PS Multi-Attribute Analysis of Six Upper Cretaceous and Jurassic Structural Closures in Belo Profond, Morondava Basin, Offshore West Madagascar*

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Abstract

Recent publications have brought attention to hydrocarbon prospectivity in the Morondava Basin off the west coast of Madagascar. This geological and geophysical interpretation yields more detail over an approximately 700 km^2 3D seismic survey covering a structurally anomalous area 100 km offshore in the Belo Profond. Six prospects were identified as structural closures in the late Jurassic to late Cretaceous formations, and described using RMS amplitude extractions, spectral decomposition, and seismic-limited AVO analyses. Challenged by igneous lithologies, a Bouguer gravity map was applied to discriminate between the bright amplitudes of the prospects and of the intrusive sills that permeate the Early Jurassic units and spread upward through the section.

Distal siliciclastic sediment deposited from the east during the Late Jurassic to Upper Cretaceous in Morondava Basin, captures in its architecture the latent movement on failed Karoo rift faults, and the development of the Davie Ridge, which contributed sediment from the west. Abundant igneous sills lace the 1.5 km of sediment supplied during the drift phase in the Mesozoic, intruding along weak bedding planes and fault surfaces, and underpinning flower structures within the limits of this survey. The presence of intrusive sills increased trap sizes but may have locally impacted the reservoir quality and compartmentalized closures where they migrated up into the reservoir interval. The overlying sedimentation was deposited during the current passive margin structural domain and is comprised of roughly 1 km of sediment thickness. It includes a dramatically thick and extensive Mass Transport Complex, originating to the east and associated with a possible Oligocene/Miocene shelf collapse.

Within the six prospects this study describes, there is little evidence for igneous lithologies. The Belo Profond study area contains considerable hydrocarbon reservoir potential: nearly 2.5 km of sand, shale; sufficiently deep organic material for thermal maturation; structures derived from uplift, erosion, transpression and transtension, and igneous intrusion, creating potential traps; faults and deep seal breaches providing migration pathways. Any fluid escape or leakage in the shallow regional seals across the survey are localized and minimal, given seepage records across the region. The vertically-overlapping stacked prospects appear to be the best area of interest.

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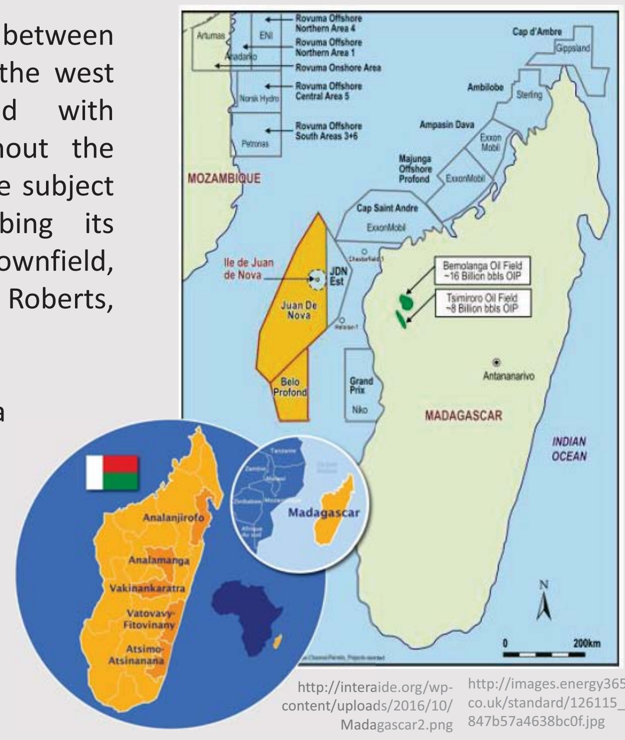
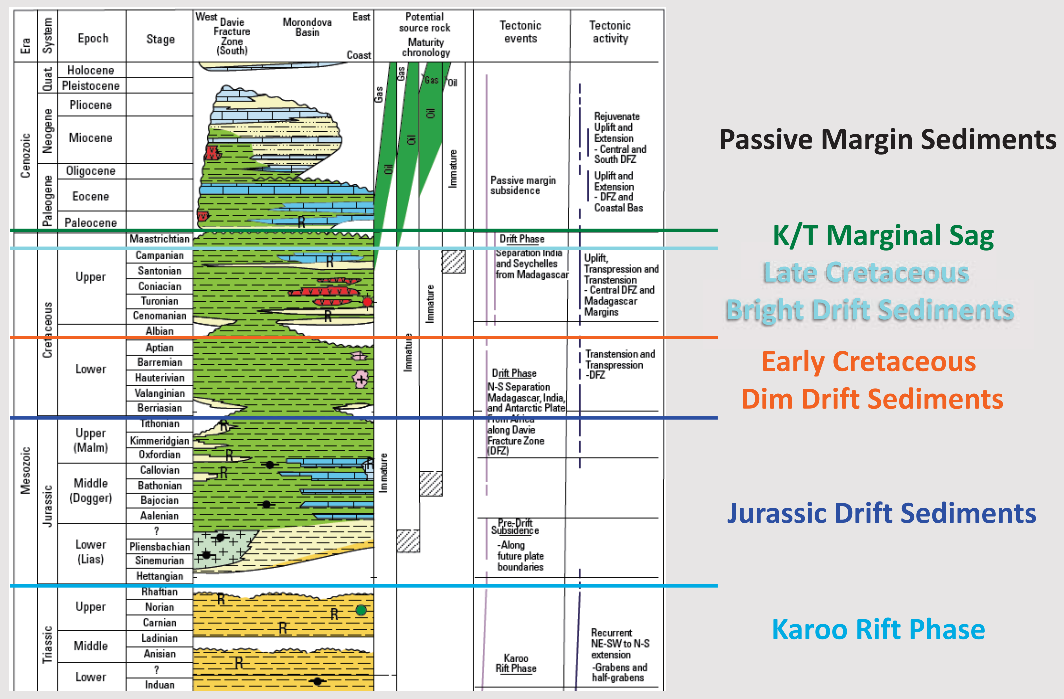
MORONDAVA BASIN GEOLOGIC CONTEXT

The Morondava Basin is located between the coast of Mozambique and the west coast of Madagascar. Filled with continental deposition throughout the Mesozoic, this area has been the subject of many publications describing its character and prospectivity (Brownfield, et al., 2016; Dirkx, r., et al., 2016; Roberts, et al., 2013).

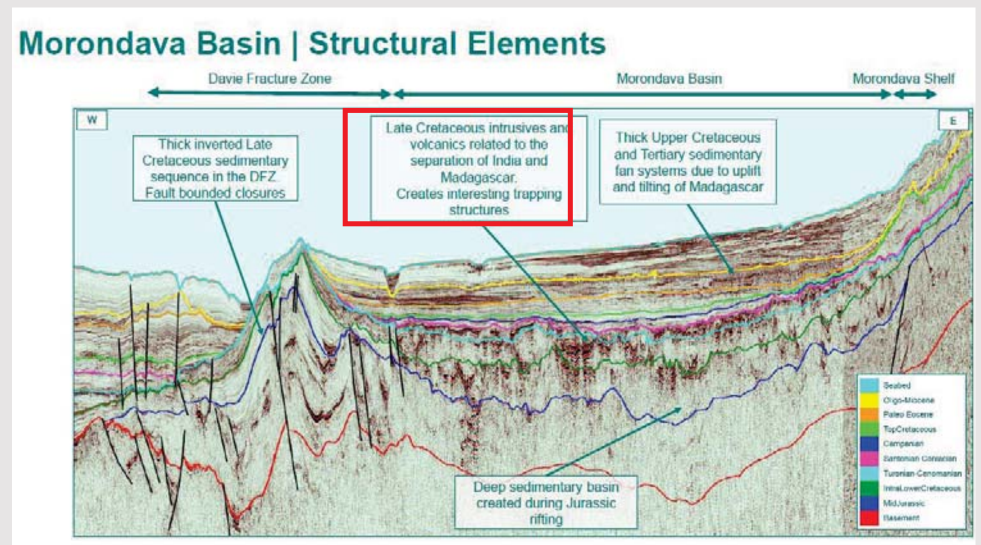
Belo Profond is a protraction area within this basin, just south of the Juan de Nova (JDN) area. The Area 3 survey is located on the east side of Belo Profond, and covers nearly 800 km^2.





Modified from Brownfield, et al., 2016)

A failed rift of Triassic Karoo sediments comprises the structural basement for the intervals of interest in Area 3. These extensional faults form the basis for later fracturing throughout the survey. Overlying that are parallel sediments that were uplifted and experienced considerable erosion toward the end of the Jurassic, resulting in a high-relief late Jurassic Unconformity (Dirkx, R., et al., 2016).



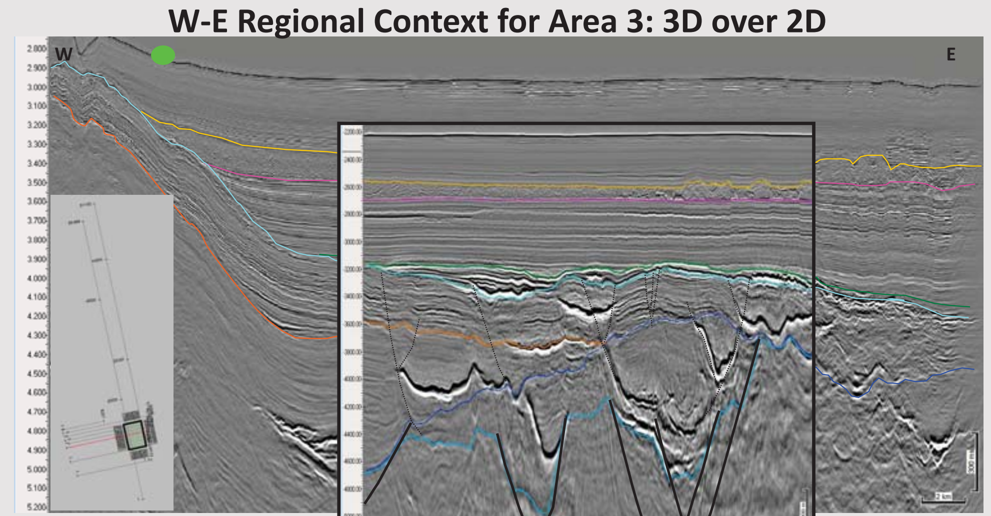
Dirkx, R., et al., 2016)

Though rifting continued at Seychelles to the east of Madagascar, the Cretaceous in the Morondava Basin is characterized by drift sedimentation. Continued transform movement along the Davie Ridge created sediment to fill in accommodation space left, and the onlap of clastic sediment and potentially carbonate development through the early-mid Cretaceous. The uppermost Cretaceous is characterized by brighter and less even deposition, followed by the marked presence of transpression and transtension in the form of low-relief flower structures. These structures are linked to Jurassic projections of rift faults, and occurred nearly concurrently with emplacement of igneous bodies, which exaggerated these low-relief structures into the pop-up anticlines. These sills burst in along faults and weak bedding planes and fault planes, occasionally cracking up through the existing stratigraphy. A greater abundance of igneous bodies intruded to the east than the west, but the examples to the west are fewer, but thicker and more expansive.

The thin Marginal Sag interval was deposited while these last tectonic movements were settling into their current position, but before the quiescence of the modern passive margin. The Marginal Sag interval has an onlapping relationship to the top Bright Drift, as well as a ductile deformation response to the emplacement of the intrusive igneous bodies, unlike the passive margin sediments just above them. It is likely that Marginal Sag strata act more as a seal than an addition to the reservoir units below.

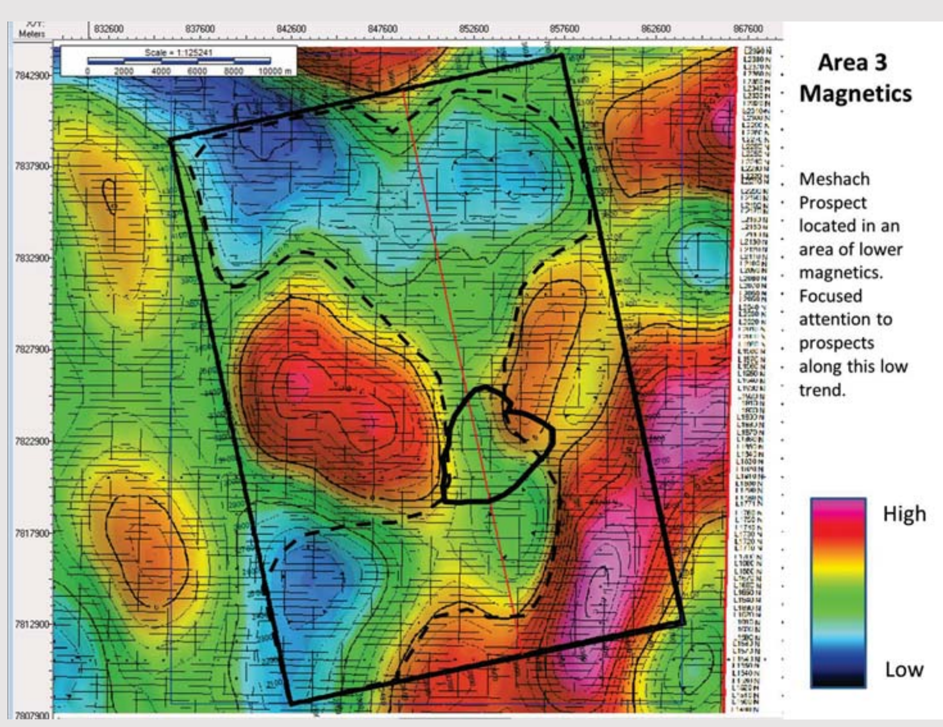
The uppermost unit in the section is the Passive Margin structural domain, which has persisted to the present. Containing roughly 1 km of sediment above the Maginal Sag Unconformity, the Passive Margin features largely even parallel stratigraphy, not much broken by faults or channels, with one exception: a dramatically thick and extensive Mass Transport Complex, originating to the east and associated with a possible Oligocene/Miocene shelf collapse.

