Exploring the sub-salt play in the frontier Amadeus Basin – Insights from potential field data analysis

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Background

Santos Ltd (Santos) entered into the southern Amadeus Basin (**Figure 1**) via a partnership with Central Petroleum Ltd in 2012 to explore the sub-salt and intra-salt plays of the Neoproterozoic lower Gillen-Heavitree Petroleum System. A central basin high and focus for regional hydrocarbon migration was postulated to have formed as a result of deformation and loading of the basin to the south (580–530 Ma Petermann Orogeny), and later deformation and loading to the north (450–300 Ma Alice Springs Orogeny). The primary exploration objective was the Heavitree Quartzite, a fluvio-marine sandstone that had flowed gas from Magee-1 (drilled 1992), the only well to test the Neoproterozoic sub-salt play in this frontier basin at that time. Subsequently, a second test of the play, the Southern Amadeus Joint Venture's Mt Kitty-1 well, flowed gas from fractured granitic basement. This test confirmed the existence of an extensive sub-salt petroleum system as well as the excellent sealing capacity of the Neoproterozoic evaporites. Gas flows from both wells recorded helium contents of ca 6–9% in addition to hydrocarbon and inert gases.

In 2013 Santos acquired over 1500 km of regional 2D seismic across the Southern Amadeus Joint Venture (SAJV) permits (**Figure 1**). This survey was the first regional seismic dataset acquired over the southern Amadeus Basin; it resulted in the identification of two significant sub-salt structures, named Dukas and Mahler. The Dukas lead, located north of Murphy-1, comprises a large and broad basement roll-over mapped on three seismic lines (**Figure 2**). Post-salt reflections are clearly imaged, but data quality is highly variable where salt mobilisation has occurred with basement locally difficult to image. Infill seismic is to be acquired in 2016 to advance both the Dukas and Mahler leads to drillable prospects.

In areas where seismic coverage is sparse (as it is across much of the southern Amadeus Basin) or of poor quality, higher spatial density magnetic and gravity surveys can be used to interpolate trends between seismic and well control. In 2014, Santos contracted FROGTECH to update the SEEBASE™ Depth-to-Basement Model of the Amadeus Basin (Munroe *et al* 2004, FROGTECH 2005). The model was calibrated with the newly acquired regional seismic data to provide a high-resolution depth-to-basement model for the Amadeus Basin and to place the primary sub-salt

