Exploring the sub-salt play in the frontier Amadeus Basin – Insights from regional 2D seismic and potential field data

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SUMMARY

Early exploration of the frontier Amadeus Basin in the Northern Territory has been limited due to its size and remoteness, along with complexity of structuring and limited early success. The primary exploration targets of the southern Amadeus are the sub-salt and intra-salt plays of the Neoproterozoic lower Gillen-Heavitree petroleum system. Two wells have tested the sub-salt play, both flowing gas with high helium content, confirming the sealing capacity of the Gillen evaporates despite two significant orogenic events.

In 2013, the first regional framework of 2D seismic was acquired over the southern Amadeus. In areas where seismic coverage is sparse, or of poor quality due to halotectonics, higher spatial density magnetic and gravity surveys have been used to interpolate trends between seismic and well control and create a high resolution depth-to-basement model. Alternate methods of seismic processing have also been trialled to improve sub-salt imaging.

The newly acquired seismic and depth-to-basement model are revealing the architecture of the basin and provide a regional perspective of the sub-salt and intra-salt plays. With improved seismic imaging large sub-salt structures are emerging beneath the complex folds resulting from thin-skinned deformation.

Learnings from the challenges associated with acquisition and processing, along with a better understanding of the complex halotectonics, will have significant implications for future exploration in the region.

Key words: Amadeus Basin, Neoproterozoic, seismic, potential fields, halotectonics

INTRODUCTION

The Neoproterozoic to Devonian Amadeus Basin is a complex depocentre, initiated approximately 1000 Ma ago as a component of the Centralian Superbasin. It covers an area of 170,000km^2 in the Northern Territory and Western Australia and is bounded to the north by the Arunta Province and to the south by the Musgrave Province. On the northern margin of the basin up to 14km of sediments are preserved (Edgoose, 2012). The basement generally shallows to the south and east of the basin, with a sub-basin forming locally south of Murphy-1, resulting in a broad central region of elevated basement along this section of the basin (Figure 1).

Five petroleum systems have been described in the basin (Marshall, 2003) with the Ordovician succession supporting commercial gas and oil production. The Neoproterozoic sub-salt play is a primary target in the southern Amadeus and has been proven with gas flows from the two wells that have tested the play, Magee-1 and Mt Kitty-1.

For a basin with proven petroleum systems, the Amadeus has been relatively under explored. Prior to the acquisition of the 2013 seismic data, there were no regional seismic lines and a poor understanding of the structural complexity related to salt mobilisation.

Recent analysis and interpretation of the newly acquired seismic data, along with the 2014-2015 SEEBASE™ depth-to-basement model, has provided fresh insights into the hydrocarbon potential of the basin; identifying syn-sedimentary thrusting, and deformation in response to the Petermann Orogeny in the form of inverted normal faults and faults detaching in the Neoproterozoic salt.

Pre stack depth migration has also been trialled and proved to be an effective method for improving seismic resolution below the salt. Optimal processing and recording parameters identified from the PSDM processing trial will be used in future infill seismic acquisition.

METHOD AND RESULTS

Acquisition

In 2013 Santos acquired 1586 km of 2D seismic over an area totalling 43,000 square kilometres in the southern Amadeus Basin, with seismic lines ranging from 18.6 km to 387 km in length. The objective of the survey was to provide a regional structural and stratigraphic framework in areas with little or no existing seismic data, linking previously isolated 2D grids and identifying key leads to be addressed by a later infill program.

Acquisition, conducted by two Terrex seismic crews, commenced on 25th August 2013 and finished on 13th November 2013, with daily acquisition averaging 18km per day. The locations of the lines are shown in Figure 1 and details of the recording parameters are shown in Table 1.

The seismic data were collected with an active spread consisting of 480 live channels, with 25m source and receiver intervals. Numerous changes were made to the recording parameters on a line-by-line basis due to ongoing processing and test line evaluation throughout the acquisition period.

Challenges associated with acquisition included spread damage from cattle, camels and dogs which occurred both randomly and more frequently around water bores. With limited camp moves and large distances to cover, travel times between the camp and line became excessive with round trips sometimes exceeding 5 hours, limiting production at times.