W-E Regional Context for Area 3: 3D over 2D

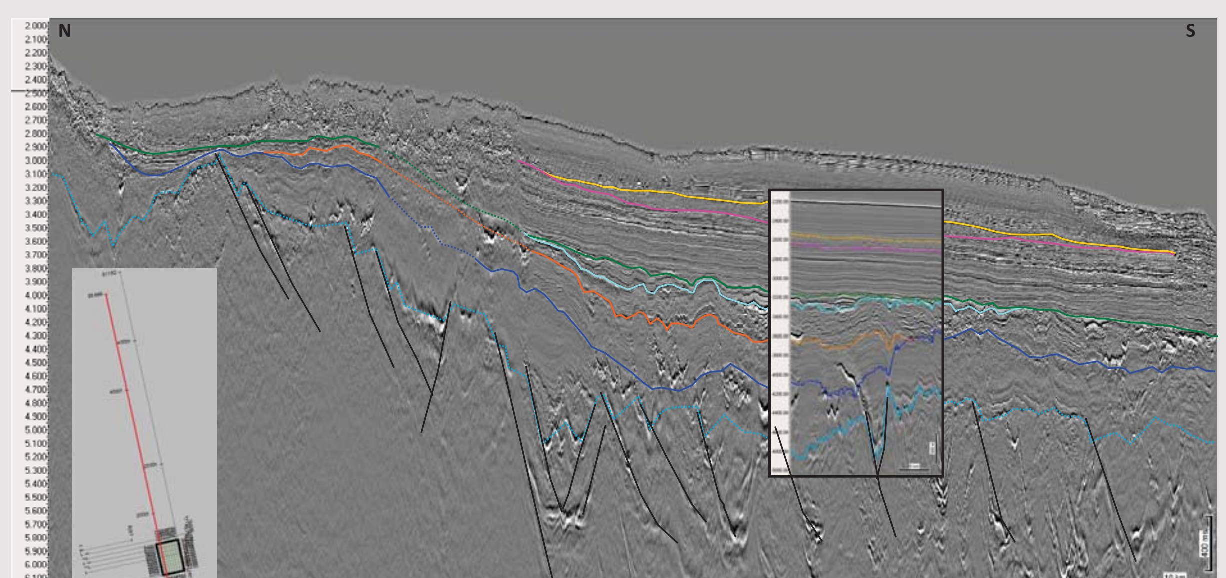


2D: PSTM Mids (Angle Stack 12-24) Line 0500

3D: Full Stack Depth XL 3450



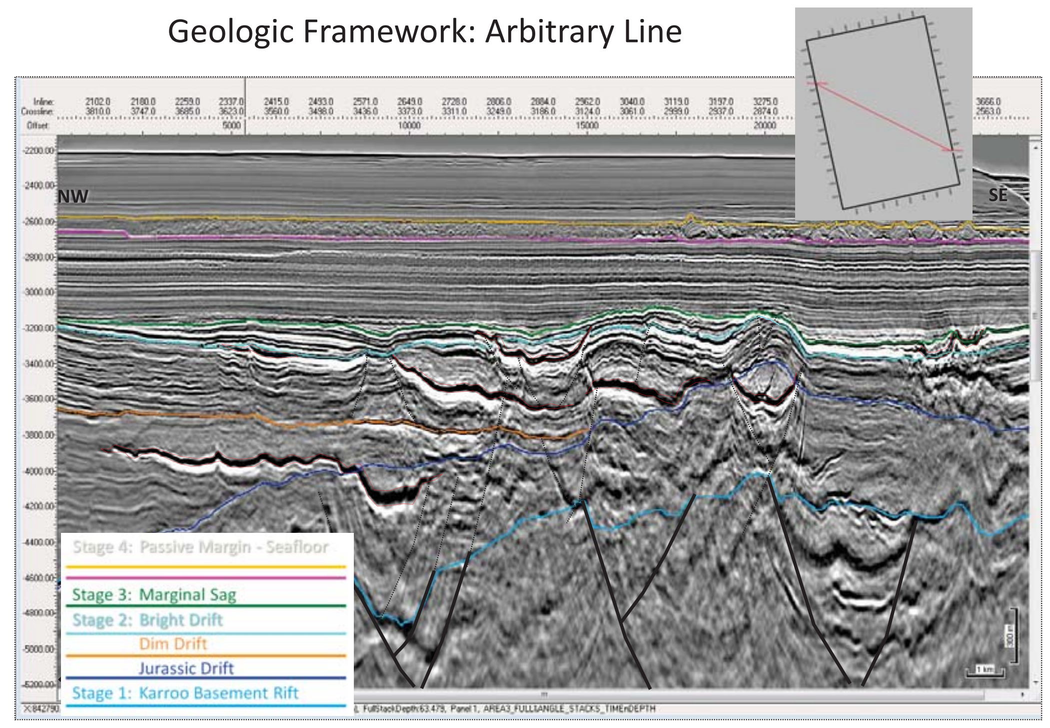
N-S Regional Context for Area 3: 3D over 2D



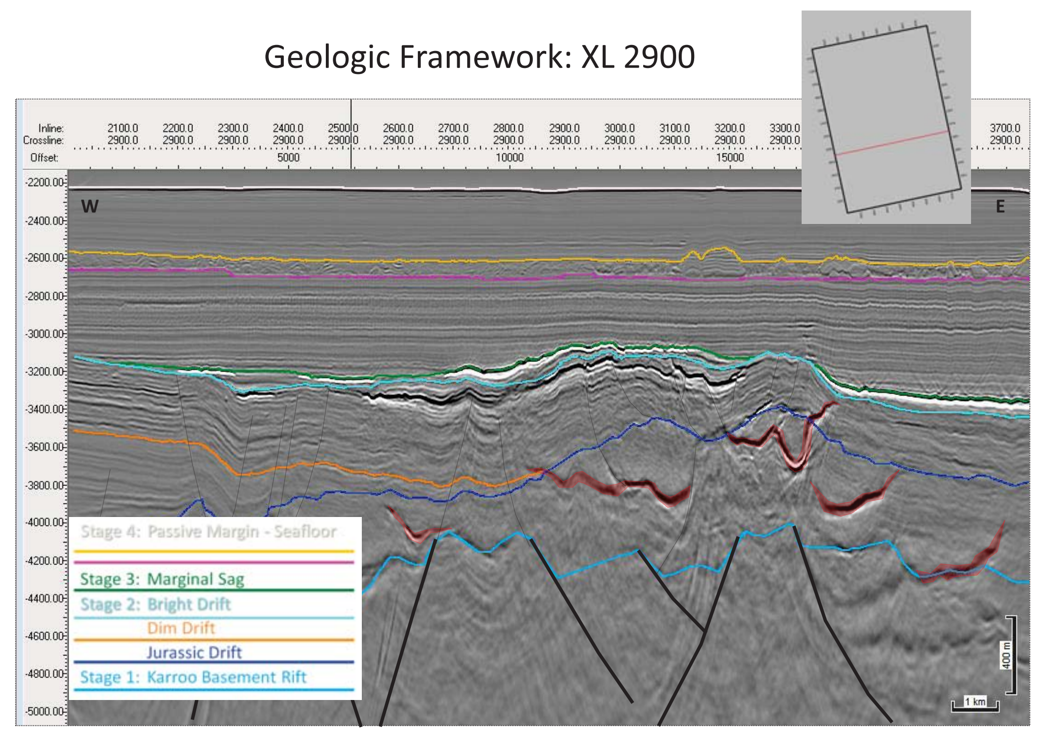
2D: PSTM Fars (Angle Stack 24-36) Line 1180

3D: Full Stack Depth IL 2330

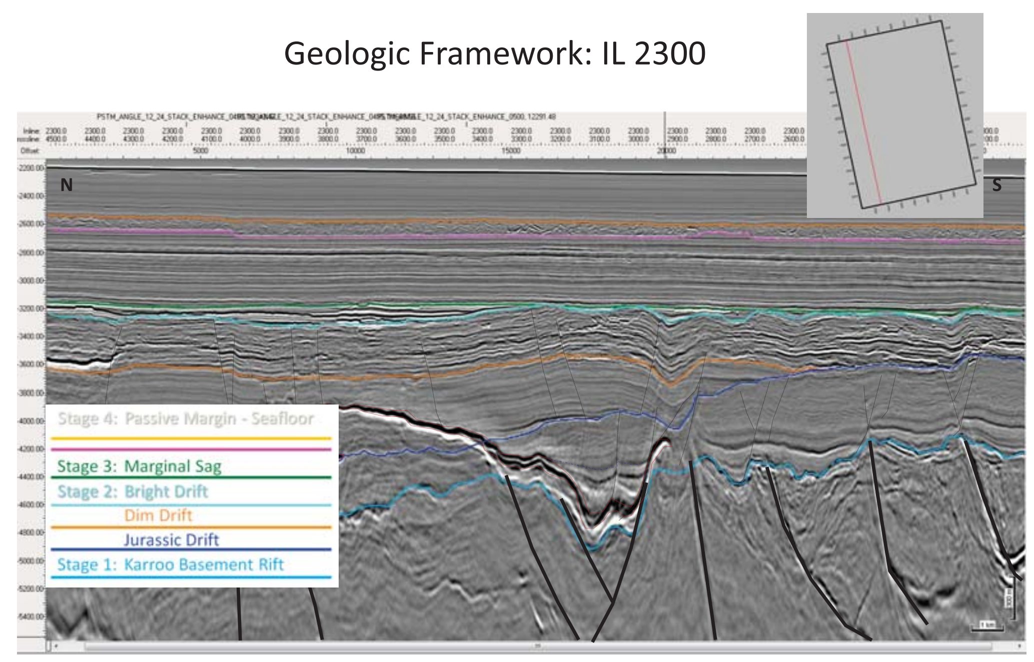
Geologic Framework: Arbitrary Line



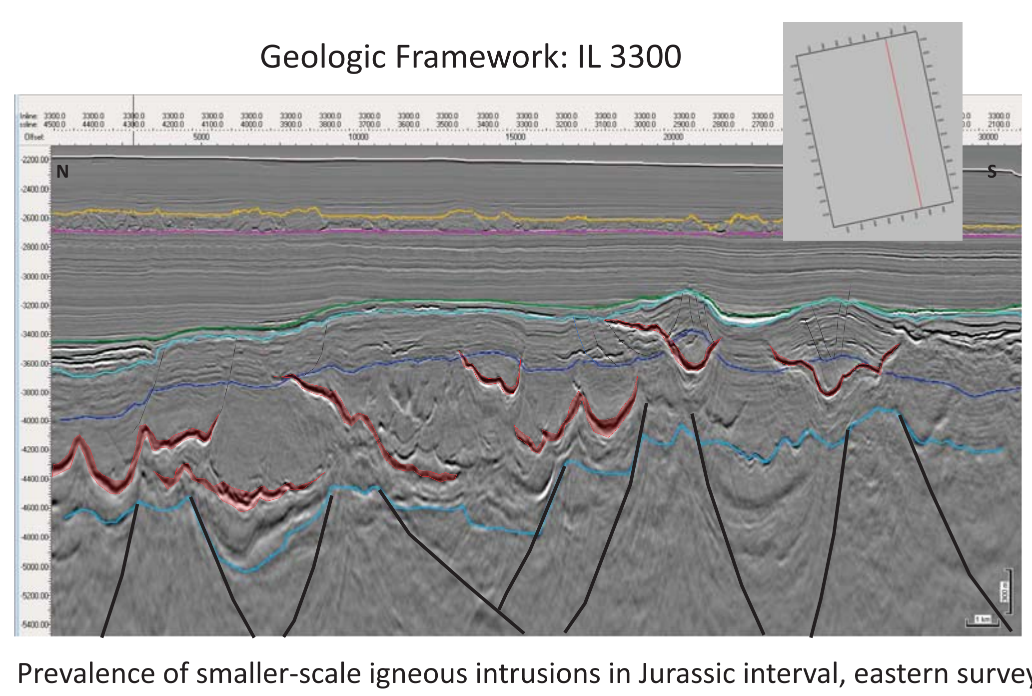
Geologic Framework: XL 2900



Geologic Framework: IL 2300



Geologic Framework: IL 3300

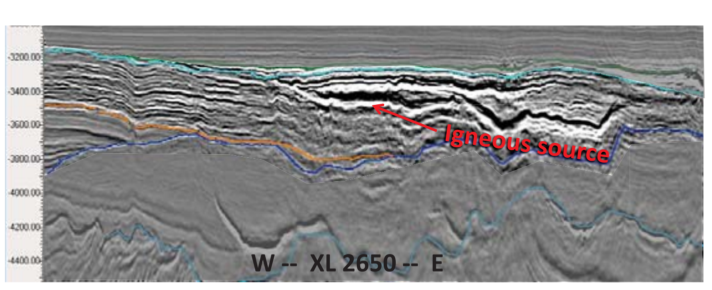


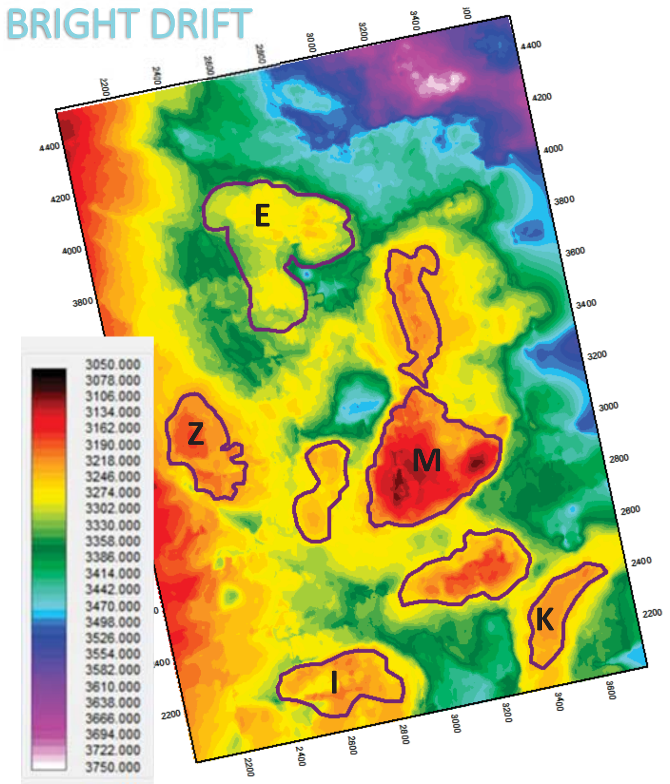
Prevalence of smaller-scale igneous intrusions in Jurassic interval, eastern survey