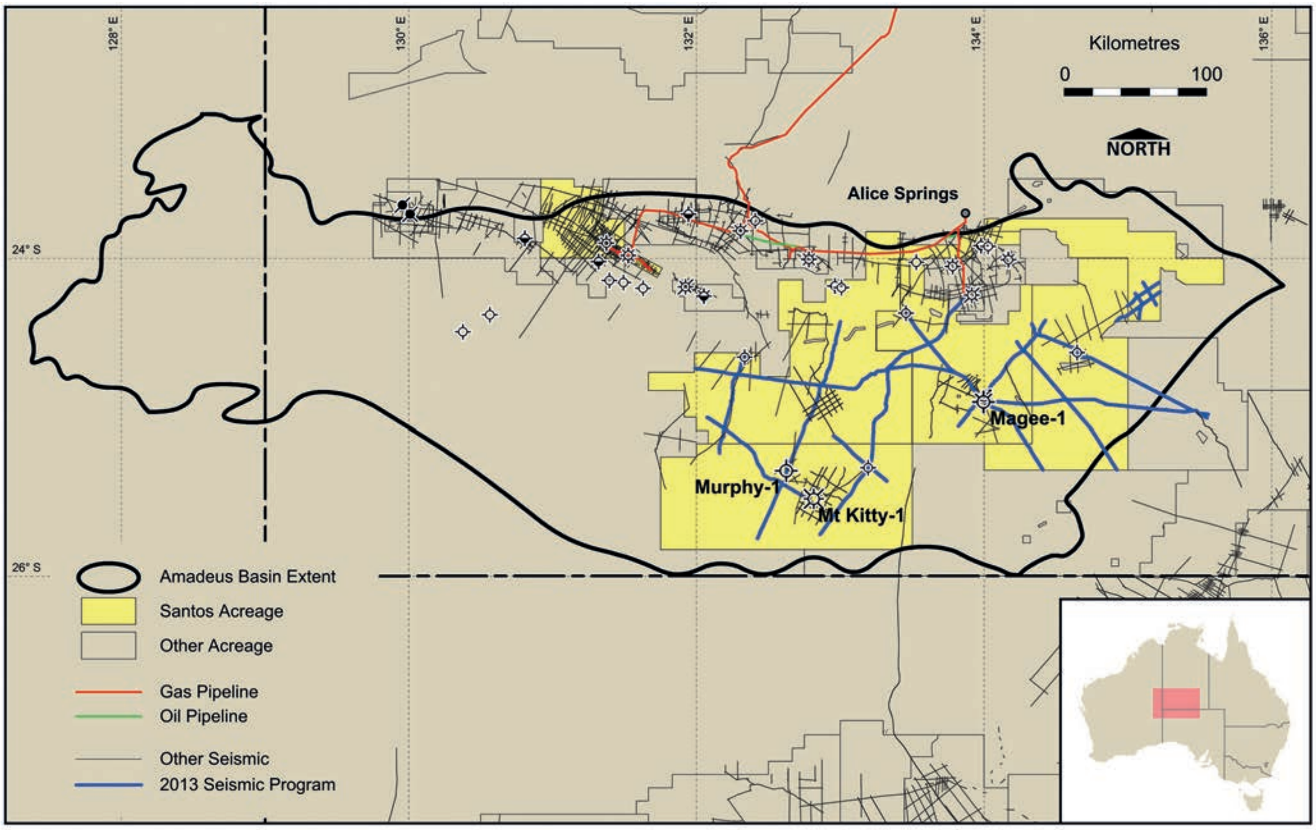

Figure 1. Amadeus Basin map highlighting Santos acreage, regional seismic lines acquired in 2013 AMSAN seismic survey and key well locations.

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play into a regional perspective. The updated depth-to-basement model was then used as a guide for planning the upcoming infill seismic program over the key leads identified (**Figure 3**).

SEEBASE™ Depth-to-Basement Model

The depth-to-basement study was undertaken in two stages as new data became available, with the first stage in the eastern Amadeus Basin in 2014 and the second in the western Amadeus Basin in 2015 (**Figure 4**).

The 2014–2015 SEEBASE™ depth-to-basement model is based on an interpretation of high-resolution gravity and magnetic data, and is 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 (Munroe *et al* 2004, FROGTECH 2005).

The interpretation of basement structure below the Amadeus Basin is largely based on magnetic data. Basement below the central and eastern parts of the Amadeus Basin consists of several NNE–SSW-trending zones of more felsic and more mafic rock, heavily intruded by granitoids. This basement is interpreted as a continuation of the Albany-Fraser Orogen to the south, in agreement with Betts *et al* (2011). The western part of the Amadeus Basin is situated above a newly-defined micro-craton, the Gillespie Terrane. The SEEBASE™ depth-to-basement model, basin shape, intrabasinal deformation style and deformation style in exposed basement surrounding the Amadeus Basin, all illustrate the strong influence of basement on basin evolution.