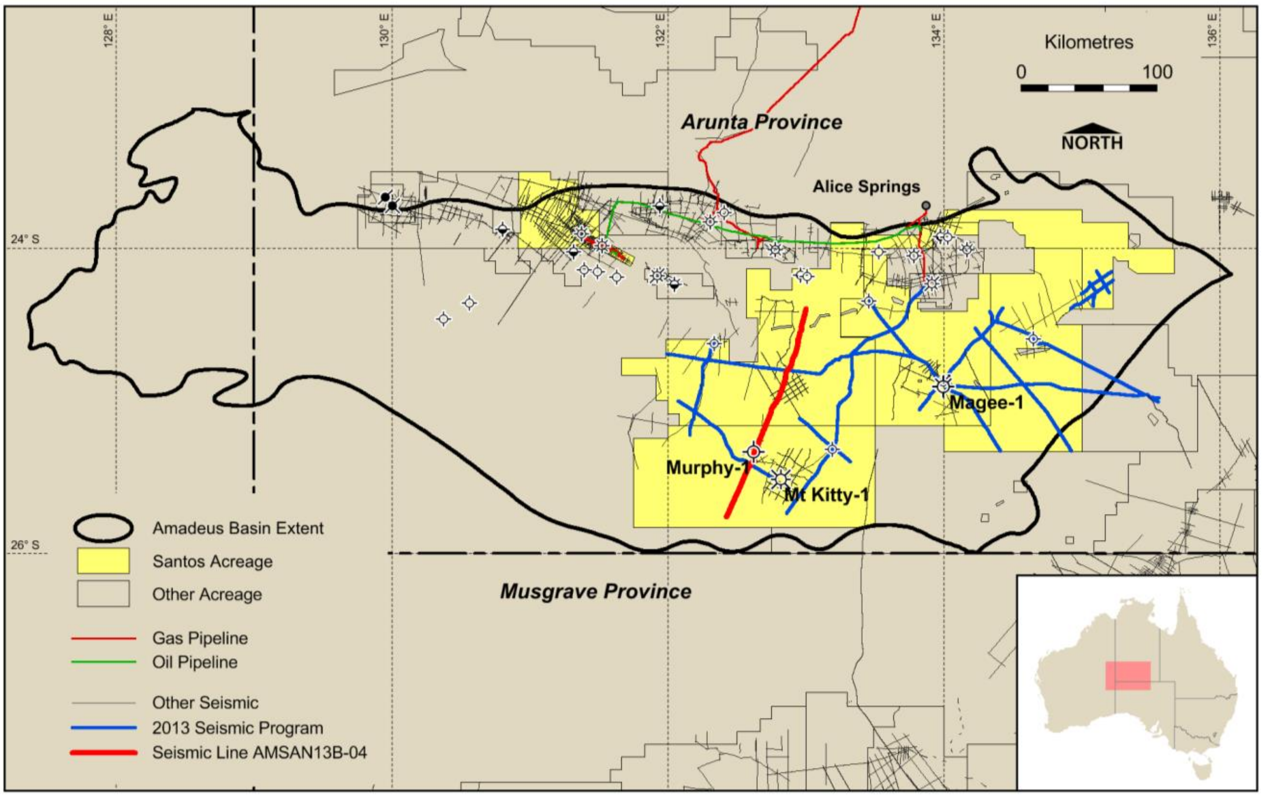


Figure 1. Amadeus Basin map highlighting Santos acreage, regional seismic lines acquired in the 2013 AMSAN seismic survey and key well locations. Seismic line AMSAN13b-04 highlighted in red.

Processing

Processing of the seismic data was carried out by CGG in their processing centre in Perth, Western Australia. Fourteen 2D lines were processed through a pre-stack time migration sequence.

The basic steps in the 2D pre-stack time migration workflow are summarised below;

- Pre-processing
- Denoise
- Refraction statics
- Amplitude adjustment
- Velocities and Dip Move Out Correction
- Migration

Pre-Stack Depth Migration

While some of the 2013 seismic data processed using pre-stack time migration is excellent quality, in areas of intense salt mobilisation the data quality deteriorates significantly. Hence a pre-stack depth migration trial was undertaken on part of seismic line AMSAN13B-04 (Figure 1) to determine if imaging of the sub- and intra-salt packages could be improved with a different processing stream.

The velocity model was built in several steps, from initial stacking velocities through to the final depth interval velocity model for PSDM (Figure 2), calibrated with the geological model. Comparing the PSTM and PSDM stacks generated from the final velocity model (Figure 3a & b) highlights imaging improvements along the test line at basement level, as well as improvements within supra-salt succession. The trial has also resulted in learnings to optimise recording parameters (Table 1) for future seismic programs.

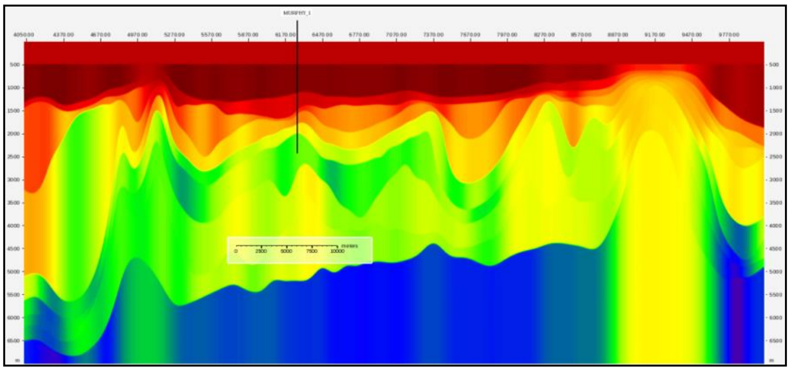


Figure 2. Final interval velocity model for PSDM from geological interpretation of the initial PSTM stack

