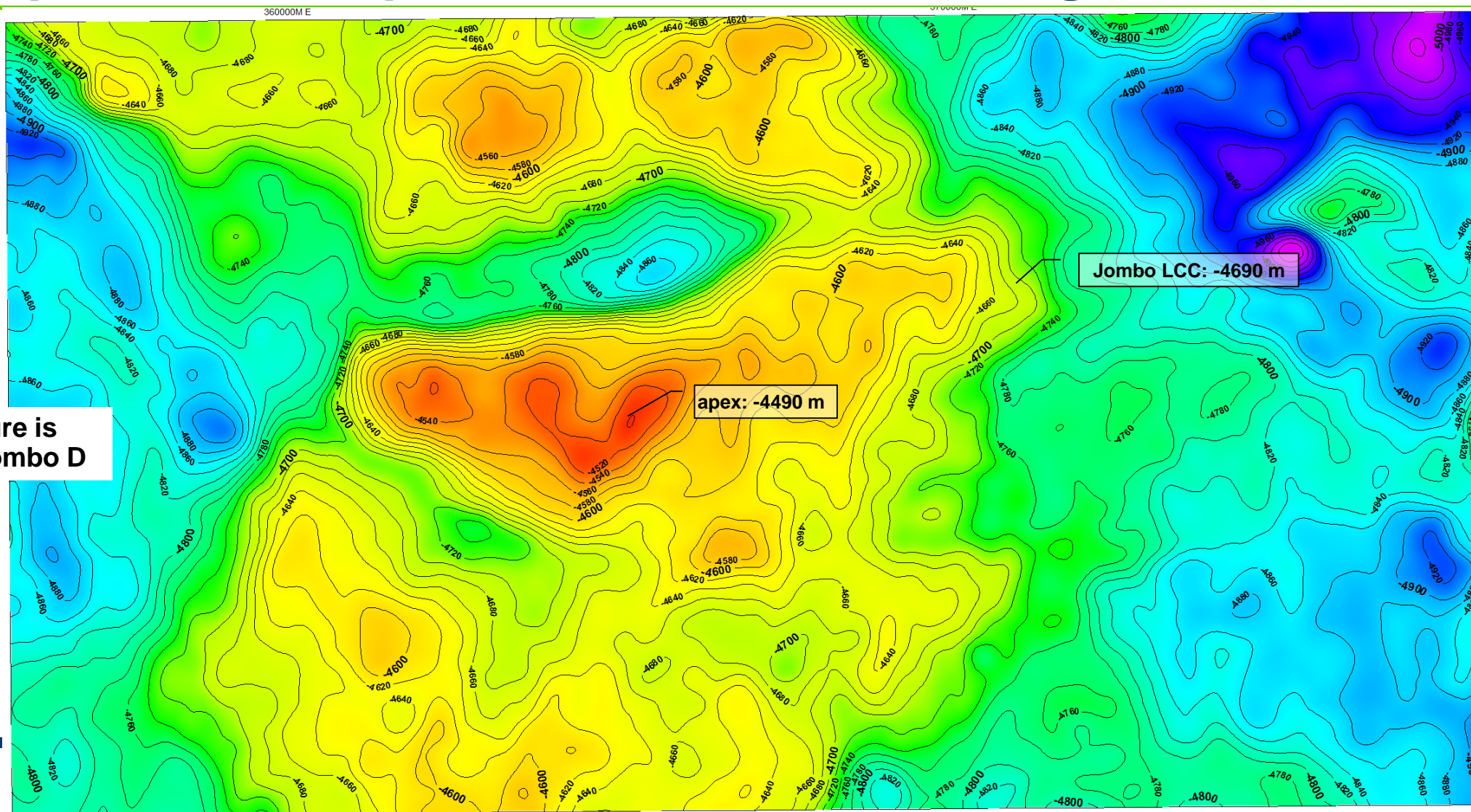
Turonian „Green“ depth structure, CI: 25 m

- ▶ Large compound forced fold structure 175-250 km² areal closure (4690 m- 4740 m contour), crest @ 4490 m (~3000m bml).
 - ▶ Robust closures not sensitive to depth conversion, mapped on high quality PSDM 3d data.
- ▶ Thick reservoir section ~500m thick
 - ▶ Good potential for stacked pay analogous with Paleocene reservoir systems, where laterally extensive shales between the fans can be mapped
 - ▶ Many of the intrusions stop at the base of the interpreted reservoir package
 - ▶ “Amoeba-shaped” complex structural closures are entirely due to underlying Turonian sills
- ▶ Laterally extensive deep marine shales should form an effective top seal. No faulting observed.
- ▶ Oil-mature Albian source rocks (immediately) underlying reservoir – simple migration pathways
 - ▶ Favourable timing: traps created during Turonian, charge modelled from late Cretaceous onwards, main oil window was reached in Eocene