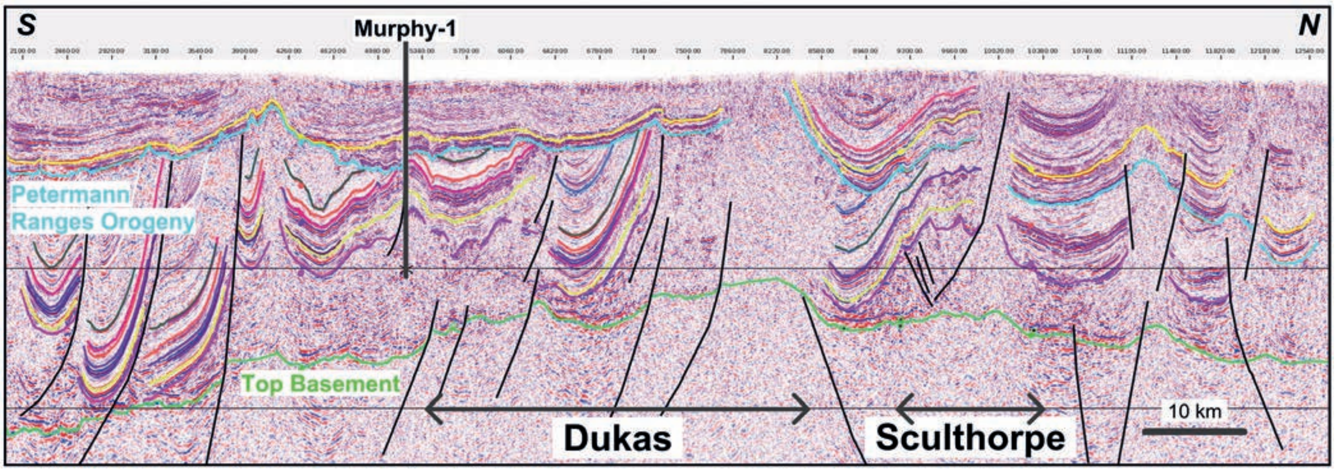

Figure 2. Regional N–S seismic line AMSAN13b-04 from 2013 AMSAN seismic survey highlighting the Dukas lead (see **Figure 3** for line location).

