Satellite Gravity Mapping of Post-Salt and Pre-Salt, Santos Basin, Brazil

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Abstract

Recent advances in satellite altimeter data processing combined with the advent of three additional satellite altimetric missions in the past decade can now improve the accuracy and the resolution of derived altimetric gravity data.

I demonstrate that satellite altimetric gravity data now have sufficient accuracy and resolution to (a) locate and identify individual larger salt domes in the Santos South Area, and (b) locate and identify the Jupiter and other discoveries in the pre-salt deep water Santos Basin.

In the Santos South Area the first vertical derivative (1VD) of the satellite altimetric residual isostatic gravity data shows a strong correlation between the location of larger salt diapirs (>4km width) and gravity gradient lows. Smaller salt-features (<2km width) are not resolvable in the satellite altimetric residual isostatic gravity data

Most pre-salt discoveries appear to be associated with positive satellite altimetric gravity gradient anomalies, which may reflect the combined gravitational effects of the structural highs in the pre-salt and the underlying basement.

Introduction

A satellite altimetric gravity data set is derived using satellite-based sea surface height observations, also known as satellite altimetry. Because sea water is a fluid it will adjust to the local variations in gravity and hence the height of the sea surface can be used to estimate the local gravity field. This method has been refined over the past two decades along with the constant improvement in the quality of the satellite observations.

A number of new satellite altimetry missions have been executed since 2010: the GOCE mission now delivers unprecedented accurate geoid/gravity field data in the 200-400 km wavelength range, whilst Cryosat-2 delivers new high resolution sea surface height observations. In addition the Jason-1 satellite completed a full geodetic mission as part its end-of-life cycle in 2012. As a result, the amount of altimetry data available to marine gravity field determination has tripled in recent years, with the quality of the altimetric gravity field nearing that of marine gravity observations in many regions (Christensen and Andersen, 2015).

In the past satellite altimetric gravity data over the Santos Basin have been used to map and interpret (a) larger-scale regional geological features associated with continental and oceanic crust and mantle boundaries (Gomes et al., 2011, and Stanton et al, 2014) and (b) the regional petroleum system (Dickinson and Schiefelbein, 2015).

However, the recent advances in satellite altimeter data processing (Andersen et al., 2010) combined with the advent of three additional satellite altimetric missions in the past decade can now improve the accuracy and the resolution of derived altimetric gravity data.

In this paper I demonstrate that satellite altimetric gravity data now have sufficient accuracy and resolution to (a) locate and identify individual larger salt domes in the Santos South Area, and (b) locate and identify the Jupiter and other discoveries in the pre-salt deep water Santos Basin.

Data

The satellite altimetric gravity data used in this study is a re-processed version of the DTU13 free air gravity field [Andersen et al., 2014].

The satellite altimetric gravity data has been derived using satellite-based sea surface height observations from five geodetic missions: Geosat (15 months, 1985/1986), ERS-1 (11 months, 1994/1995), Jason-1 (13 months, 2012/2013), Cryosat-2 (36 months, 2010/2013), and Saral/AltiKa (12 months, 2013). The satellite altimetric height data has been converted to free air gravity data using the double re-tracking methodology described by Andersen et al. (2010).

The satellite altimetric gravity data is mapped on a 1 arc-minute by 1 arc-minute world-wide grid (~2km by ~2km) covering all marine regions of the world including the Arctic Ocean up to the North Pole. Figure 1 shows the satellite altimetric free air gravity data over offshore southern South America. Onshore the EGM2008 data has been used (Pavlis et al., 2012).

The data set has been post-processed to minimize noise artefacts present in the original free-air gravity data set. The re-processed data set has also been fully Bouguer corrected using Bullard-A (Bouguer Slab) Correction, Bullard-B (Spherical Cap) Correction), and Bullard-C (Terrain) Correction with a terrain density of 2.67 g/cm^3. The Bullard-C Terrain Correction has been carried out to a distance of 167km. using a high-resolution inner-circle terrain model and a lower-resolution outer-ring terrain model. The residual isostatic gravity has been computed by subtracting modelled isostatic gravity effects from the fully Bouguer corrected data.

The local accuracy of the satellite altimetric gravity data is influenced by water depths and proximity to land. Several comparisons of the re-processed satellite altimetric gravity data and modern marine gravity data sets have been published [Christensen and Andersen, 2015 and 2016]. These comparisons indicate that the accuracy of the re-processed satellite altimetric free air gravity data is in the [1.0 mGal; 2.0 mGal] range.

The data has been low-pass filtered with a cut-off wavelength of 13km. Hence the spatial resolution of the satellite altimetric free air gravity data is 6.5km.