PSDM XL 2640 across Jombo D, with „inflated“ sill



Near top Turonian depth structure, Jombo D segment

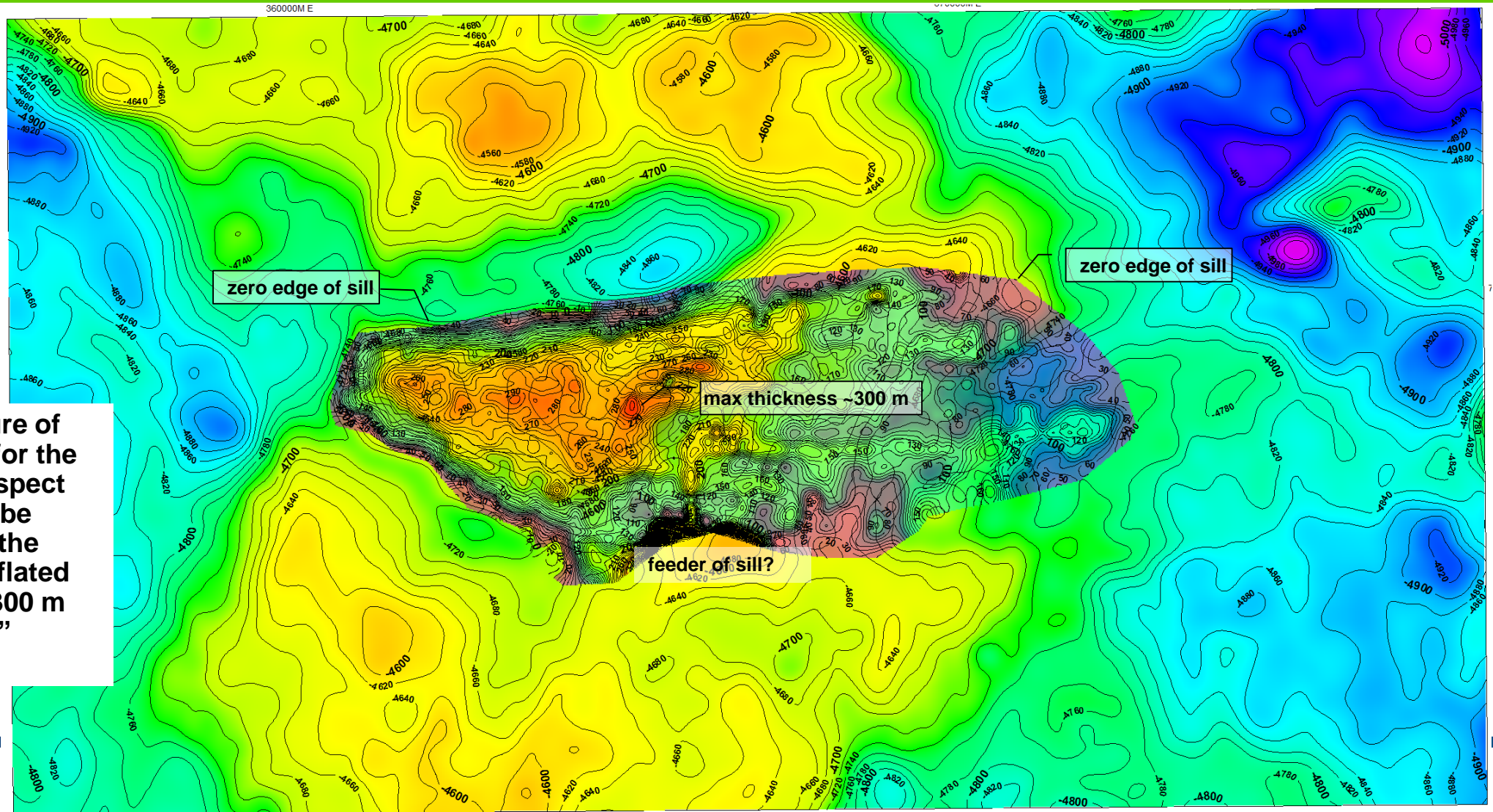


► Vertical closure is