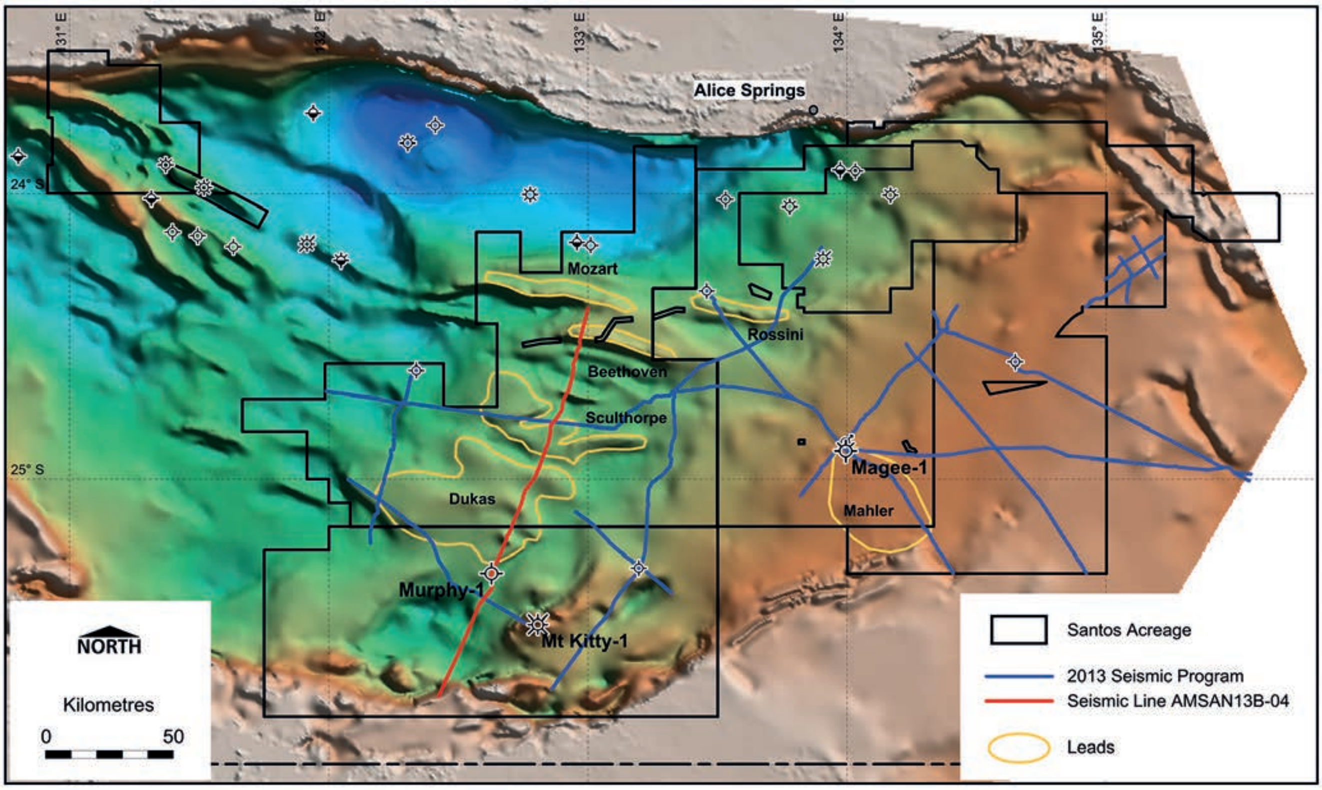

Figure 3. 2014–2015 SEEBASE™ image with sub-salt leads, 2013 AMSAN seismic survey and key wells highlighted.

In various parts of the Amadeus Basin, depth-to-basement can be mapped with a relatively high level of confidence on the basis of magnetic data (eg 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 parts. The presence of thick metasedimentary rock packages is likely to have facilitated local basement-involved deformation.

Within the Amadeus Basin, an interpretation of the gravity data is not straightforward. A comparison of all available geological data (wells, surface geology), seismic data and potential field data, shows that the Bouguer gravity is controlled by variations in depth to basement, variations in basement composition and density variations of intrabasinal units. The latter density variation makes depth-to-basement interpretation on the basis of gravity data alone difficult, but with the aid of high-pass gravity filters and calibration with wells, seismic data and cross-sections, this feature can be used successfully to map high-density intrabasinal units.

2D seismic data from two areas proved particularly useful for calibrating and interpreting the gravity data. The 2013 AMSAN seismic survey in the eastern Amadeus Basin across the Dukas lead illustrates the largely detached nature of deformation related to the Petermann Orogeny and the local presence of basement-involved deformation associated with the Petermann Orogeny. The survey also allows the linking of elongate, short- and intermediate-wavelength, positive gravity anomalies to deformation features. This is particularly clear along line AMSAN 13b-04 shown in **Figure 2**; this line was used to construct a regional gravity model across the eastern Amadeus Basin (eastern line in **Figure 4**). However, due to the common presence of seismic wash-out zones in the 2013 AMSAN seismic data and the largely detached deformation style (**Figure 2**), variations in basement topography and their reflection in the gravity data are often ambiguous.

The 2014 seismic survey across the Mereenie area in the central northern part of the Amadeus Basin illustrates a mainly basement-involved style of deformation, attributed to the Alice Springs Orogeny that is reflected in the gravity data. Moreover, although situated in a regional negative gravity anomaly that partially coincides with a deep foreland basin related to the Alice Springs Orogeny (eg Hermannsburg cross-section, Warren and Shaw 1995), basement in the Mereenie area is much shallower than originally expected.

The insights gained from these two areas were used for a regional interpretation of the gravity data.

Elongate, short- to intermediate-wavelength, NW–SE- to E–W-trending and locally ENE–WSW-trending gravity anomalies (eg on high-pass filters of the Bouguer gravity with wavelengths up to 300 km) characterise the central to eastern parts of the Amadeus Basin. These mainly reflect tilted to deformed high-density intrabasinal units (**Figure 4**). The principal high-density units within the Amadeus Basin are carbonate rocks of the Bitter Springs Formation. Where these carbonate rocks are upturned, they are clearly reflected in the high-pass gravity data. Similarly, wash-out zones on seismic data, interpreted as brecciation zones resulting from salt mobilisation, clearly show up as local positive gravity anomalies. The positive gravity signal is attributed to brecciated high-density residuals (eg anhydrite, dolomite) from halite migration as confirmed by well data. The trend and extent of folded Bitter Springs carbonate rocks and the potential extent of the brecciated zones has now been mapped in improved detail using various filters of the gravity data and constraining datasets. This mapping has been used to assess the subsalt plays. The trend of elongate short- to intermediate-wavelength intrabasinal gravity anomalies can be linked to the effects of the Petermann Orogeny in the central and southern parts of central and eastern Amadeus Basin, and the Alice