KEY STRUCTURAL FEATURE: POP-UP ANTICLINES IN BRIGHT DRIFT

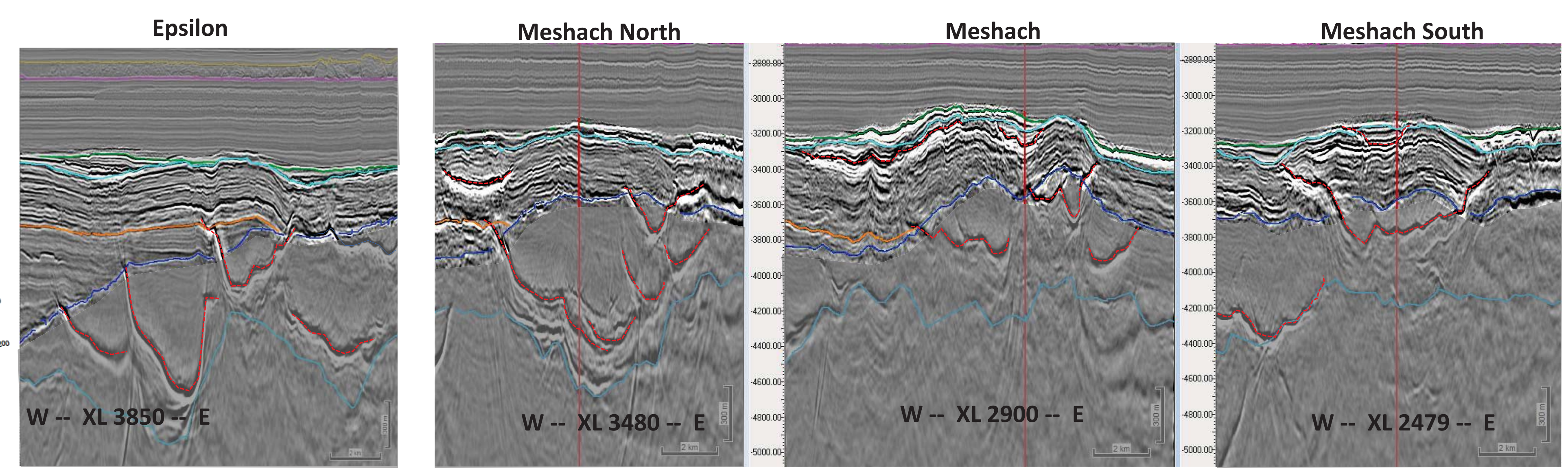
Brightest amplitudes in RMS extraction likely highlight intrusive sills. Sourced from deeper intrusions, the stratigraphy-cracking character of sills is clearly visible in the Bright Drift interval, in many places filling in shallow stratigraphy.

These pop-up closures were structurally increased by igneous intrusion, seen by an increase in unit thickness. Regardless of timing in the petroleum system history, the sills have a negative impact on prospectivity: reservoir quality and thermal history, reservoir compartmentalization, seal breach, etc.





Within the context of the 2D lines above, it becomes obvious how localized and anomalous these pop-up anticlines are within the Morondava Basin.



Multi-Attribute Analysis of Six Upper Cretaceous and Jurassic Structural Closures in Belo Profond, Morondava Basin, offshore west Madagascar

Irewole Ayodele[1], Joyce Smith*[2], Adeleke Orimolade[1], Glen Penfield[1], Babafemi Falaye[1]

[1]South Atlantic Petroleum Ltd, [2]JECSmith Consulting

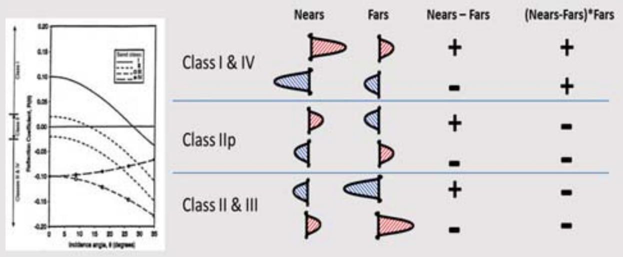
INTRODUCTION

The Belo Profond Area 3 3D survey covers a small but distinctive area within the Morondava Basin, between the west coast of Madagascar and the Davie Ridge. Recent publications have described the possibility of good reservoir potential in this area, and underscore the building interest in this emerging frontier basin (Brownfield, et al., 2016; Dirkx, R., et al., 2016; Roberts, et al., 2013). This project aimed to describe reservoir presence and quality of identified traps in the Cretaceous and Jurassic sediments, and assess their visible geophysical character through specially processed multi-attribute ranges. A literature review of the Morondava Basin and thorough mapping of the Area 3 survey led this team to determine five potential play types, and map potential trapping structures in the deep subsurface below a series of regional unconformities. The greatest challenge to many of those structures is the abundant igneous sills that lace the Cretaceous stratigraphy. The six prospects described here are those identified with the greatest reservoir presence, quality, and volume.

METHODOLOGY

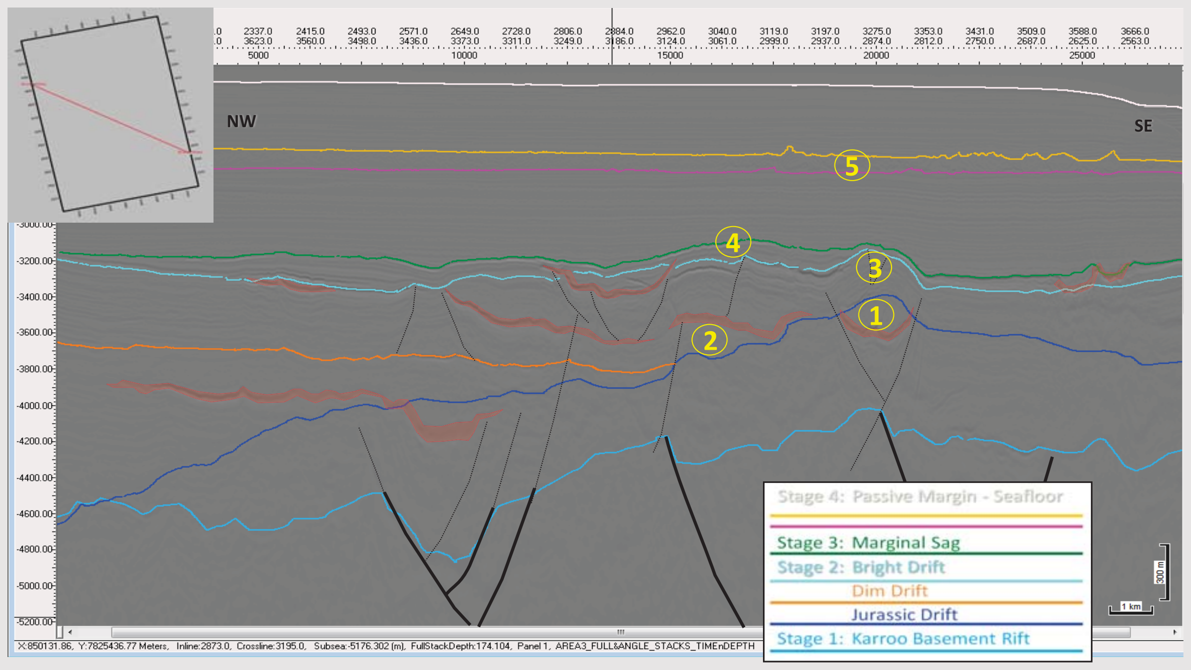
This investigation focused solely on interpreting the existing Area 3 3D survey Full Stack (Time and Depth). Volume amplitude assessment of geophysical attributes were evaluated at each prospect (RMS, Sum, etc.), as well as spectral decomposition along the horizon surface to identify depositional patterns or features.

Well data was not available to calibrate results in this frontier basin, ~100 km distance offshore. Angle stacks (Near Stack = 4-15°, Mid = 15-26°, Far = 26-37°) were used for an attribute-comparison AVO assessment: (Nears-Fars)*Fars, dividing resulting reservoir intervals into one of two typologies: Class I & IV and Class II, IIp, & III.



Unconditioned gathers were not available for inclusion in this project, but a trapezoid filter was applied to filter out any noise prior to comparing the angle stack amplitudes. IHS Kingdom software and the Geology/Geophysics module were used at every stage of this analysis.

AREA 3: PLAY TYPES



Play 1: Structural Closures on the end Jurassic Unconformity
Prospects identified along the N-SSW high of a high-relief unconformity overlain by a regional shale. The sediments have very dim reflectivity, due to their depth and their proximity to common intrusive igneous sills: *Prospect Alpha*.

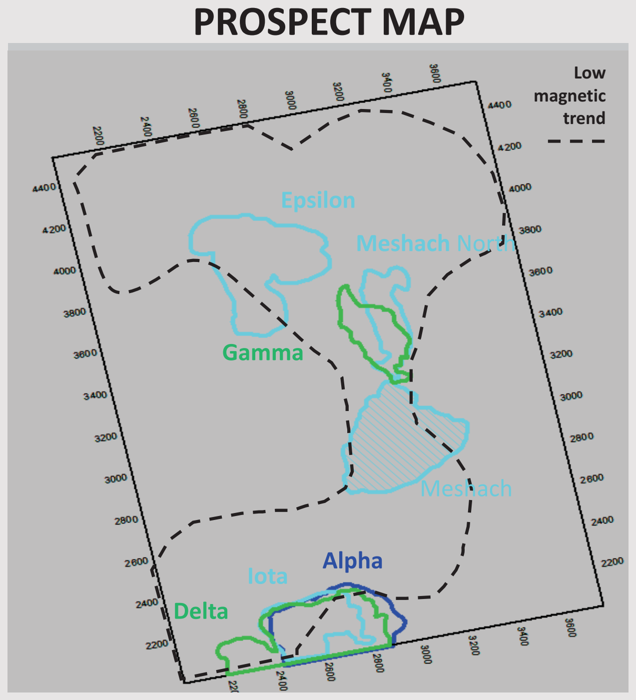
Play 2: Cretaceous Onlap Pinchouts onto the late Jurassic Unconformity
Cretaceous sediments were deposited against the N-SSW trending high on the end Jurassic Unconformity. Bright packages downlap and pinch out: *Prospect Gamma and Prospect Delta*.

Play 3: Structural Closures in the Cretaceous Bright Drift
Pop-up closures structurally increased by igneous intrusion that fall within the low-magnetic trend: *Prospect Epsilon, Prospects Meshach, Prospect Iota*.

Play 4: Features in the Marginal Sag
This thin interval is rife with very bright amplitudes that largely conform to underlying stratigraphy, not cutting through like intrusive sills of drift sediments below. This interval operates largely as a seal: *West Channelform*.

Play 5: Features in the Passive Margin
Largely sealing, the key feature within the Passive Margin section is the expansive *Mass Transport System*.