~200 m for Jombo D

Turonian „Green“ depth structure, Cl: 20 m

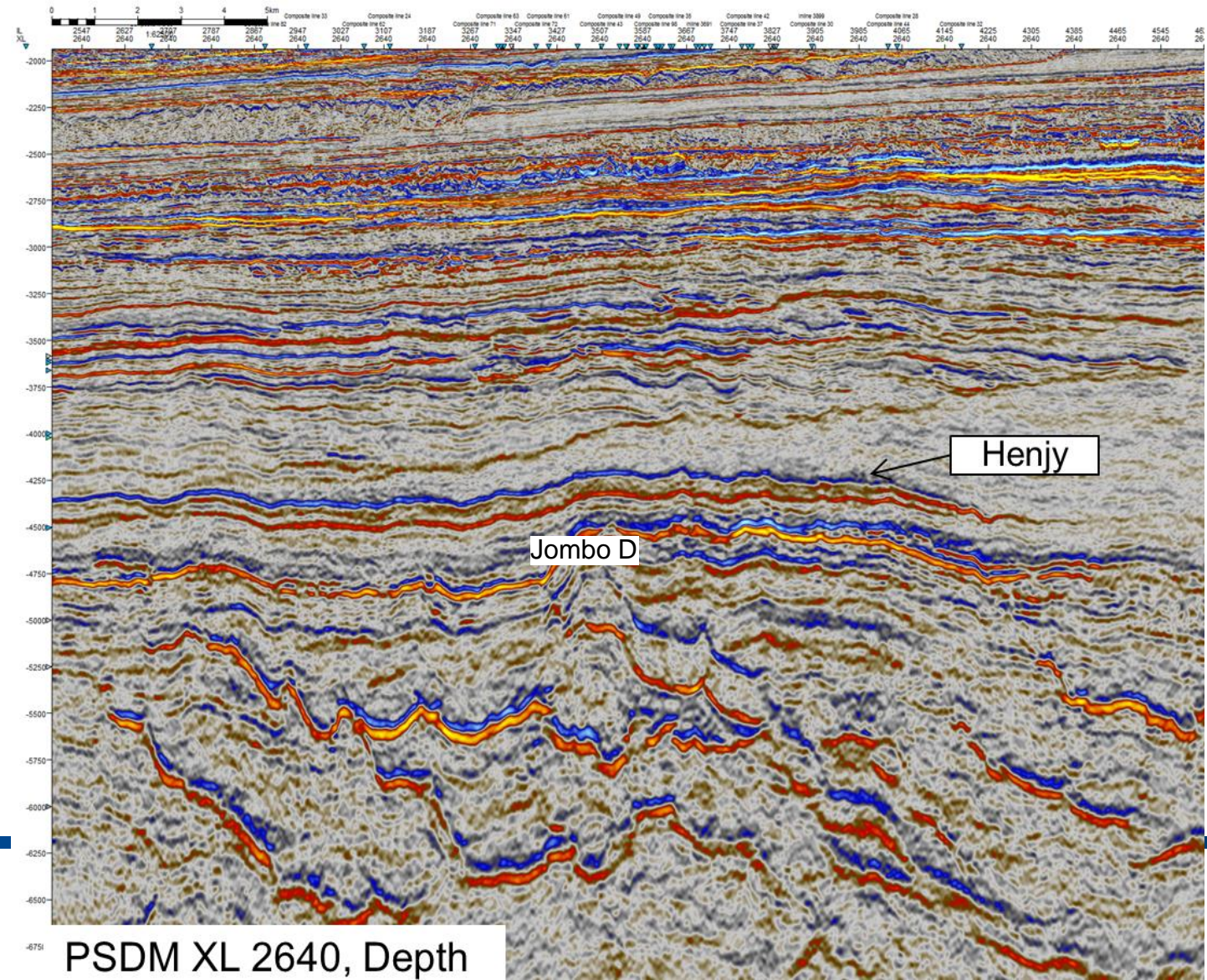
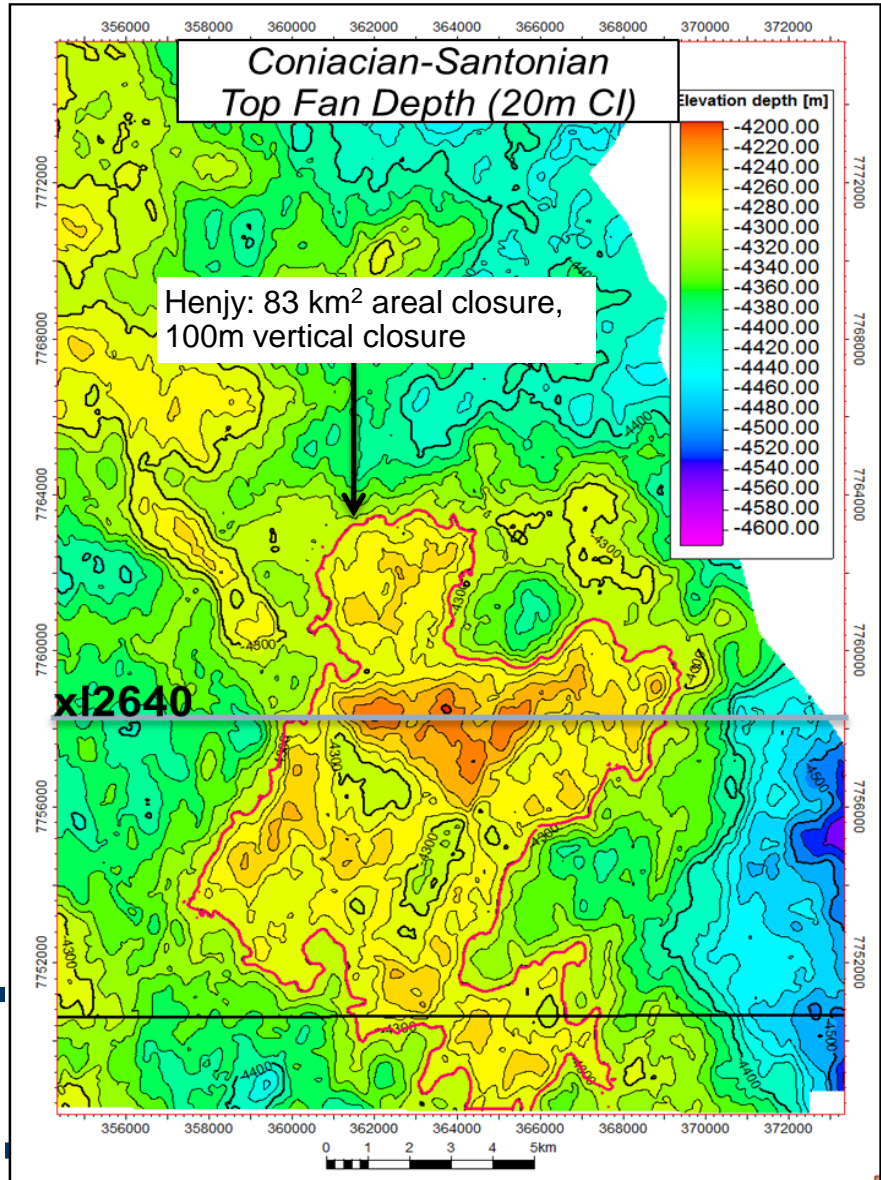
1:50000
0 1 2
KILOMETRES