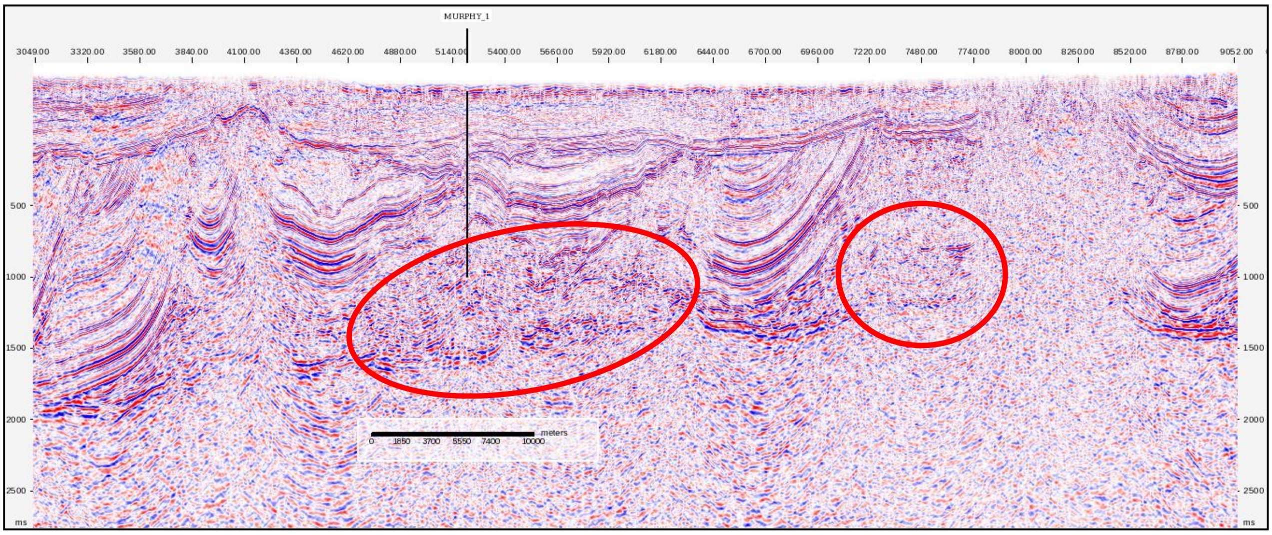


Figure 3. a) PSTM stack using the final velocity model

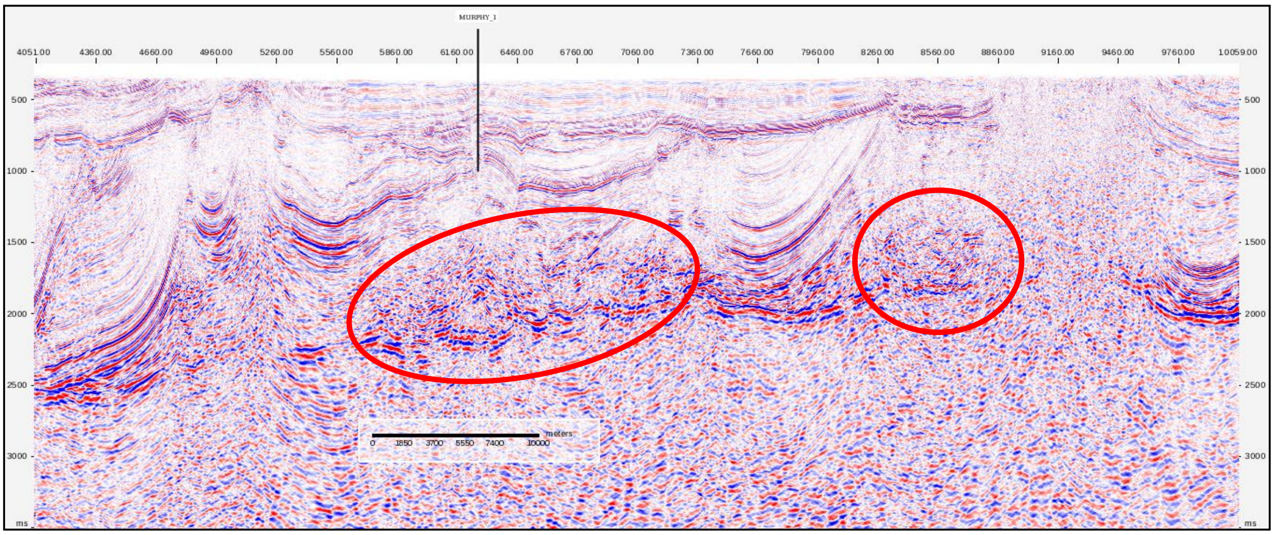


Figure 3. b) PSDM stack using the final velocity model. A comparison between the time pre-stack time migrated and pre-stack depth migrated stacks over a portion of the test line AMSAN13b-04, corresponding to the velocity model in Figure 2. Red circles highlight areas of improvement at the intra and sub-salt target levels.