PROSPECT MAP



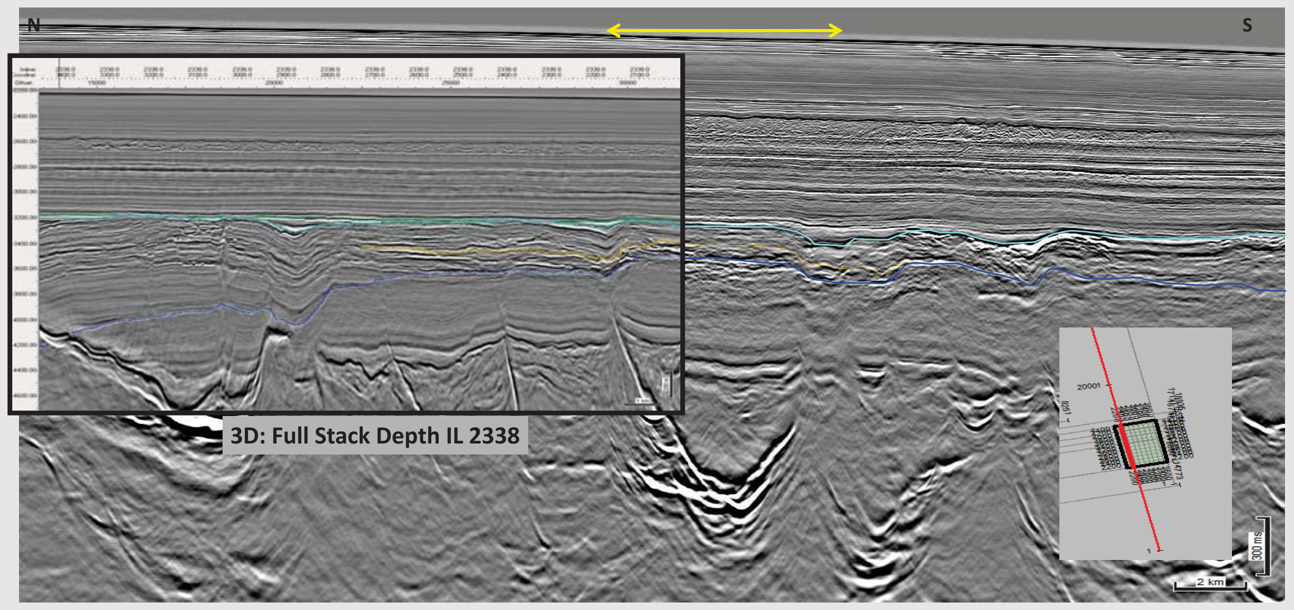
PROSPECTS ALPHA, DELTA, IOTA

These stacked prospects in the south-southwest of Belo Profond Area 3 are from three separate plays, with closures that likely extend off the survey, thereby increasing trap sizes but in that area the reservoir presence and quality is for now unknown.

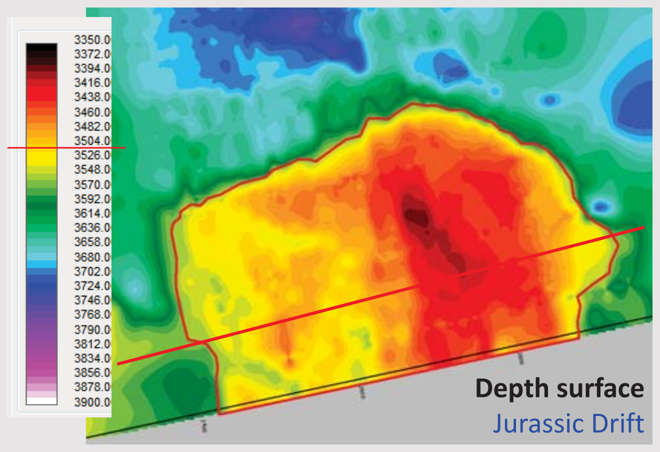
The image to the right is the 3D survey lined up with the 2D vintage data with horizons traced to determine shape and extent of the reservoir to the south. The exact size of the traps is difficult to estimate, but the 2D line shows these structures likely close south of the 3D survey, likely doubling the calculated size.

Regional context suggests a closure to the south, nearly doubling size of closure (~3 km^3).

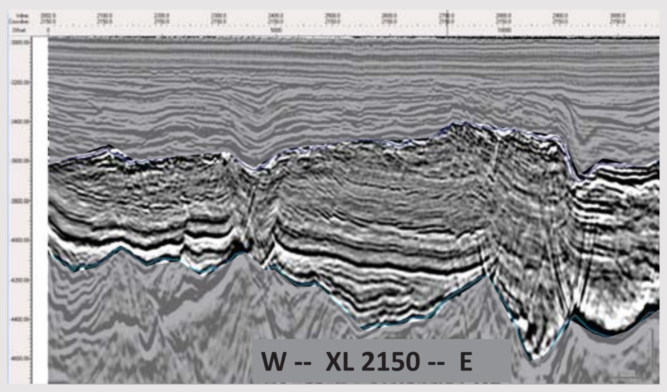
2D: PSTM Fars (Angle Stack 24-36) Line 1180



Prospect Alpha: Structural Closure in Jurassic

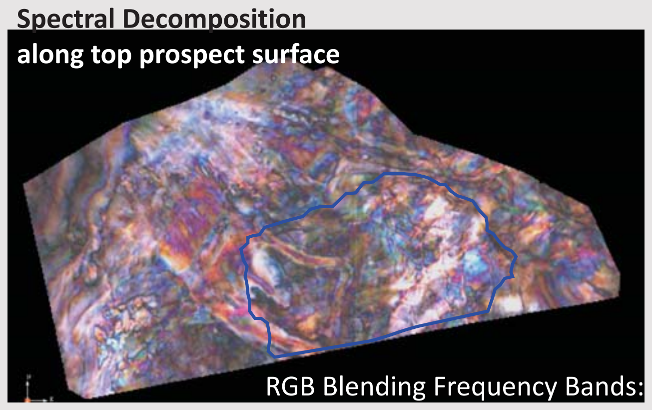


Closure size shown: 21 km^2 (1.5 km^3)



Dim, parallel stratigraphy with regular fracture patterns due to small-scale movement on rift faults. No notable conformance of bright reflectors to structure. Small bright spots appear disconnected, likely show fault compartmentalization.

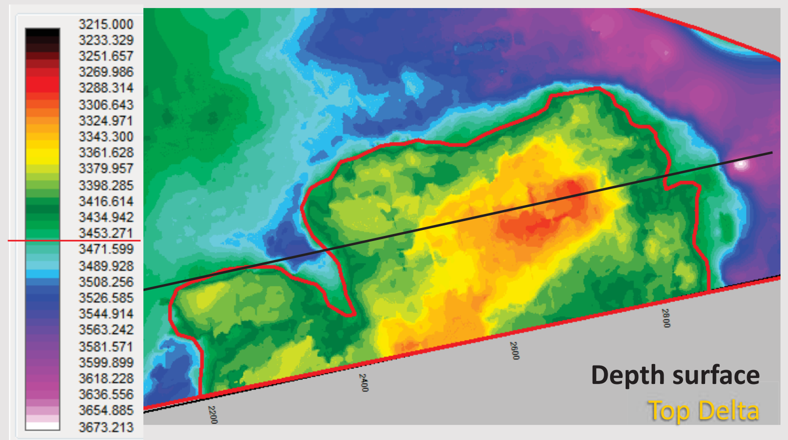
Spectral Decomposition



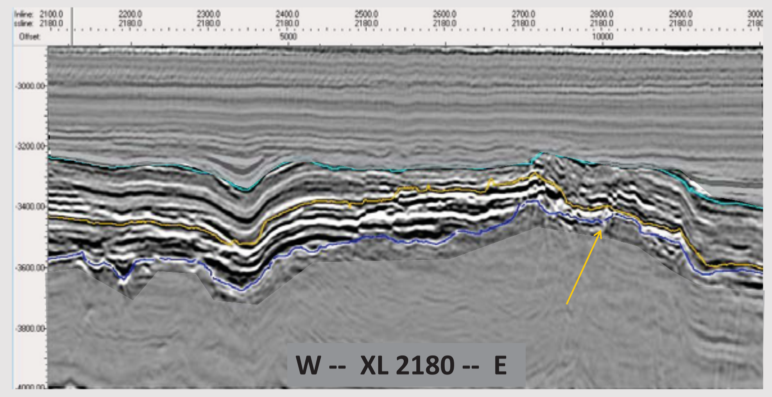
RGB Blending Frequency Bands: 17.2(red), 23.3(green), 29.4(blue)

Jurassic Drift is clearly an unconformity surface: Note faulting, appearance of scours on Spectral Decomposition.

Prospect Delta – Pinchout Structure



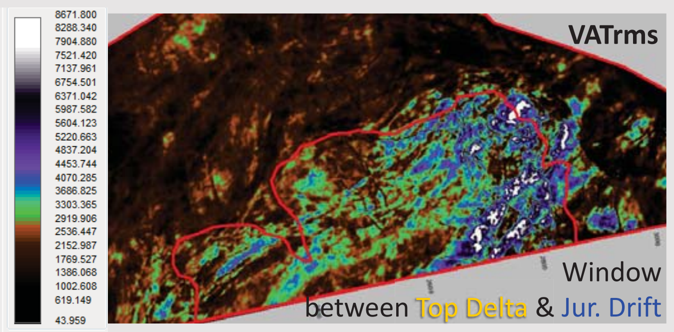
Structural closure shown: 22 km^2 (0.979 km^3)



Bright, alternately ordered and chaotic bedding suggests:

- Carbonate lithology: organic buildup or mound later subjected to faulting.
- Thin igneous intrusions that follow stratigraphy.

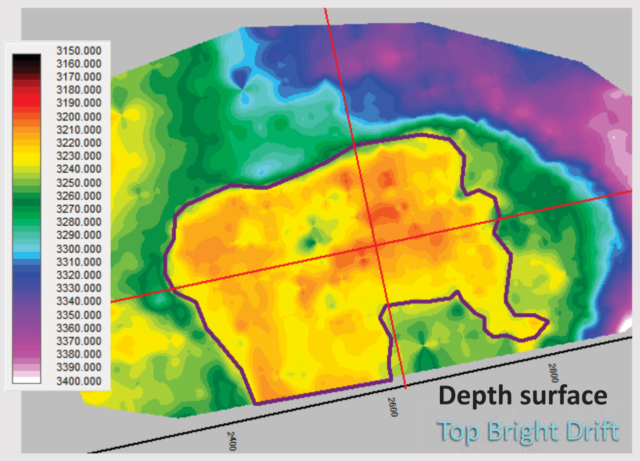
Spotty brightness continues above Top Prospect surface, possibly indicating a broken seal.



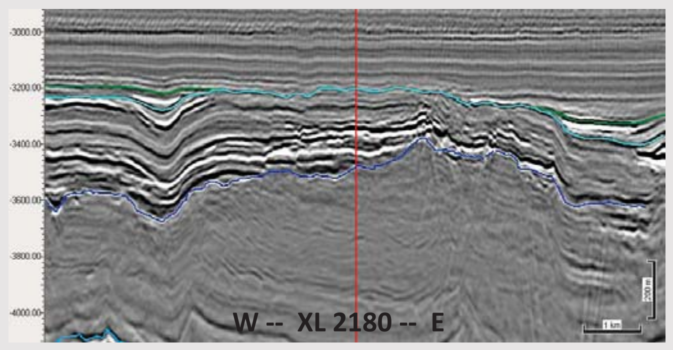
Brightest areas associated with pinchout, colored gray.

Bright amplitudes in RMS extraction are on trend with the crest of structure, aligned with small-scale faulting where prospect is most thin, matches pattern in Spec. Decomp.

Prospect Iota: Pop-up anticline in Bright Drift

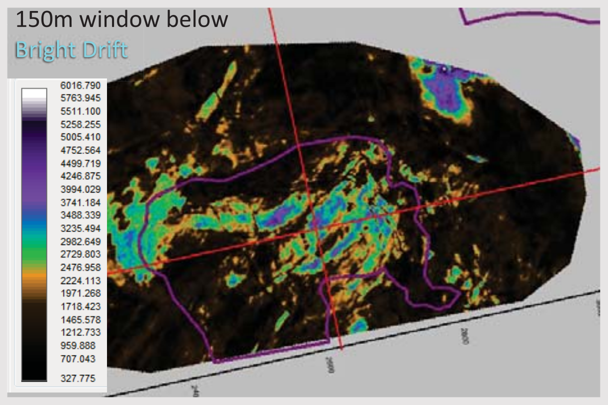


Closure size shown: 12.6 km^2 (0.189 km^3)



Brightest amplitudes centered beneath the crest of the structure, but do not come from top surface (eroded top).