Jombo D depth structure and „vertical“ isopach of underlying sill



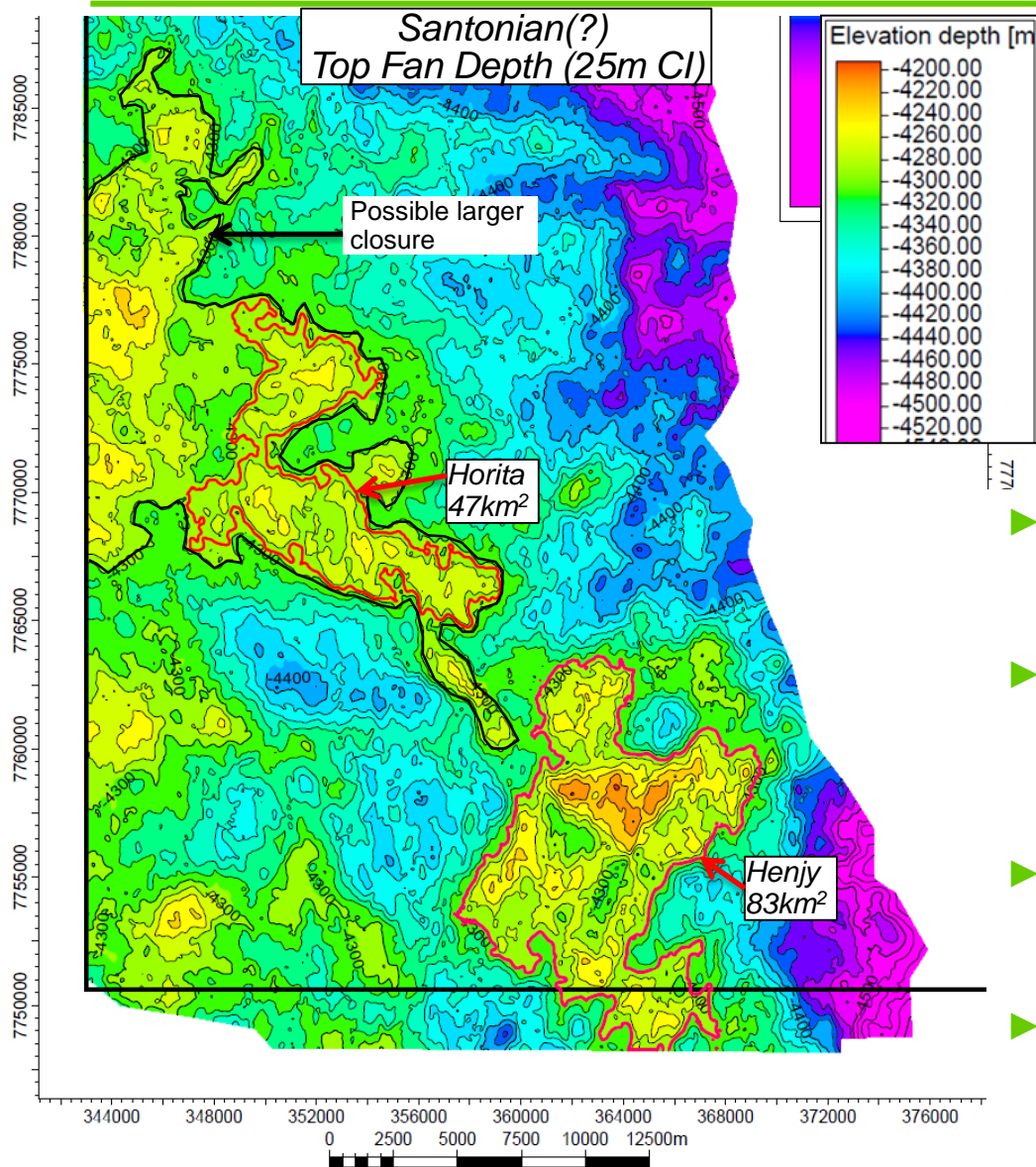
- ▶ Vertical closure of about 200 m for the Jombo D prospect segment can be explained by the underlying inflated sill with its ~300 m max “vertical” thickness