Parameters	Southern Amadeus 2D 2013 survey	Recommended Parameters
No. channels per shot record	480	700-1500 Depending on recording system
Nominal stacking fold	240	350-375
Recording array	Symmetrical Split spread,	Symmetrical Split spread,
Nominal offset range	5987.5– 12.5 – x – 12.5 – 5987.5 m	7000(7500) – x – 7000(7500) m
Correlated record length	5 secs	
Recorded sample interval	2 ms	2 ms
Source interval	25m	10-20 m
Receiver interval	25m	10-20 m
Bin size	12.5m	5-10
VP and Receiver numbering	Increment 1	
Source Parameters		
Source type	Vibroseis	Vibroseis
Vibrator type	I/O AHV 4	I/O AHV 4
Vib Control	VE464	VE464
Number of Vibrators	3 Vibes Inline.centred on half station, 70% force	3 Vibes Inline.centred on half station, 60-80% force
Sweep frequency	5-90Hz,8-80Hz,10-80Hz,10-82Hz & 12-80Hz	6(8)-80(90)Hz
Sweep type	Linear	Linear
Sweep length	12 secs	10-16 secs
Number of sweeps per VP	1	1
Front & Back – end tapers	500 msec/ 300msec	250 msec/ 250msec
Instrumentation		
Recorder	Sercel SN428	Sercel SN428/FairField Nodal
Filters	Hi cut 0.8 Nyquist Linear Phase Low cut out	Hi cut 0.8 Nyquist Linear Phase Low cut out
Data Format	SEG-D	SEG-D, SegY
Auxiliaries	TB,100Hz,Pilot,DPG Ref, Sweep Auto-Correlation	TB,100Hz,Pilot,DPG Ref, Sweep Auto-Correlation

Table 1. Southern Amadeus 2013 2D seismic survey parameters and parameters recommended for future 2D seismic acquisition following PSDM trial

Interpretation

The 2013 AMSAN13B seismic survey in the central and south eastern Amadeus Basin illustrates the dominantly thin-skinned nature of deformation associated with the ~600-520 Ma Petermann Orogeny, in addition to local basement-involved deformation. The Neoproterozoic Gillen Salt Member of the Bitter Springs Formation is very thick and mobile controlling deformation in the west of the area of interest, but thins to the east. The Early Cambrian Chandler Salt becomes diapiric and structurally controlling in the east. Thrust faults associated with the Petermann and other Late Proterozoic movements appear to detach primarily within the Gillen salt.

Strain for sediments above the Lower Gillen Member appears to be focused on the basin margins, with steep duplexes and overturned beds immediately in front of the Musgrave and Arunta blocks. For example, the Petermann Nappe to the west of the Santos acreage exhibits completely overturned beds. A more distal expression of the Petermann Orogeny deformation is seen as the thrust stacking imaged on seismic line AMSAN13B-04 (Figure 4). The 2013 survey allows the linking of these deformed beds, to elongate, short and intermediate-wavelength positive gravity anomalies. The anomalies are NW-SE and E-W trending, and locally ENE-WSW trending; a consequence of upturned high density carbonates of the Loves Creek and Johnnys Creek members of the Bitter Springs Formation.

Seismic wash-out zones also correspond to local positive gravity anomalies and are interpreted to be zones of intensely brecciated carbonate and anhydrite uplifted as a result of salt mobilisation. A potentially large basement feature has been interpreted beneath one of these brecciation zones in the southern part of the basin. Although basement imaging is locally poor even after PSDM processing, the interpretation is supported by the 2014-2015 SEEBASE^{TM} depth-to-basement model and appears to be a regional high (Figure 4). This feature is not specifically related to the long wavelength, regional E-W trending positive anomaly seen on the gravity data and is unlikely to extend throughout the basin as the gravity model appears to suggest. Further seismic is planned to confirm the interpretation and delineate the structure.

Towards the eastern flank of the basin, inverted normal faults have been identified. These faults are inferred to be primarily ~1080-1040 Ma Giles Event basement faults that were reactivated during the Petermann Orogeny. This has resulted in the formation of a large inverted basement block (Figure 5), tested at its down dip limit by Magee-1, which flowed gas from the sub-salt Heavitree formation at a sub-economic rate. The Gillen salt is relatively thin at this location, and the seismic imaging is generally very good quality.

Possible carbonate stringers within the Gillen salt have been identified across the basin based on seismic character analogous to South Oman (Figure 6). These are interpreted to be local carbonate platforms formed during deposition of the Gillen evaporite sequence and subsequently deformed during salt mobilisation to form floating rafts (Grotzinger & Al-Rawahi, 2014).

A 2014 seismic survey across the Mereenie area in the central northern part of the Amadeus Basin illustrates a mainly basement-involved style of deformation. This can be primarily attributed to the ~450-310 Ma Alice Springs Orogeny, which generally originated in the north. There is also an indication of earlier movement on the Mereenie fault, suggesting that the deformation effects of the Petermann Orogeny extend, at least locally, into the northern part of the basin.