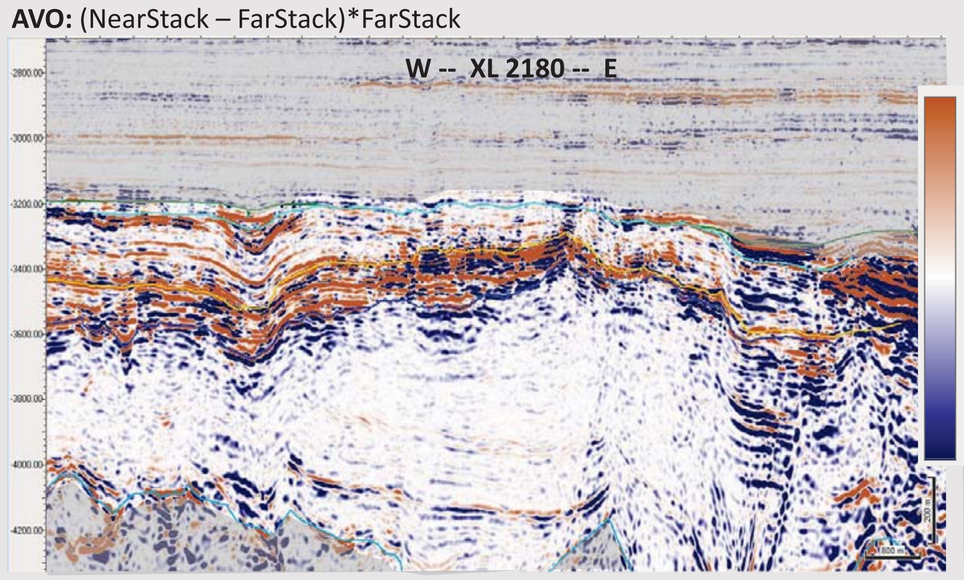
VATrms
150m window below
Bright Drift



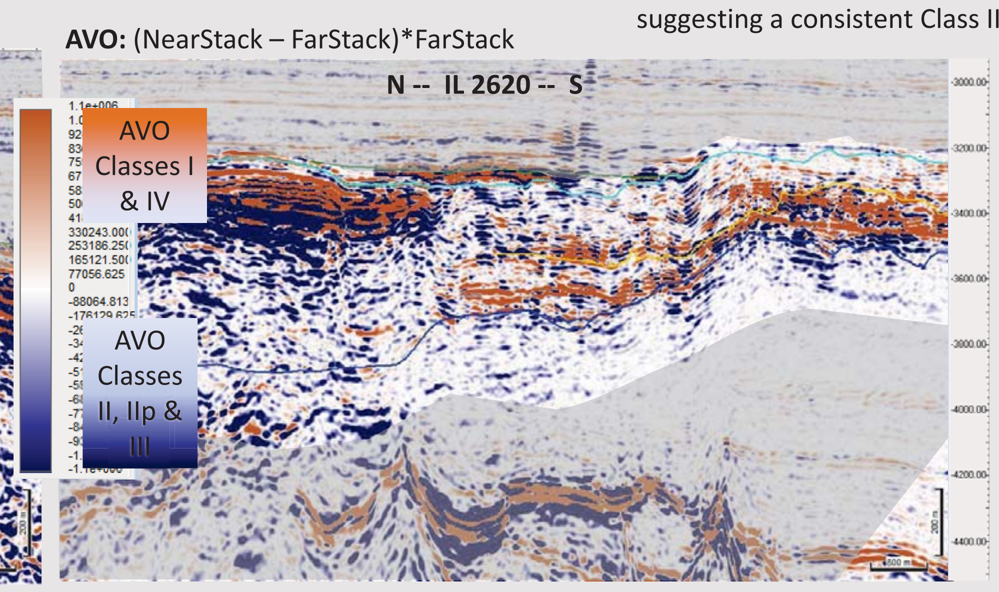
AVO Approximation for ADI Prospects:

Prospect Alpha: Upper portion of Jurassic Sediments shows mostly negative values, suggesting a consistent Class II or III lithology.

AVO: (NearStack – FarStack)*FarStack



AVO: (NearStack – FarStack)*FarStack



Prospect Delta: Vertical "column" distribution of AVO classes suggests carbonate build-up architecture; elsewhere seen with sills.

Prospect Iota: Dim interval just beneath Top Bright Drift is largely positive, indicating AVO classes I or IV.

AAPG Annual Convention & Exhibition 2018, Salt Lake City, UT, USA; Monday, May 21, 2018 Poster Session; Theme 1: Diagenesis and Reservoir Quality in Conventional and Unconventional Clastic Reservoirs II (SEPM)

GEOLOGICAL & GEOPHYSICAL ANALYSIS for DEFINING and HIGH-GRADING EXPLORATION PROSPECTS

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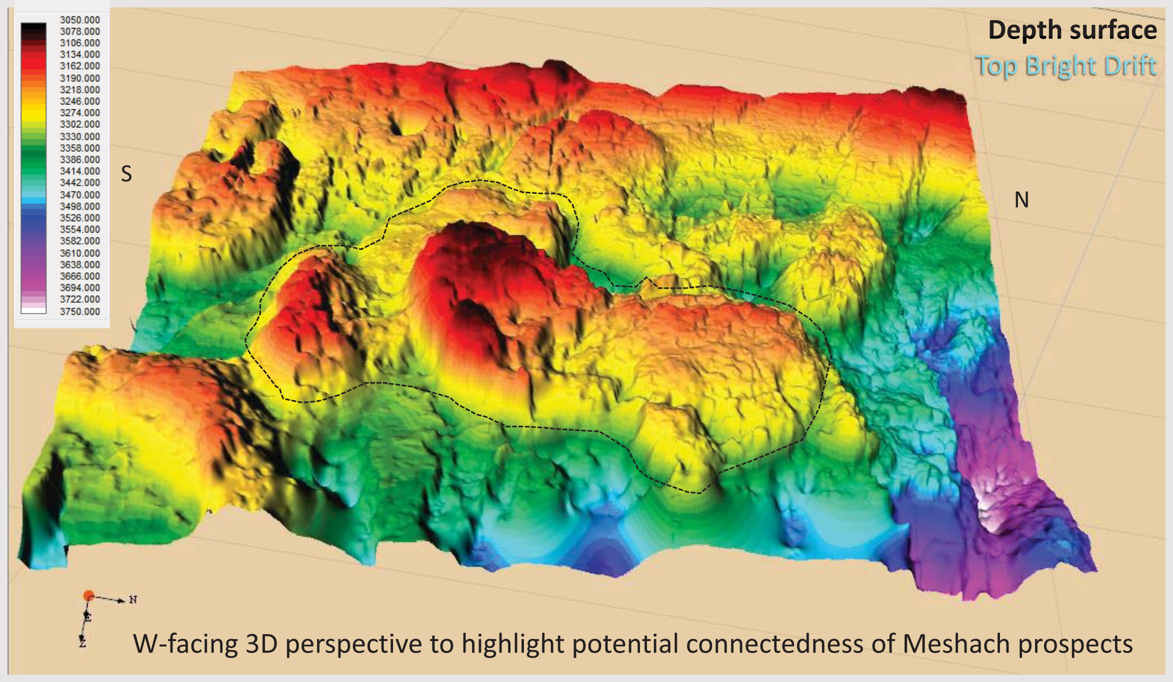
SAPETRO

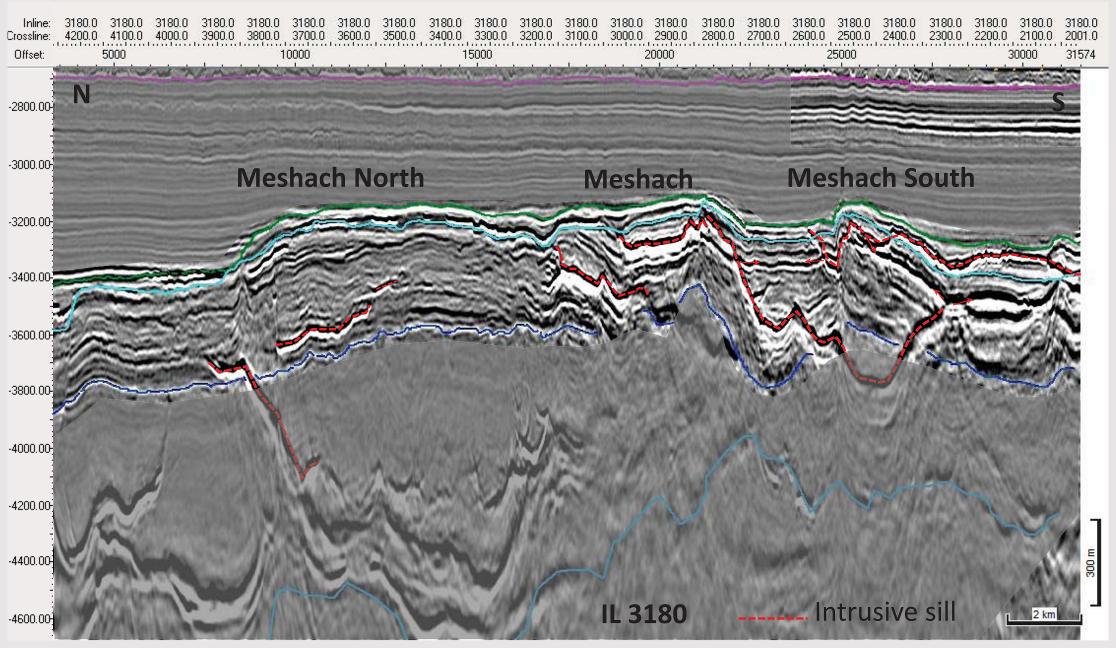
PROSPECTS MESHACH

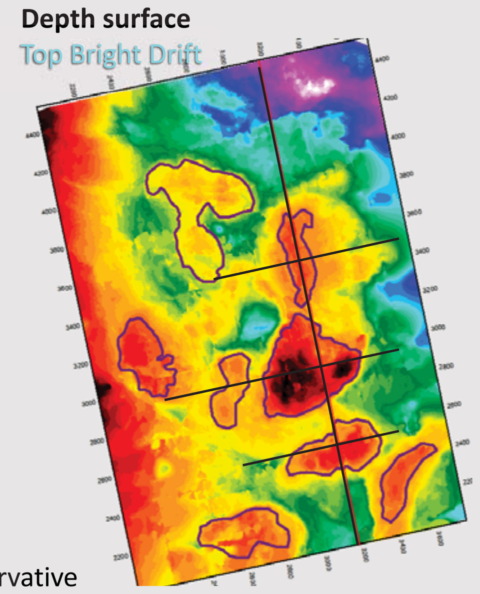
Located in Play 3, the Meshach Prospects have been identified as three distinct structural closures that may all share a closing contour: Meshach, Meshach North, and Meshach South.

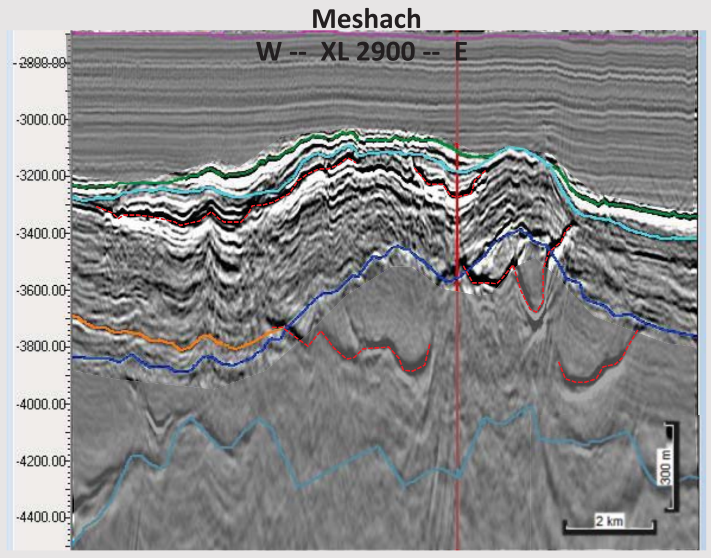
The internal architecture of the Meshach Prospects can best be seen in Meshach North, which contains parallel stratigraphy except for a few thicker, irregular packages in the uppermost layers. Meshach North has far fewer igneous intrusions than seen within southern two structures. Both Meshach and Meshach South have characteristic intrusive sills laced through the upper portion of the reservoir unit, increasing the structural relief, but dramatically decreasing prospectivity. Meshach North has intrusive sills below the reservoir unit, but not extensively within. Meshach North overlaps Pinchout Prospect Gamma.



W-facing 3D perspective to highlight potential connectedness of Meshach prospects





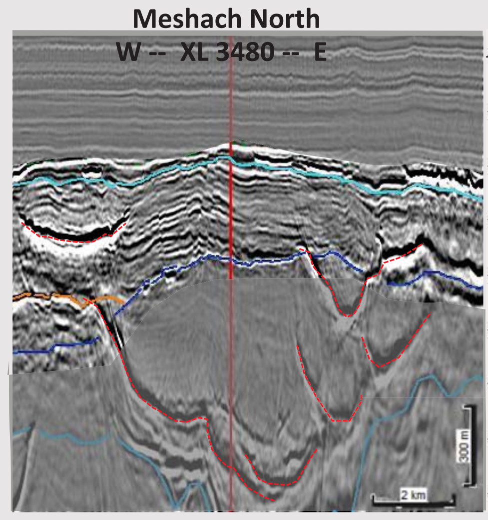


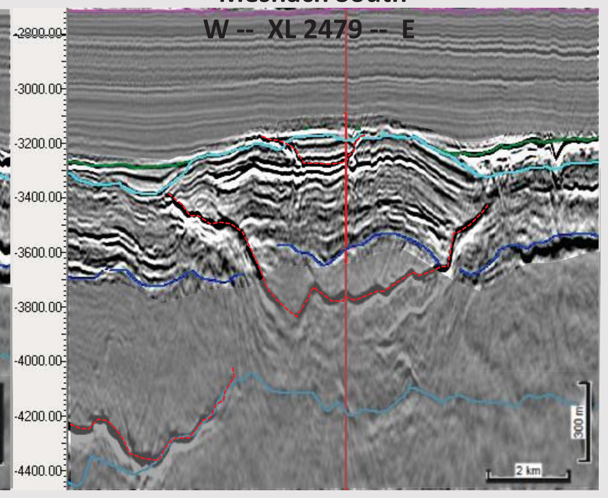
The structural closure shown on the map is 9.2 km² (0.146 km³), which is a very conservative estimate, assuming that only Meshach North is filled to its closing contour. However, a much larger upside potential persists for full Meshach closure, increasing to 88 km² (4.8 km³). There is a risk that the intrusive sills have caused internal compartmentalization.

The interval between Top Bright Drift and the green unconformity contains a thick trough with dim seismic character, in contrast to units just above and just below. Using a RMS amplitude extraction, the dim trough shows no contour conformance to the structure. Extractions on the entirety of Meshach only yield outlines of the igneous intrusions within the upper stratigraphy.