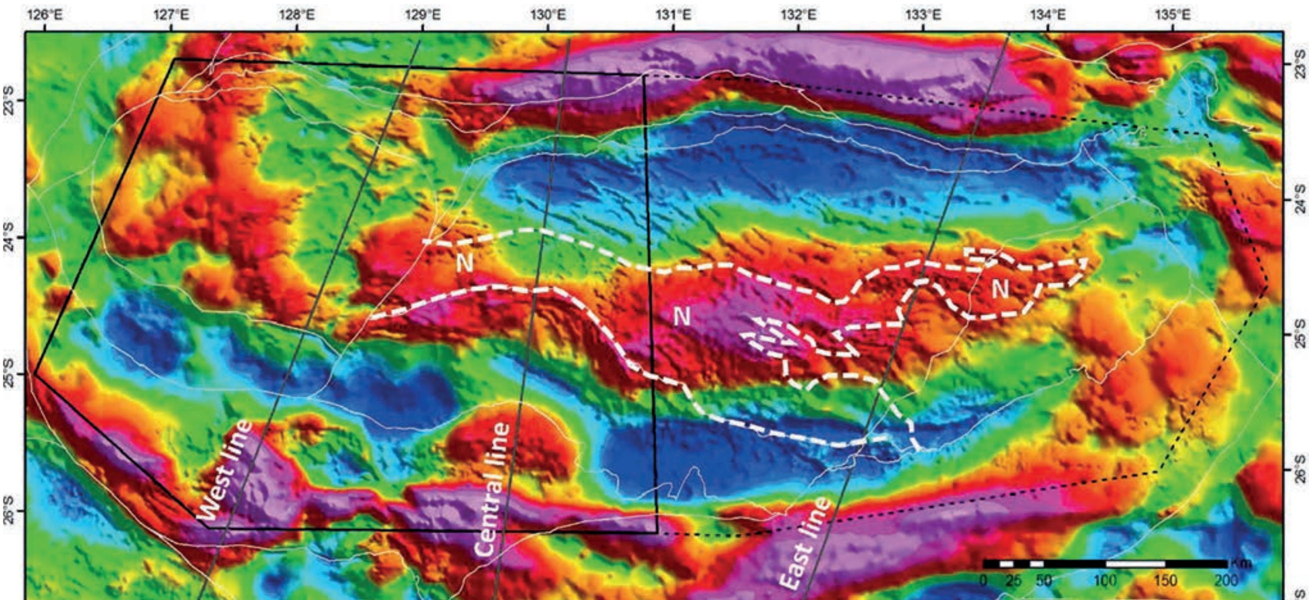

Figure 4. HP300 km Bouguer gravity image showing a central positive gravity anomaly (red tones), flanked to north and south by negative gravity anomalies (blue-green tones) below the basin edges. Dashed white line shows zone where high-density Neoproterozoic units are present at surface. Basement terrane boundaries are shown by thin white lines. Phase 1 outline in dashed black, and Phase 2 outline in solid black.

Springs Orogeny in the northern part of western Amadeus Basin and central to northern parts of central and eastern Amadeus Basin, and to pre-existing changes in basement topography.

The northern and southern margins of the central and eastern Amadeus Basin are characterised by regional negative E–W-trending, intermediate- to long-wavelength gravity anomalies, whereas the central basin is characterised by a regional positive gravity anomaly.

The results of gravity modelling and integrated interpretation of all datasets indicate that there is no single regional basement high within the Amadeus Basin; 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 (**Figure 4**). The central E–W-trending positive gravity anomaly results mainly from the widespread occurrence of shallow high-density intrabasinal units, but also partly from 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) and relatively low-density crust dominated by felsic intrusive rocks, and the contrast of low-density crust with very high-density crust and shallow mantle of the central Musgrave Province. The northern negative anomaly corresponds to 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 an extremely strong positive gravity anomaly that is associated with the Arunta West Terrane to the north, resulting from up-thrusted mantle and lower crust.

Future exploration program

A 1300 km 2D seismic infill program is due to commence in May 2016, designed to mature leads identified from the 2013 seismic survey and the 2014–2015 SEEBASE™ depth-to-basement map to drillable prospect status.

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