Santonian(?) fan, in compactional drape above Turonian forced fold

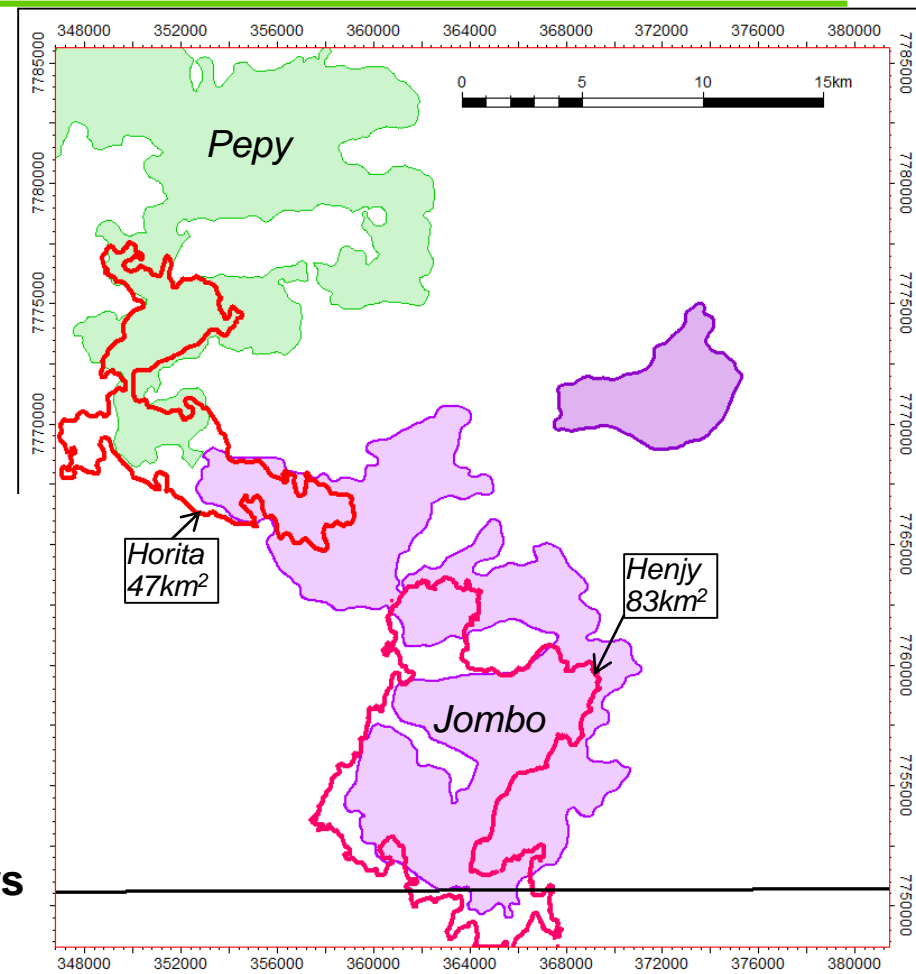


Santonian(?) 4-way closures

Turbidites in four-way closures created by differential compaction above Turonian structures



- ▶ Santonian compactional closures overlie Turonian compound fold structures
- ▶ Henjy would spill up towards Horita; Horita could be part of a larger structure to the west
- ▶ Simple migration pathways from oil-mature Turonian source rocks
- ▶ Reservoir encased in laterally extensive deep marine shales



Deepwater play types

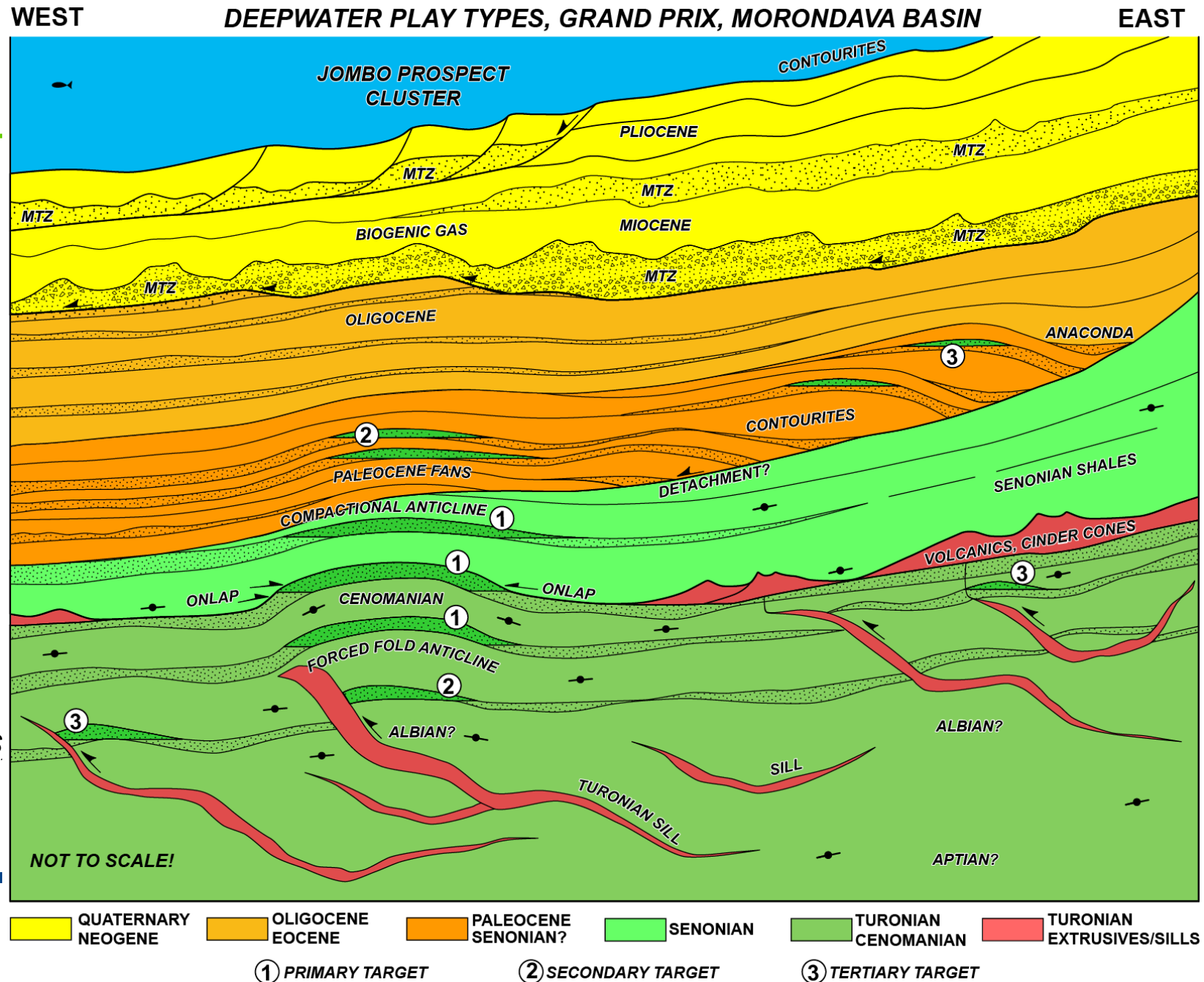
Grand Prix, offshore Morondava

The importance of sills:

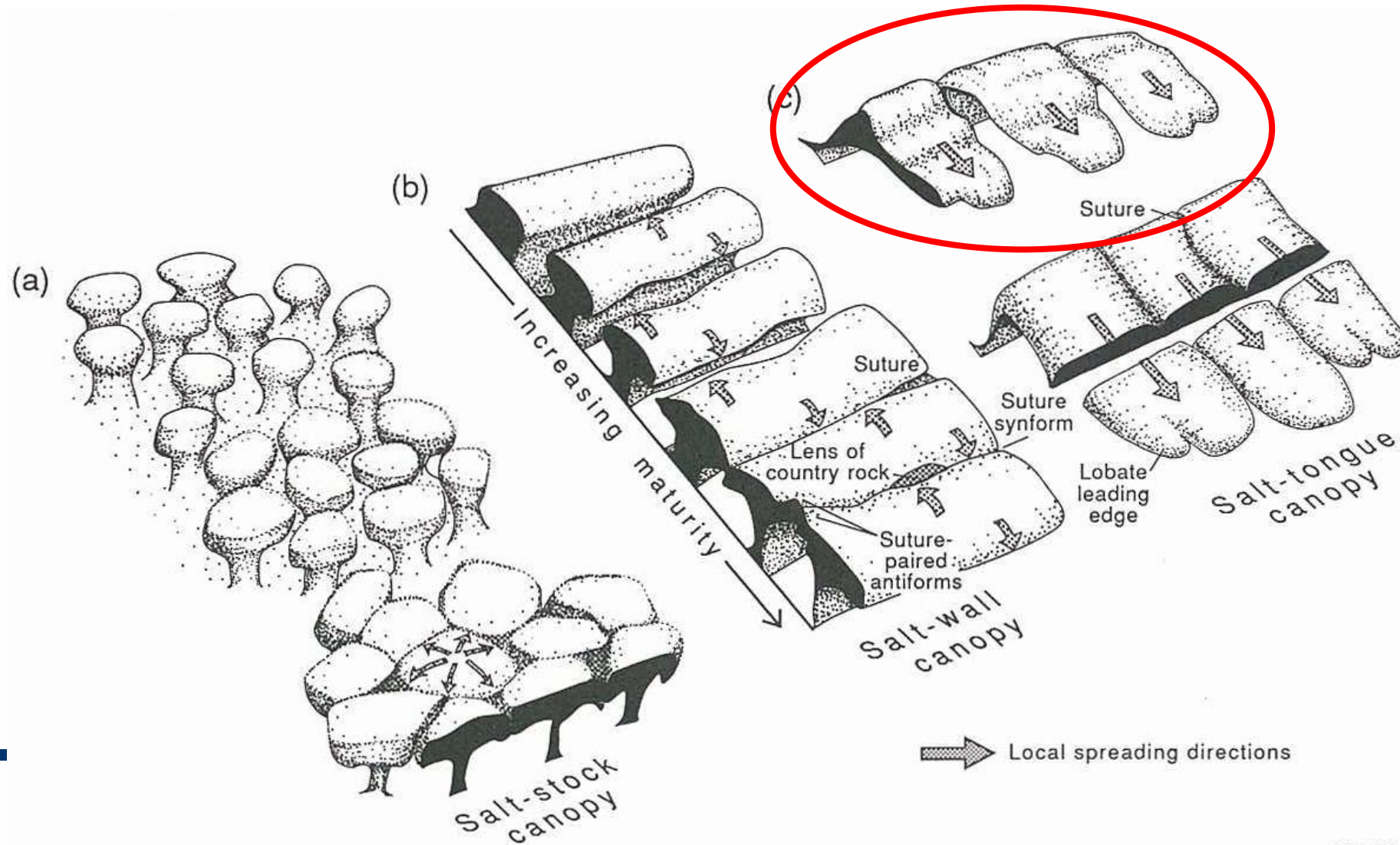
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- ▶ Four-way closures in compound forced folds within Cenomanian-Turonian, *primary target*

Other plays for the first well are considered to be:

- ▶ too complex (Oligocene strat traps)
- ▶ smallish (Anaconda area contourites)
- ▶ too deep (Albian/Aptian clastics between sills)