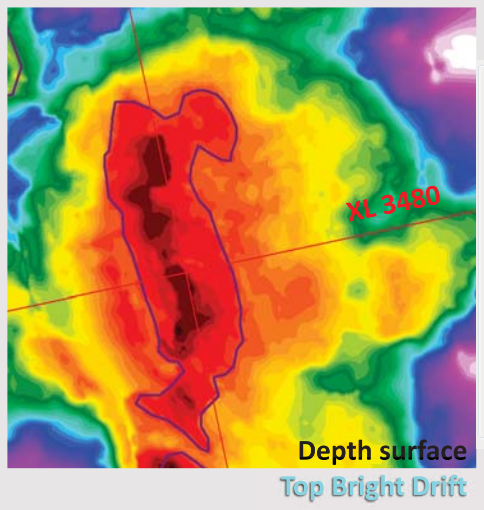
Using the (Nears-Fars)*Fars AVO assessment, the Dim interval between Top Bright Drift and Green Unconformity shows variation in AVO class, and some internal character not identified on reflectivity data. This effort is largely inconclusive.

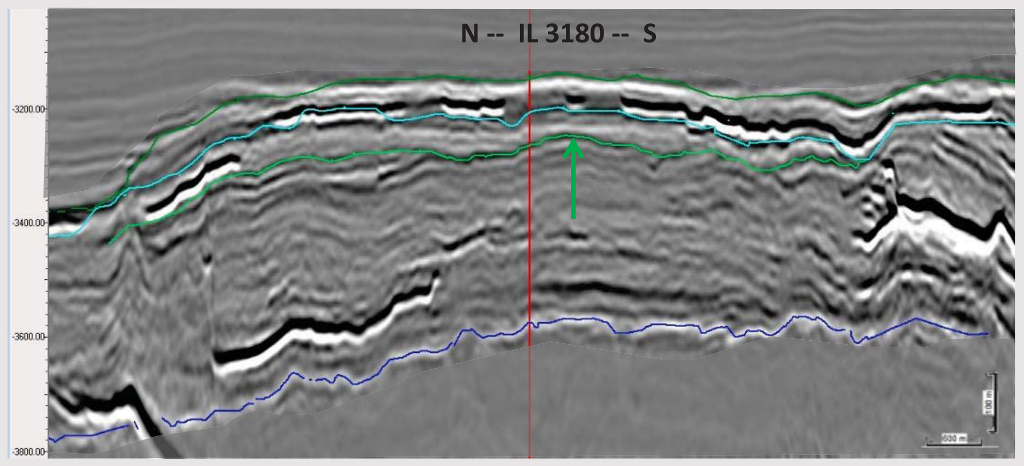
RGB Blending of Spectral Decomposition Dominant Frequencies shows structural features such as faulting along the crest of Meshach North.

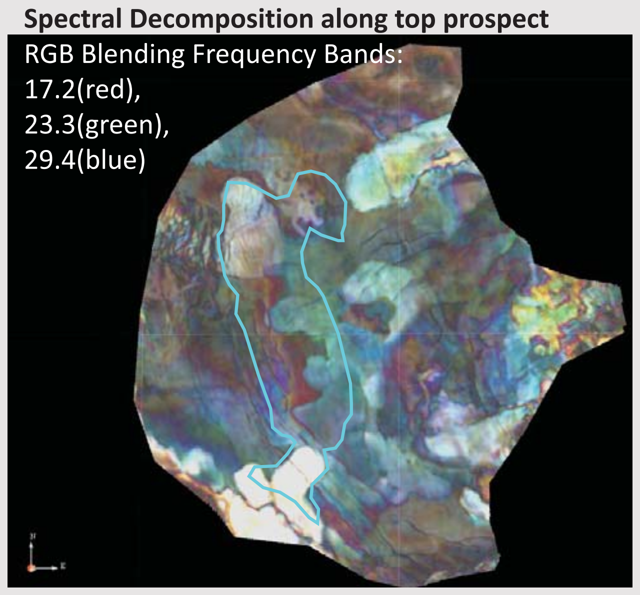




Meshach North Prospect:

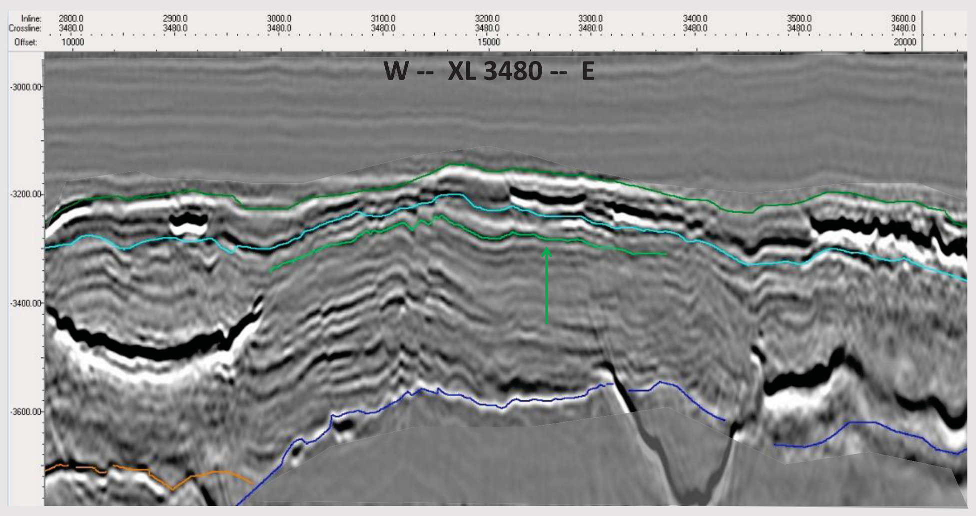


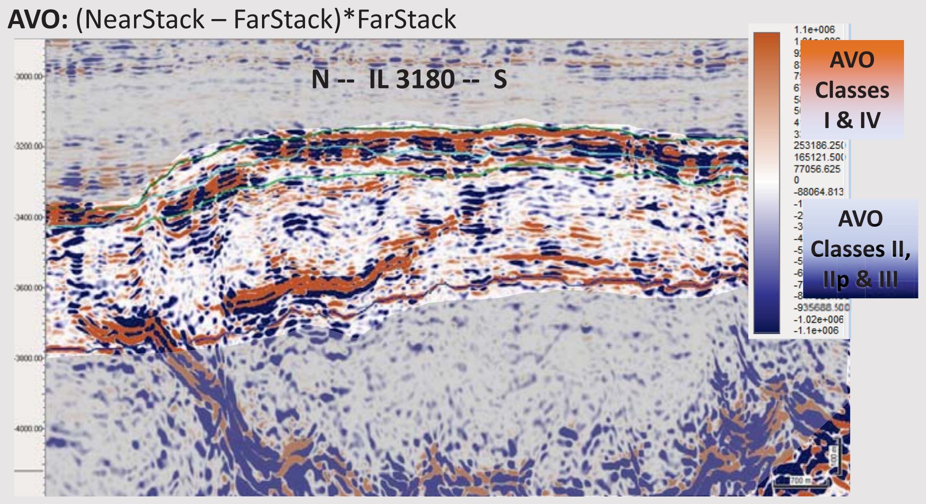




Structural closure shown: 9.2 km² (0.146 km³) Much larger upside potential for full Meshach closure, increasing to 88 km² (4.8 km³).

Interval between Top Bright Drift and the green unconformity (see right) contains a thick trough with dim seismic character, in contrast to units just above and just below. RMS extraction does not show conformance with contours in the dim interval.

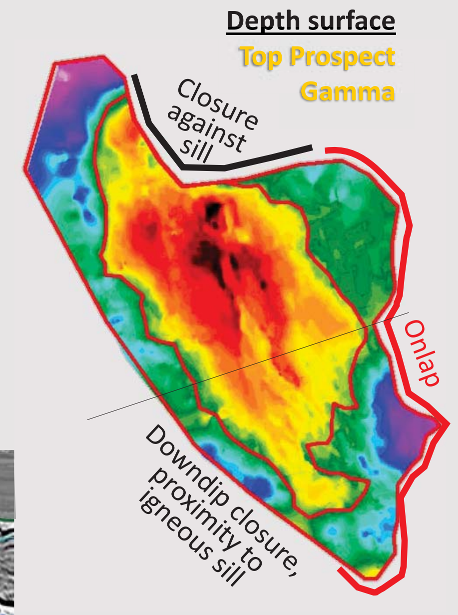


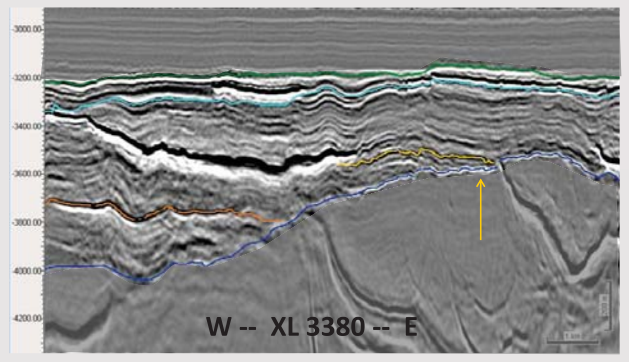


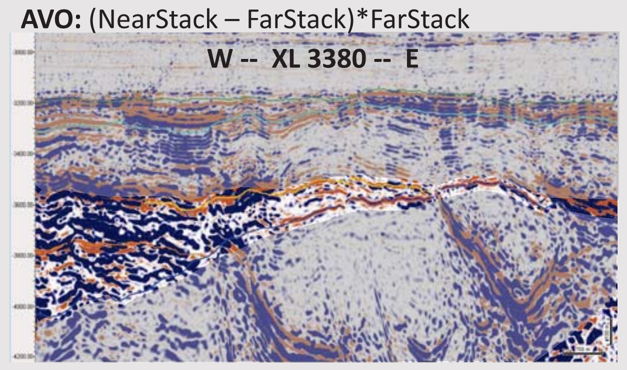
PROSPECT GAMMA

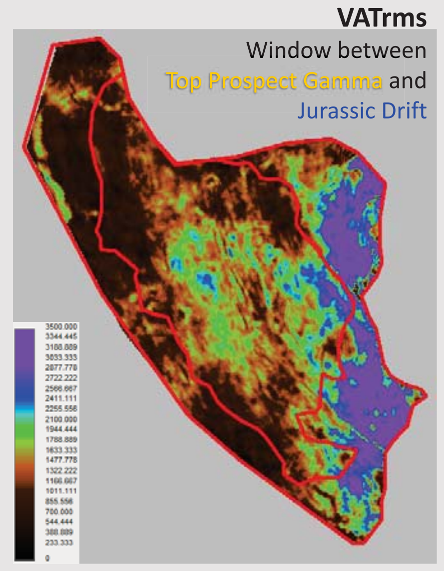
Both a structural closure and an onlap pinchout within the Bright Drift interval. Structural closure size : 9 km² (0.265 km³)

Bright onlapping peak, deformed as the base of a pop-up anticline, adjacent to igneous intrusions which comprise the closing contour to the north.









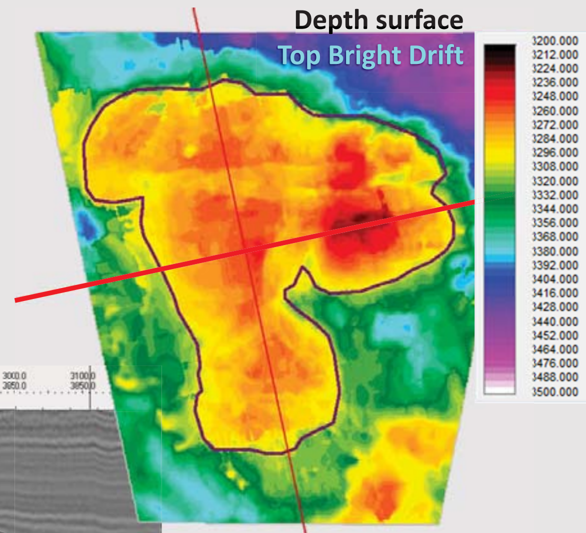
Conformance of high point of structure to bright amplitudes. Highest bright amplitudes on east of prospect are tuning effects as the surface onlaps.

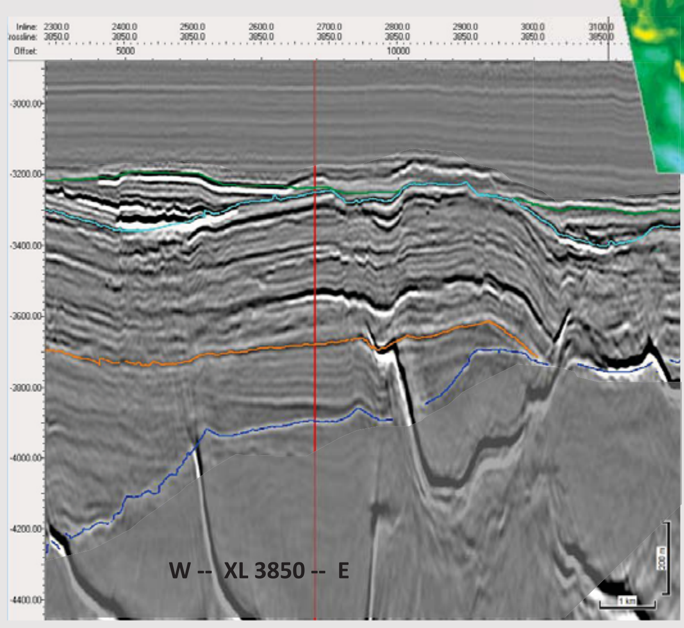
Alignment of bright amplitudes at the crest of the structure likely associated with faulting. Prospect contains faulted but ordered positive and negative responses on AVO approximations, suggesting varied lithologies within unit.