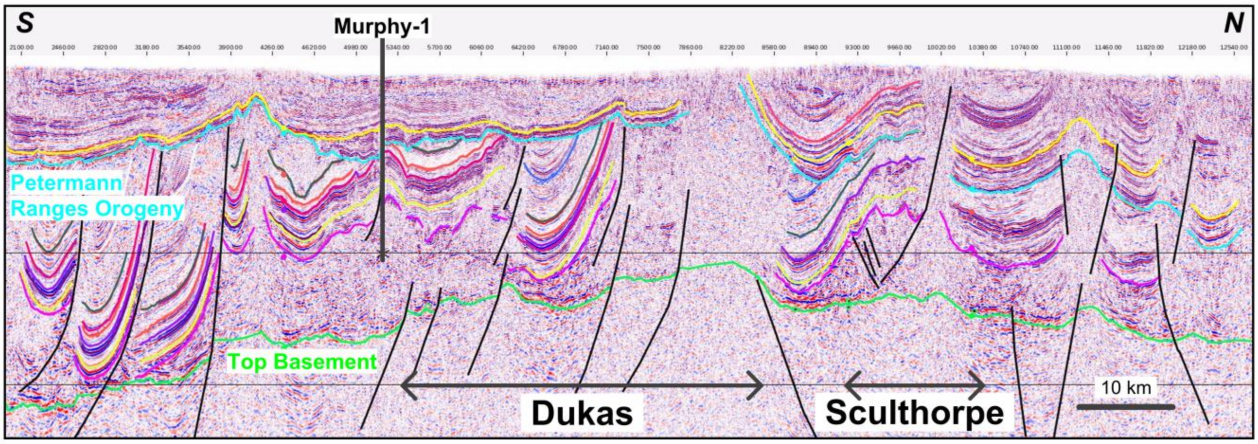


Figure 4. Seismic line AMSAN13B-04 showing thin-skinned deformation with detachment primarily within the Neoproterozoic Gillen Salt member of the Bitter Springs Formation; seismic wash-out zones occur due to brecciated sediments resulting from salt mobilisation; and an interpreted large regional basement high with two weak leads, Dukas and Sculthorpe, supported by depth-to-basement modelling.