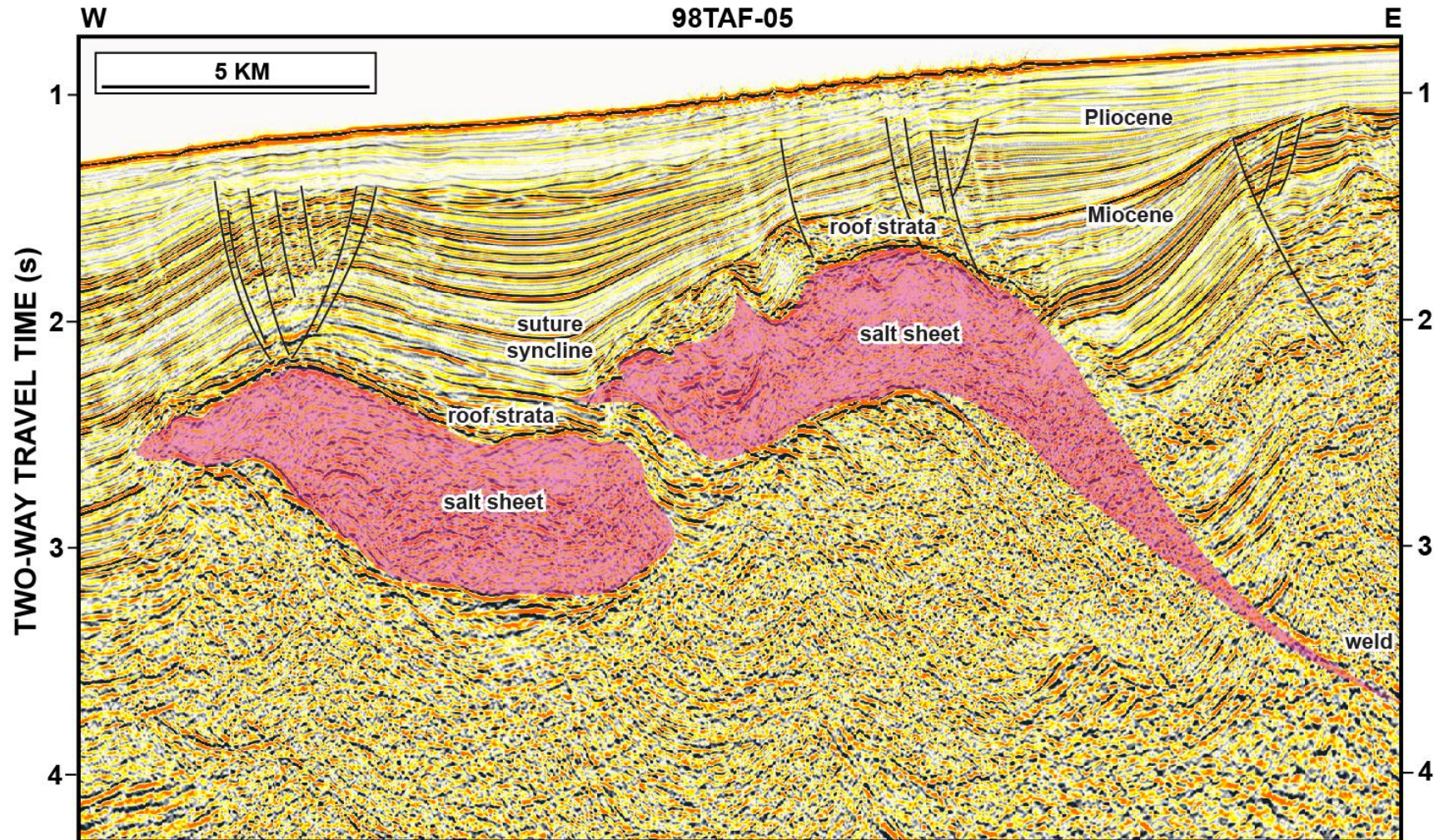


Analogy with salt tectonics?... „Sill tongues“



Jackson and Talbot (1991)

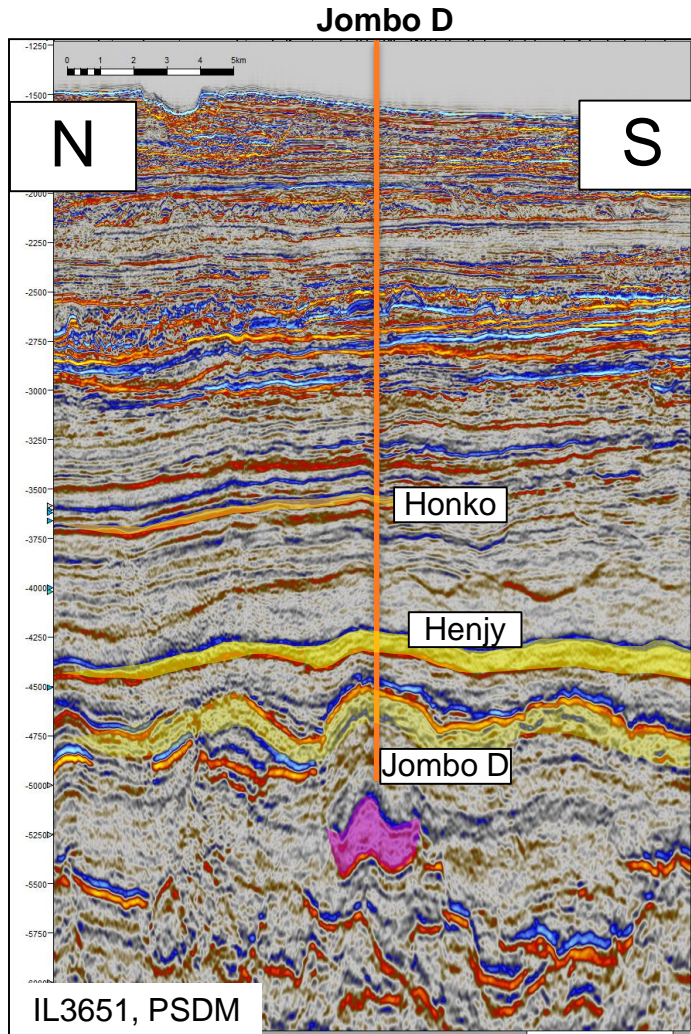
Analogy with salt tectonics? Salt tongues/sheets, offshore Morocco