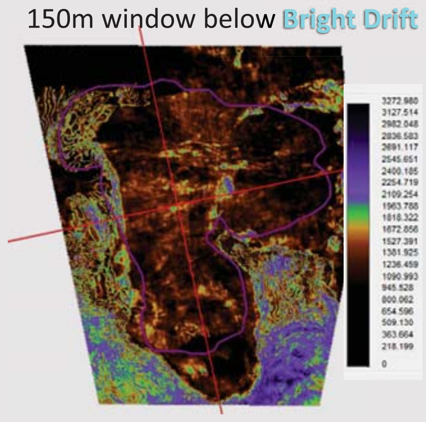
PROSPECT EPSILON

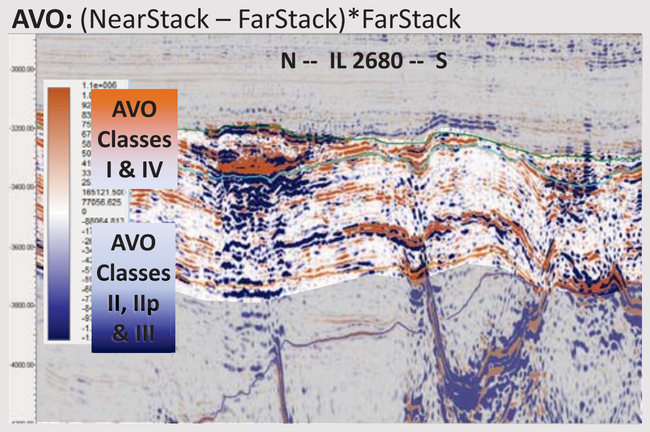
Deep intrusive sills reactivated faults in Jurassic sediments that influenced the size and shape of this structure.

Structural closure shown: 27.8 km² (0.797 km³)







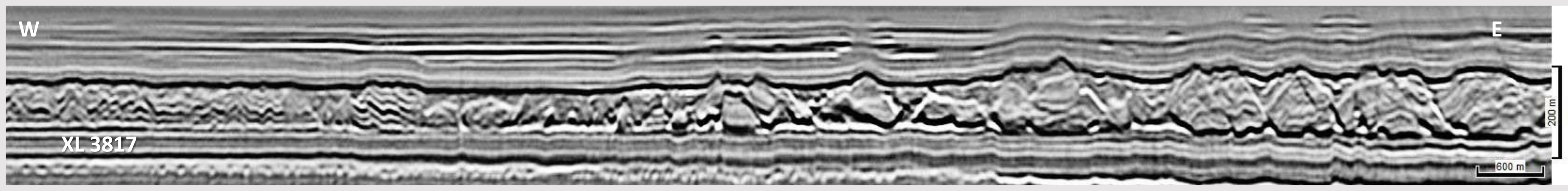


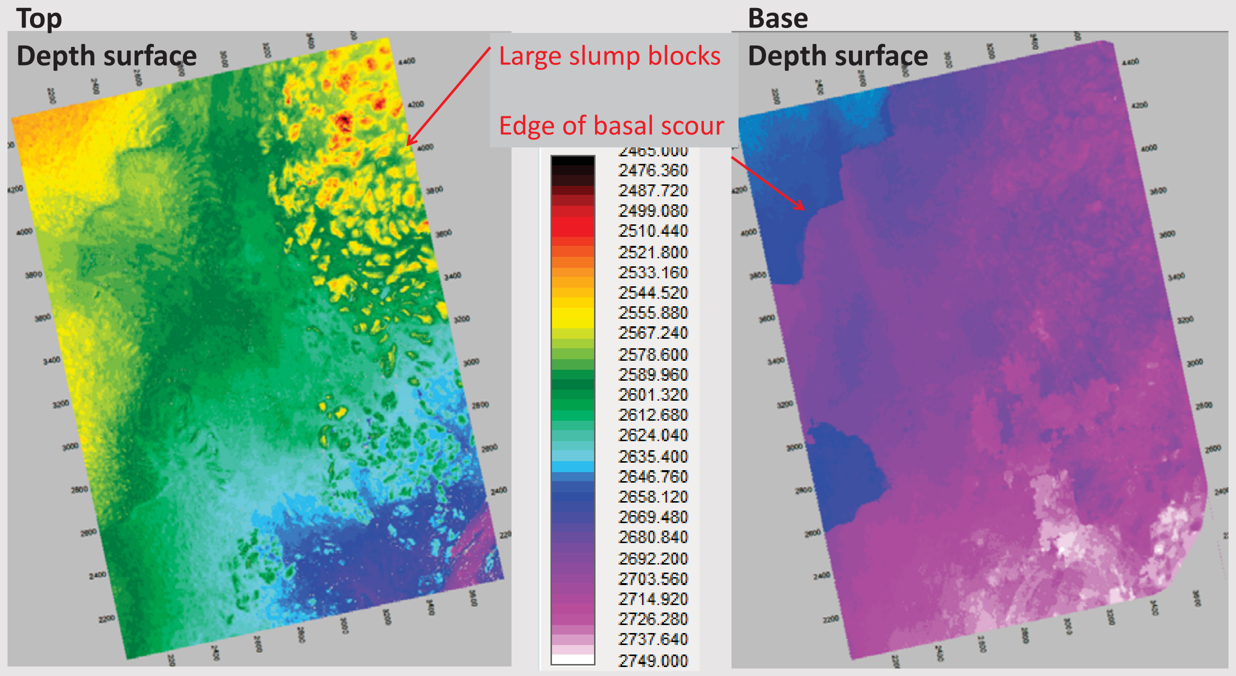
The RMS amplitude extraction over the interval shows only minor bright spots over the highs.

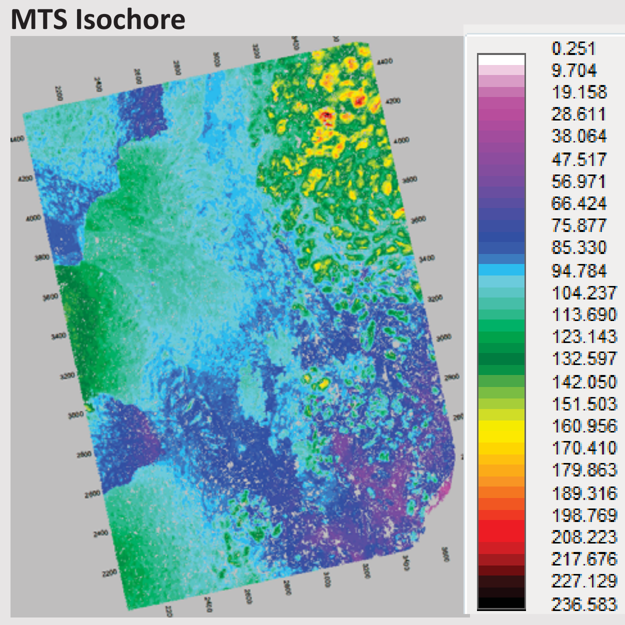
Using the (Nears-Fars)*Fars AVO assessment, an even distribution of parallel stratigraphy alternates between positive and negative (Class I&IV and Class II&III, respectively), which supports the hypothesis of stacked prospects within interval due to possible internal seals.

KEY FEATURES – AREA 3 SURVEY

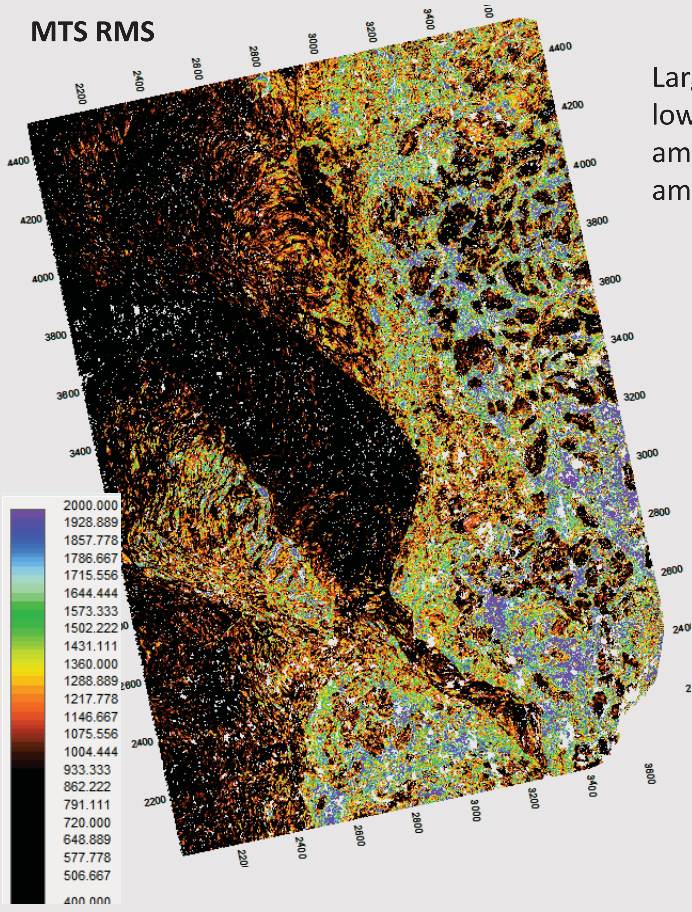
Play 5: Mass Transport System in Passive Margin







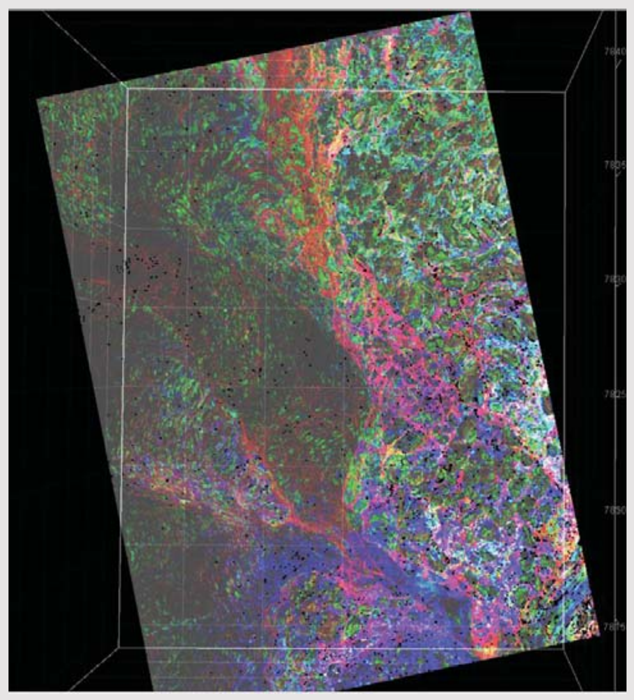
Note undulating thickness in the middle west, highlighting en echelon slumps



Large slump blocks tend to be low amplitude, with high-amplitude matrix, and low-amplitude channelform

Orientation of modern sea floor grooves largely matches up with this RMS low-amplitude channelform on previous slide. This relationship is not surprising as the MTS developed during same structural domain.

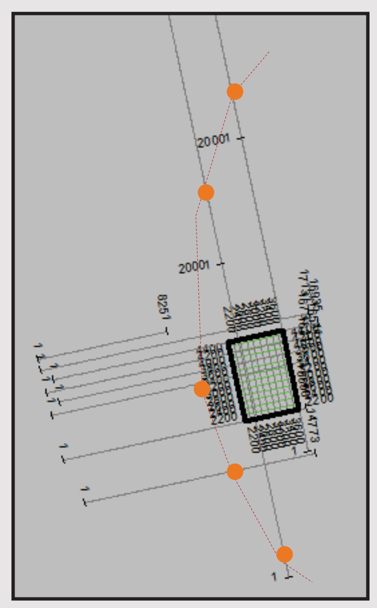
No scour appears in cross-section where the RMS dims exist, so this appears to represent a lithological variation.