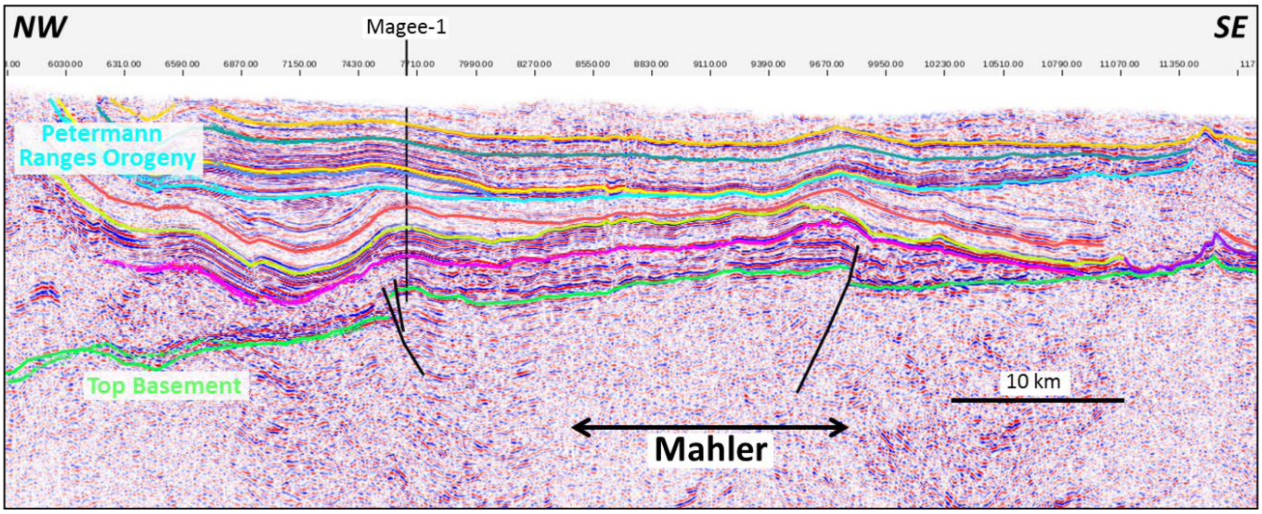
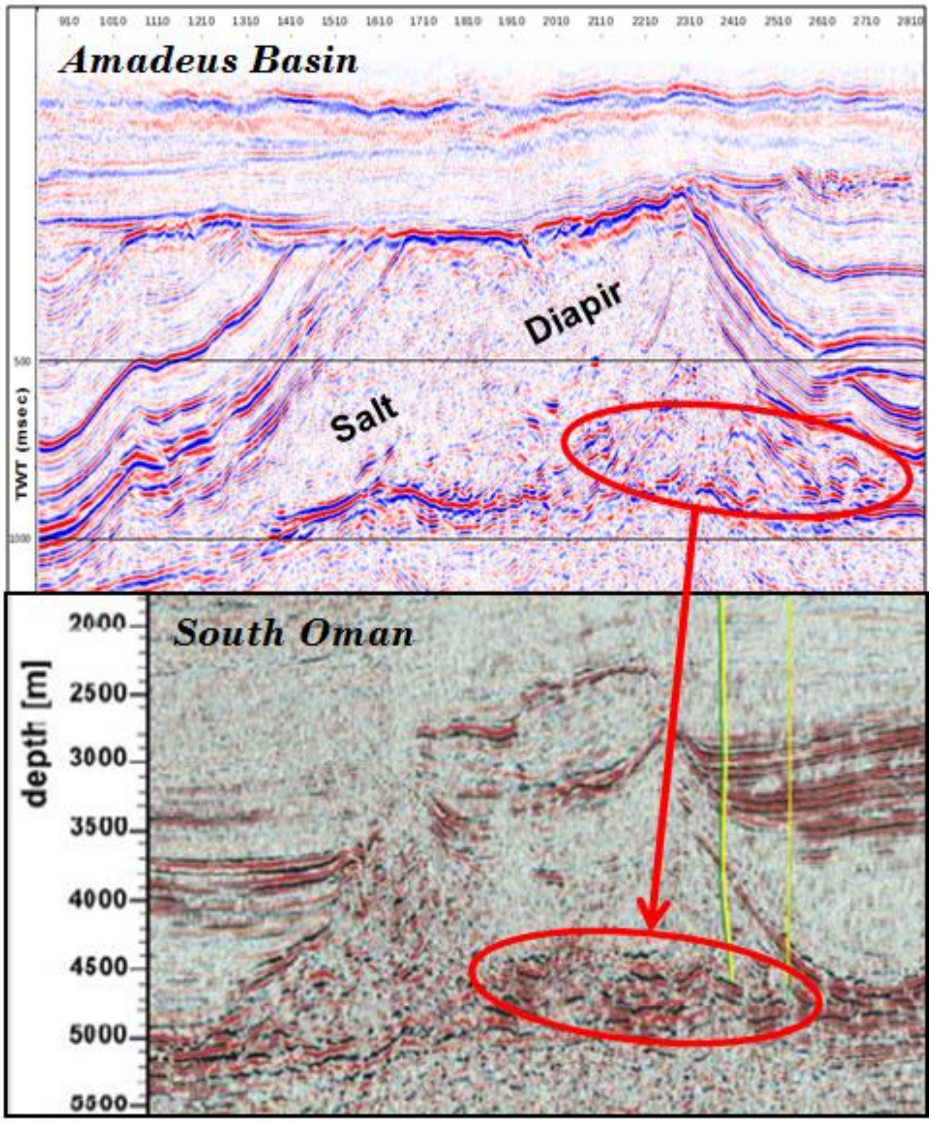


Figure 5. Seismic line AMSAN13B-06 showing inverted Giles event extensional basement faults, creating an upthrust basement feature; and the location of the Magee-1 well which penetrated basement and flowed gas from the Heavitree formation. The Neoproterozoic section, culminating with the Petermann Orogeny, thins to the east of the basin.



(from Kukla et al. (2011) Geofluids)

Figure 6. Intra- Gillen Salt Carbonate "stringers (top image) have identical seismic expression to prolific South Oman and offer stacked upside potential as a dual target with sub-salt leads.

SEEBASE™ Depth-to-Basement Model

The 2014-2015 SEEBASE™ depth-to-basement model (Figure 7) is based on an interpretation of high-resolution gravity and magnetic data, calibrated with Santos seismic and other geological data. The new model has a much higher resolution and is a major improvement in terms of basement structure and basin geometry, compared to the previous SEEBASE™ depth-to-basement model (FROGTECH, 2005).

The interpretation of basement structure is largely based on magnetic data. In parts of the basin, depth-to-basement can be mapped with a relatively high level of confidence on the basis of this dataset (e.g. eastern margin), but this is difficult to achieve across the entire basin because of the presence of a sometimes thick non-magnetic to poorly magnetic metasedimentary package in the upper basement. The presence of thick metasedimentary rock packages is likely to have facilitated local basement-involved deformation (FROGTECH, 2015).

Bouguer gravity response within the Amadeus Basin is controlled by variations in depth-to-basement, variations in basement composition and density variations of intrabasinal units. The latter makes depth-to-basement interpretation on the basis of gravity data alone difficult. However high-density intrabasinal units can be successfully mapped with the aid of high-pass gravity filters and calibration with wells, seismic data and cross-sections. The principal high-density units within the central and eastern Amadeus Basin are the carbonates of the Bitter Springs Formation, along with brecciated high density residuals from halite mobilisation, discussed previously.