Tari and Jabour (2012)

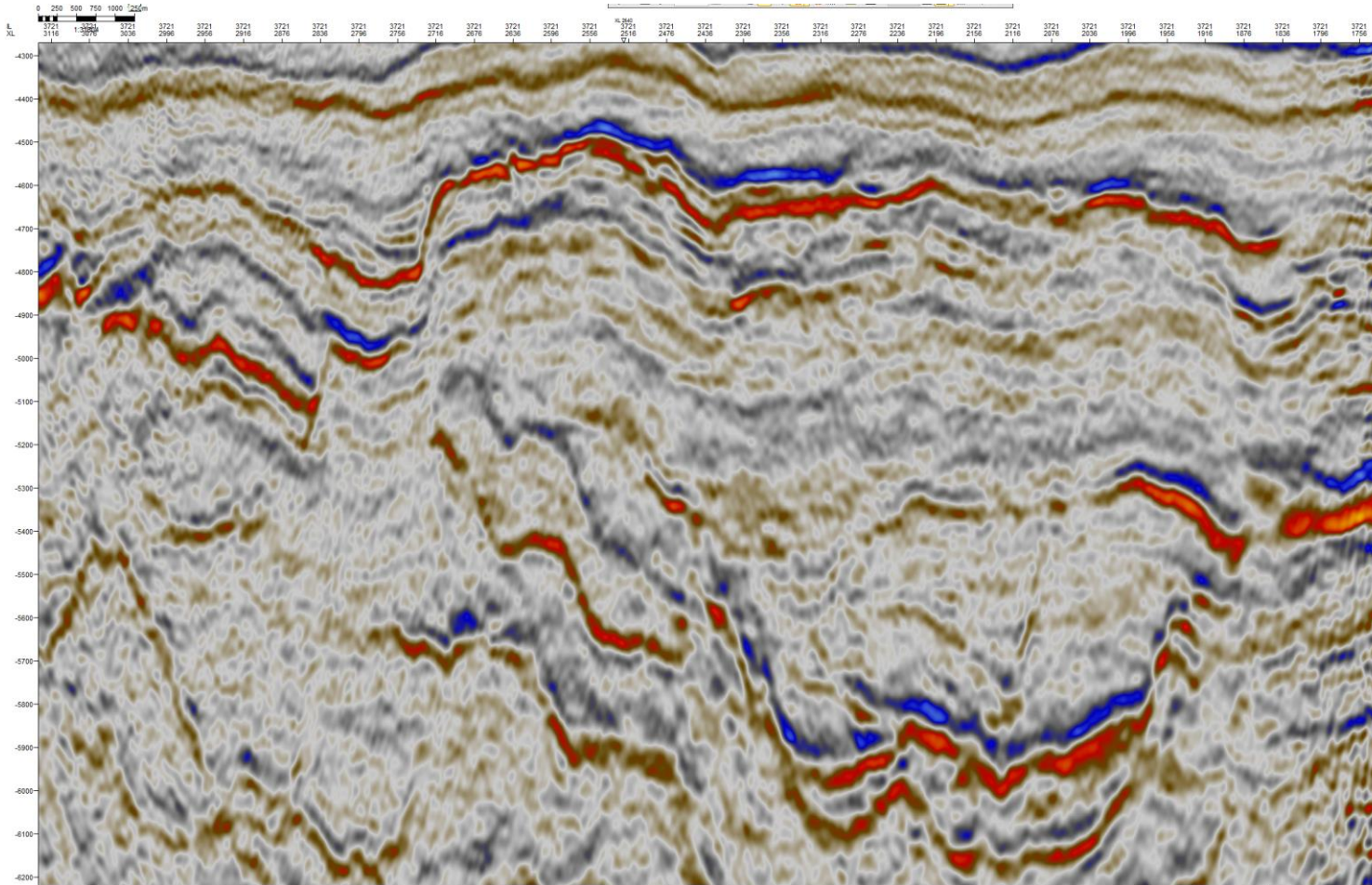
Seismic illustration of the interaction of two salt sheets to form a salt canopy in the central part of the Moroccan salt basin. As one salt sheet overrides the other, the sediments in between are getting trapped in an early-stage asymmetric allosuture (*sensu* Dooley et al. 2012). Whereas the feeder for the overriding inboard salt sheet is within the plane of the seismic section, the feeder for the outboard sheet is not.

Morondava Basin, Madagascar, exploration highlights/conclusions



- ▶ Short-lived magmatism (Turonian, ~93-91 Ma), compared to other volcanic basins (West of Shetland, Rockall, etc.)
- ▶ Lack of regional impact on maturation by Turonian magmatism
- ▶ Without Turonian sills there would not be a trapping mechanism in the Morondava basin
- ▶ Pronounced regional basinward tilt produced asymmetric sills
- ▶ Exceptional, “inflated” sills can alone account for large 4-way closures without compounding effect.
- ▶ Sufficient vertical relief for closure to be enduring through time, resulting in potential stacked pay
- ▶ Analogous with salt tectonics, i.e. salt versus sill tongues/sheets?
- ▶ The industry still has a “mental block” about magmatic basins
- ▶ This mental block could be cured by a discovery in the Morondava Basin!

PSDM IL 3721 across Jombo D, with „inflated“ sill



Acknowledgements:

- ▶ OMNIS (<http://www.omnis.mg>)
- ▶ EnerMad Corporation (www.enermad.com)