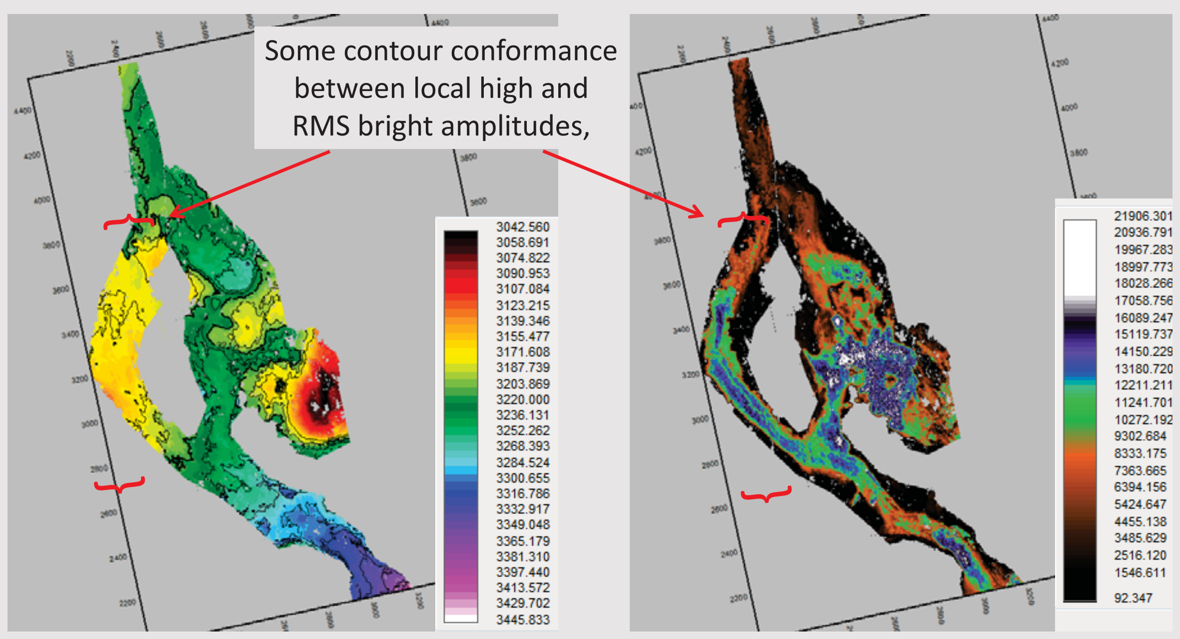
Spectral Decomposition along top MTS
RGB Blending Frequency Bands: 17.2(red), 23.3(green), 29.4(blue)

Extent measured on 2D:

Topographically limited to the west by Davie Ridge high

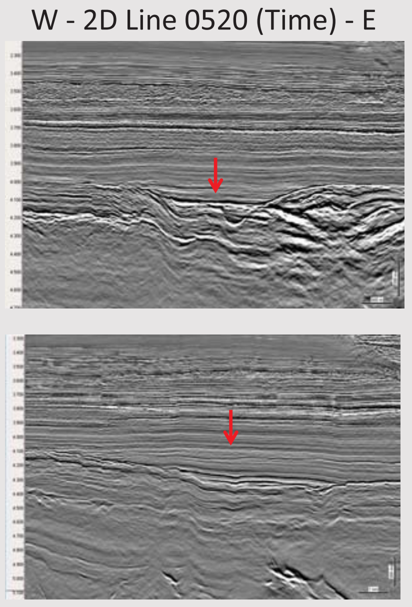


Play 4: West Channelform: feature in Marginal Sag

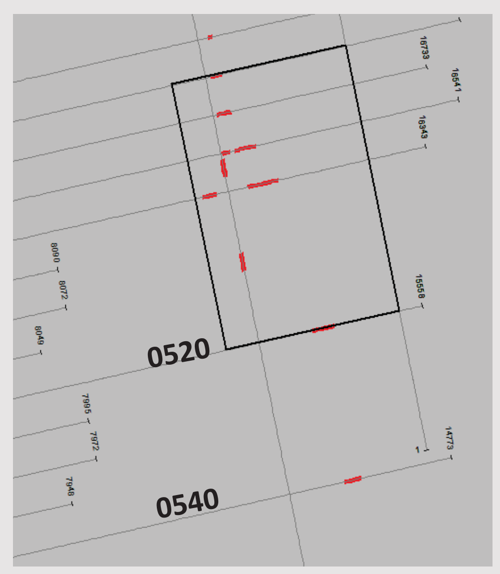


This channelform varies between 1.5-2.5 km wide.

W - 2D Line 0520 (Time) - E

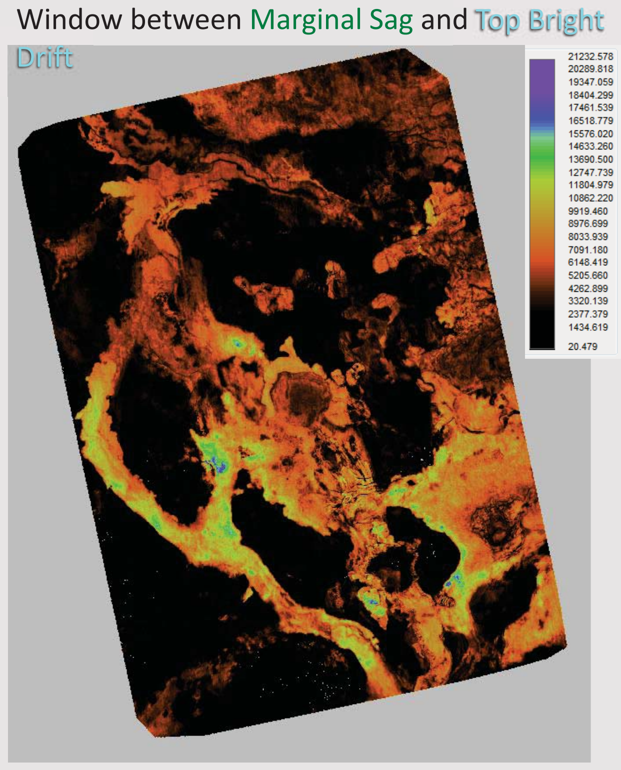


W - 2D Line 0540 (Time) - E



West Channelform traced on 2D lines- difficult to connect outside of 3D. Channel-form shape gets broader (3-4km) and thicker to the south.

VATrms
Window between Marginal Sag and Top Bright Drift

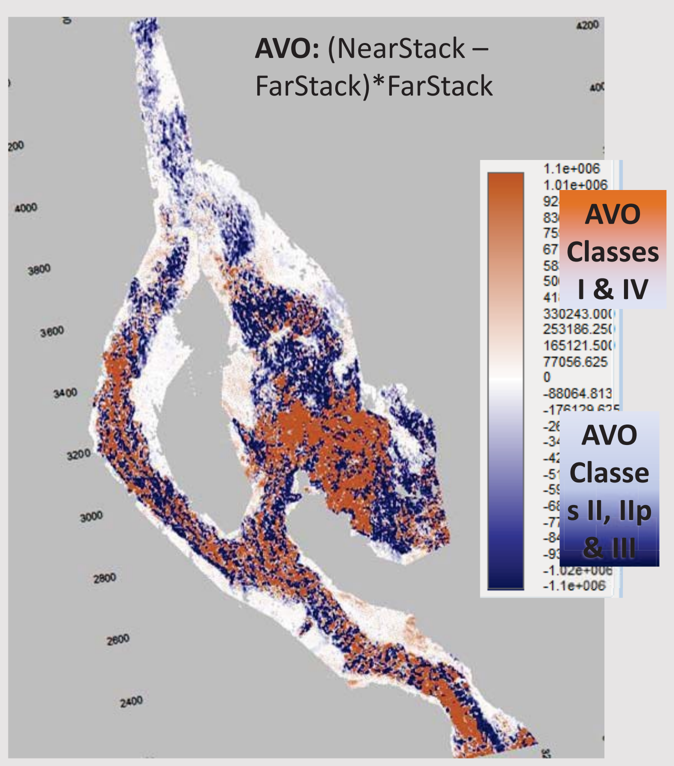


Possible scenarios for a north-to-south flowing channel with this level of consistent brightness:

1. Channel sediment lithology volcaniclastic material, ash-filled channel, both porous substrates
2. Channel sediment lithology sand or shale, which received a thin intrusion of crystalline igneous matter from the clear sill to its east, which uplifted the middle west portion along its regional SSE dip.

Area with brightest amplitudes also has high (N-F)*F values, whereas northern end is largely negative, indicating class II or III.

This bright area is also where there is highest elevation, and is indistinguishable from the clear igneous sill that rises up the Meshach high.



ESTIMATED VOLUMETRICS

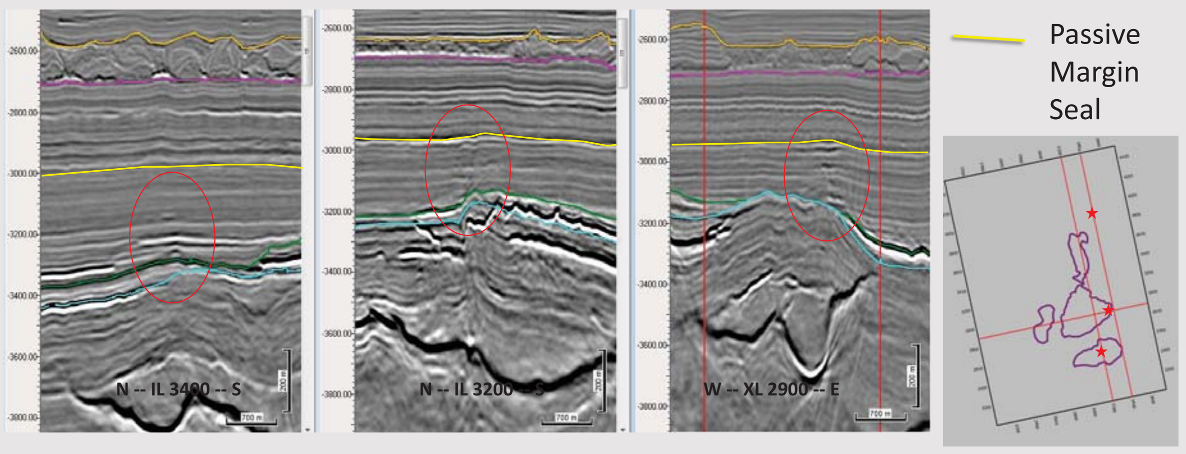
Belo Profond Area 3 contains considerable hydrocarbon reservoir potential. Six prospect closures identified and described, stacked opportunities most promising. No DHIs confirmed. Ballpark volumetrics calculated for these prospects have a total most likely unrisked volume of 1665 MMbbls, with an upside potential of 3034 MMbbls. The stacked opportunities of the Alpha, Delta, and Iota (ADI) prospects together have a most likely unrisked volume of 1152 MMbbls, and an upside potential of 1729 MMbbls. The Meshach Prospect has a most likely unrisked volume of 766 MMbbls, and an upside potential of 1022 MMbbls.

Volumetric assessments assume fill-to-spill for estimation.

Level	Closure GRV (MMm^3)			N/G	Porosity	Saturation	Bo	STOIIP (MMbbls)		
	low	best	high	best	best	best	best	**P90**	**P50**	**P10**
Meshach North	**161**	1367	4827					31.1	766.8	1022.4
Gamma	220	**293**	366					42.2	56.3	70.3
Alpha	**1554**	3108	4662	0.5	0.33	0.7	1.47	329.2	658.4	987.5
Delta	**1013**	2026	3039					207.4	414.7	622.1
Iota	**190**	380	570					40.2	80.3	120.6
Epsilon	659	**878**	1098					126.7	169.0	211.2
							TOTALS	**776.8**	**1665**	**3034**

FLUID ESCAPE OR LEAKAGE

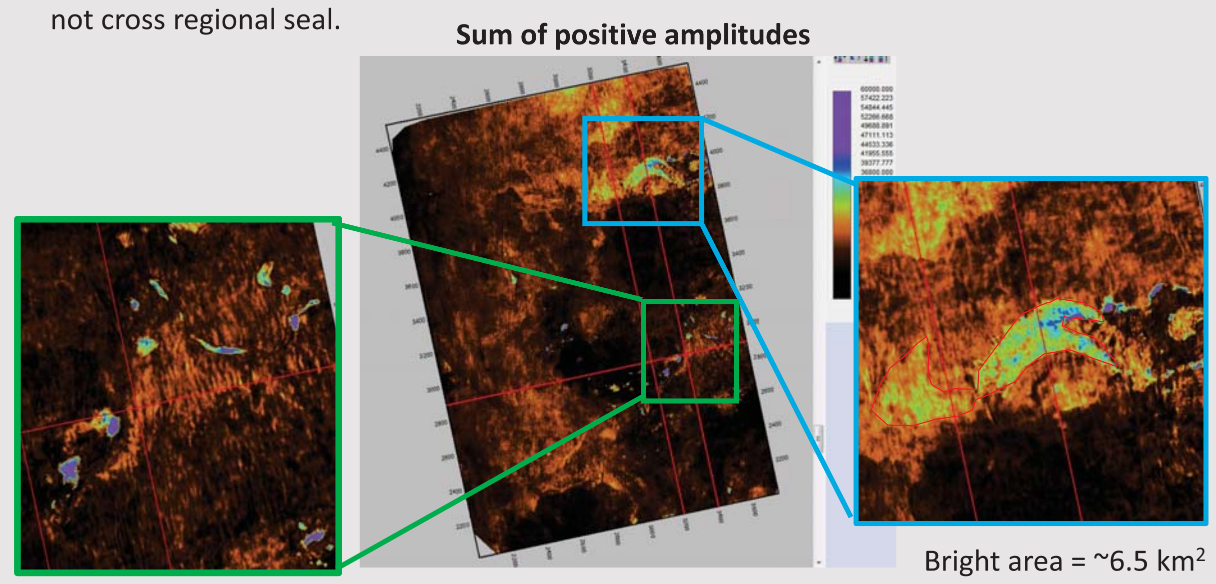
Crests of Bright Drift/ Marginal Sag anticlines



Amplitude Extraction on Passive Margin seal

Bulk positive amplitude from the top of the Marginal Sag to the Passive Margin Seal, a surface that extends unbroken over the entire survey. Leakage appears minimal and does not cross regional seal.

Sum of positive amplitudes



Bright area = ~6.5 km^2

Very small areal extent (<0.5 km^2) Brightest spots look like minor sills just above Sag surface

SUMMARY AND CONCLUSIONS

Area 3 contains structures derived from uplift, erosion, transpression and transtension, and igneous intrusion, which all create potential traps. Leaks in regional seals across survey are localized and minimal.
Presence of igneous lithologies challenges the analysis, and significantly impacts variations in geophysical properties. Prospects highlighted here show significant size, and exhibit the igneous influence on reservoir quality least.

Forward work: more data over complete areas of southern prospects, image processing to diminish the influence of dense igneous lithologies, and include offshore well data from offshore well for rock properties calibration

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