Gravity modelling, along with depth-to-basement mapping, was used to determine the nature of the regional E-W trending, intermediate to long wavelength gravity anomalies that dominate the gravity data (Figure 8). The results indicate that there is no single regional basement high within the Amadeus Basin and the regional E-W trending negative gravity anomalies at the northern and southern edge of the basin are not simply a reflection of deeper basement. The central east-west trending positive gravity anomaly is primarily due to the widespread occurrence of shallow, high-density intrabasinal units, and is also interpreted to partly reflect a gentle crustal scale flexure resulting in shallower Moho beneath the basin (as a result of tectonic loading on the margins). The southern negative gravity anomaly results from a combination of a deep Moho (thicker crust), relatively low-density crust dominated by felsic intrusive rocks, and the contrast of the low density crust with the very high density crust and shallow mantle of the central Musgraves. The northern negative anomaly results from the combination of a low-density late Palaeozoic depocentre and the low-density granite-dominated Warumpi Terrane, but is also related to the strong contrast with the extremely strong positive gravity anomaly associated with the Arunta West Terrane to the north (Figure 8).

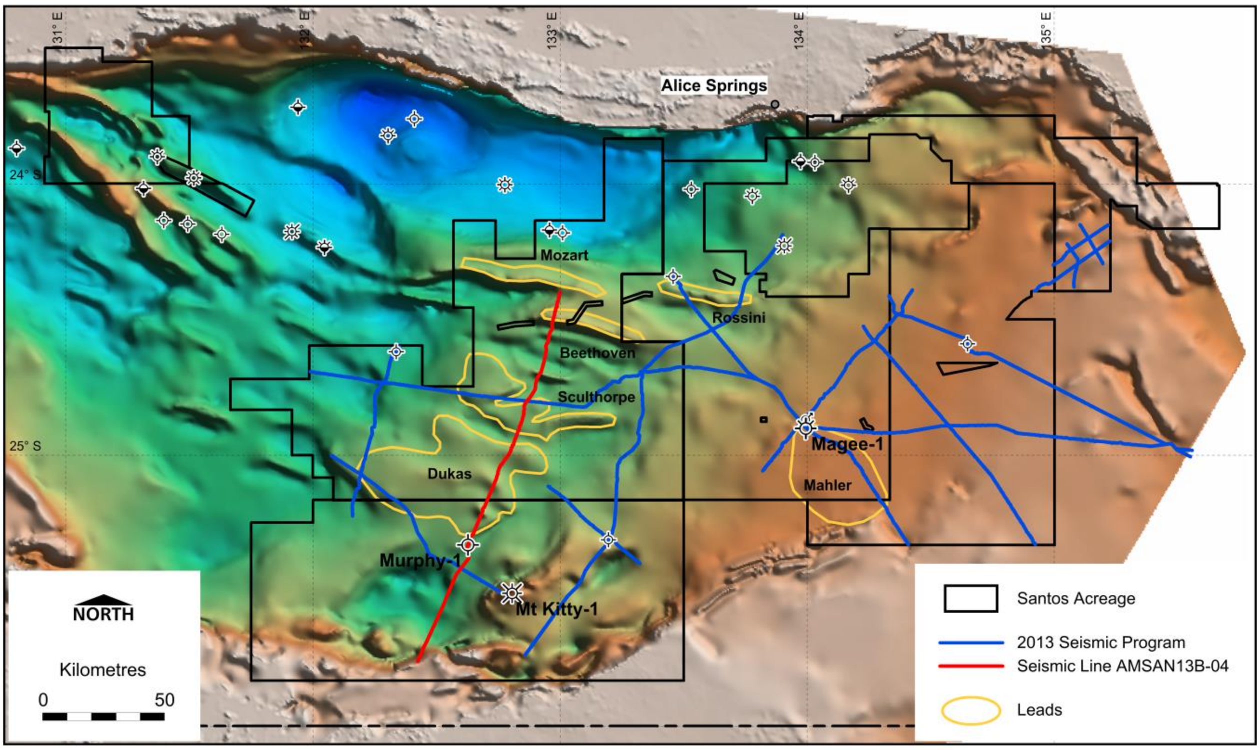


Figure 7. 2014-2015 SEEBASE™ image with sub-salt leads, 2013 AMSAN seismic survey and key wells highlighted.

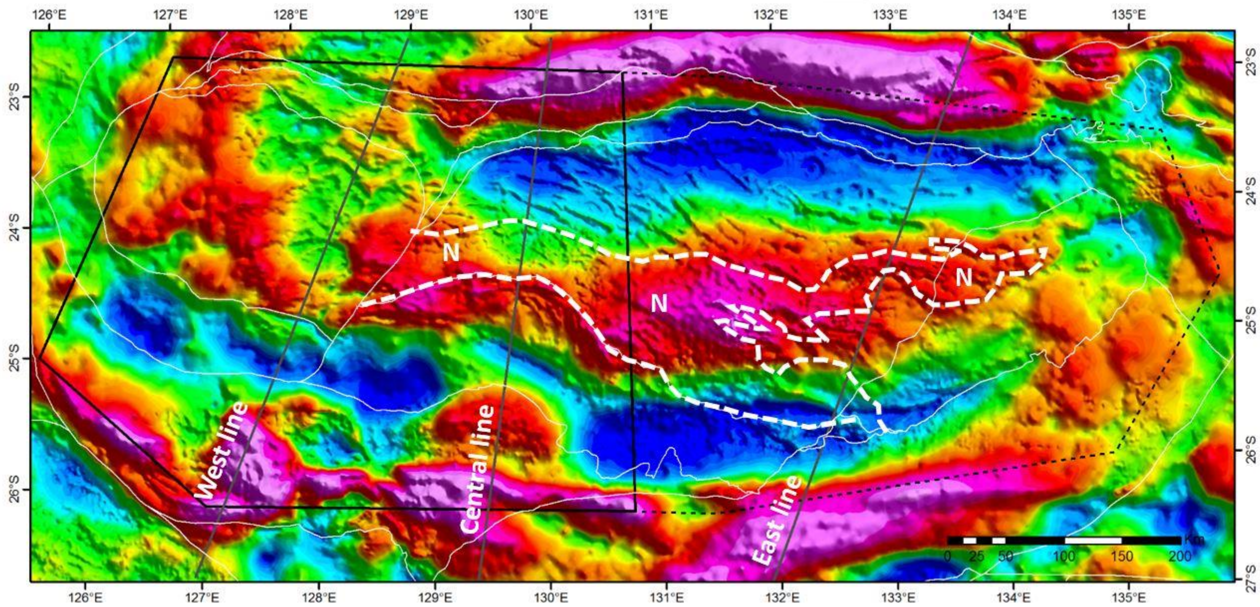


Figure 8. HP 300km Bouguer gravity image showing central positive gravity anomaly, flanked to the north and south by negative gravity anomalies below the basin edges. The dashed white line shows the zone where the high density Neoproterozoic units are present at surface. Basement terrane boundaries are shown by thin white lines. The study was undertaken in two phases; Phase 1 in the east - outline in dashed black, and Phase 2 in the west - outline in solid black.

CONCLUSIONS

The interpretation of the 2013 seismic provides a good regional framework for understanding basin structure in the southern Amadeus Basin. The Neoproterozoic-Cambrian section clearly thins rapidly to the east, due to both onlap and truncation. Salt deformation is severe in places within the deeper parts of the basin, with zones of poor seismic data quality due to ray path distortion by complex geology. While careful seismic reprocessing has resulted in some data quality improvement in these areas, poor seismic imaging is characteristic of severe salt mobilisation.

Incorporating updated potential fields data with the newly acquired seismic and other calibration data has enabled the development of an updated SEEBASE depth-to-basement model. This significantly improves our understanding of the basement architecture and evolution of the basin. The model provides a base for focussing exploration activities and interpolating trends between seismic data. This is of particular importance given the primary targets in the southern Amadeus, the Neoproterozoic sub- and intra-salt plays, are in areas affected by complex halotectonics and can be difficult to image on seismic.

Several leads, identified on the regional seismic in conjunction with the depth-to-basement model, require infill seismic to mature to drillable prospect status. This infill seismic planned for 2016 will implement optimised recording and processing parameters identified during trial reprocessing of the 2013 seismic, to improve imaging in salt-disturbed areas.

ACKNOWLEDGMENTS

Many thanks to the current and previous Santos Amadeus Basin Exploration team, Sandy Menpes (team leader), Andrew May (geophysicist), Phil Plummer (geologist and seismic interpreter) and Sandy Watters (Exploration Manager) as well as Mike Giles (Manager Operations Geophysics) and Sergey Vlasov (geophysicist). Santos also acknowledges and thanks the exploration team of our partner, Central Petroleum.

REFERENCES

Edgoose CJ, 2012. The Amadeus Basin, central Australia. Episodes 35: 256-263

FROGTECH, 2005. OZ SEEBASE Study 2005, Public Domain Report to Shell Development Australia FROGTECH Pty Ltd

FROGTECH, 2015. Amadeus Basin SEEBASE Update, Internal Report to Santos Ltd. FROGTECH Pty Ltd.

Grotzinger J and Al-Rawahi Z, 2014. Depositional facies and platform architecture of microbialite-dominated carbonate reservoirs, Ediacaran-Cambrian Ara Group, Sultunate of Oman. AAPG Bulletin, V. 98, No. 8: 1453-1494

Kukla PA, Reuning L, Becker S, Urai JL and Schoenherr J, 2011. Distribution and Mechanics of Overpressure Generation and Deflation in the Late Neoproterozoic to Early Cambrian South Oman Salt Basin. Geofluids, 11: 349-361

Marshall T, 2003. Petroleum Systems and Source Rocks in the Amadeus Basin, Northern Territory: in Cowie M (editor) 'Queensland 2003 exploration and development.' Petroleum Exploration Society of Australia (Qld/NT) 2003 Symposium: 37-42