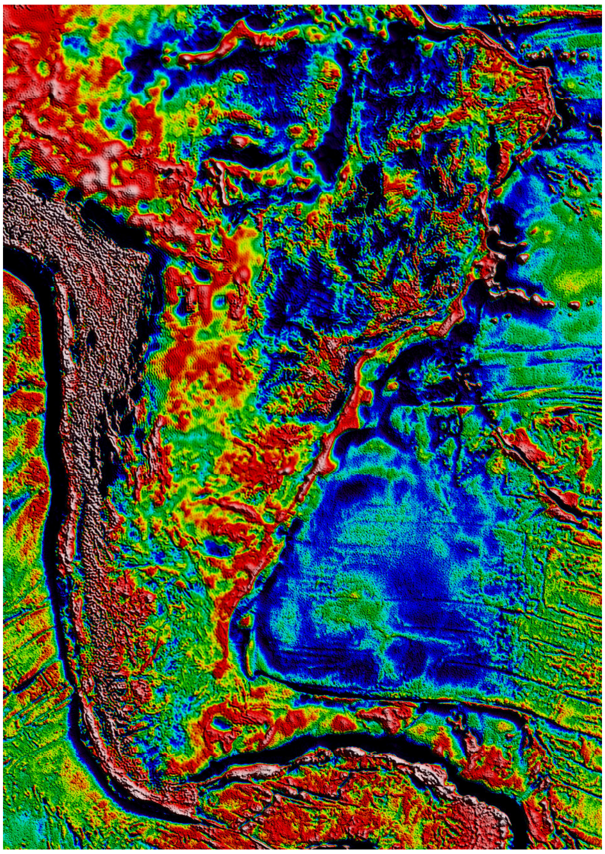

Figure 1 Offshore: satellite altimetric free air gravity data over southern South America. Onshore: EGM2008.

Regional Geology of the Santos Basin

The Santos Basin, offshore Southeastern Brazil, is a salt-bearing passive margin basin flanking the South Atlantic. The basin initially formed during the early Cretaceous as the South Atlantic began to open. The associated rifting caused grabens and half-grabens to be filled by the “syn-rift phase” Barremian fluvial/lacustrine Piccaras Formation source-rock interval of organic-rich shales deposited in anoxic lakes. This was followed by the Itapena Formation, forming a secondary limestone reservoir unit, consisting of coquinas and shell banks and marking the top of the syn-rift section (ANP, 2010).The primary carbonate reservoir unit in the pre-salt play in the deep-water Santos Basin is the early-to-middle Aptian Barra Velha Formation comprising microbialites or stromatolites, deposited in hypersaline transitional marine conditions during the onset of a regional post-rift (“sag-phase”) thermal subsidence. During the late Aptian the thick deposits of the salt-rich Ariri Formation (exceeding 2000m in thickness) created a regional seal for the pre-salt petroleum system.

Pre-salt traps are comprised of drape features over basement highs either with four-way dips closures or a combination of dip/fault closures.

Fully marine conditions were established in the Albian leading the deposit of the carbonate-dominated Itanhaém Formation. Rapid sea-level rise in the Cenomanian-Turonian drowned the Albian carbonates with the subsequent deposition of the fine-grained clastic dominated lower part of the Itajai-Açu Formation (Jackson et al, 2015).

Uplift and erosion during the Coniacian-Maastrichtian of the coastal Serra do Mar ranges caused a southeastward progradation of the basin margin into the Santos Basin. Sediment influx during the Paleocene-Eocene was limited to the northern part of the Santos Basin, whilst marine drowned-shelf conditions prevailed in the southern Santos Basin (Modica and Brush, 2004). This situation was reversed in the Oligocene as sediment influx shifted further eastwards towards the Campos basin. The northern Santos Basin became starved of sediment influx during the late Oligocene and Neogene. Meanwhile in the southern Santos Basin a new source of muddy clastic influx was established in the late Oligocene and Neogene resulting in an extensive, 1,500m-2,000m+ thick sequence of muddy deltaic deposits. This Neogene depocenter has acted as a thermal blanket burying and maturing post-salt marine source rocks.

Today the southern Santos Basin is a salt diapir and mini basin province characterized by the presence of multiple narrow and strike-trending salt ridges and diapirs, creating a series of mini-basins. The large amplitude salt diapirs are often linked to the seafloor by normal faults (Modica and Brush, 2004)

Santos South Area

The Santos South Area is located approximately 120km off the coast of the State of Caterina, Brazil in an average water depth of 300m. The area holds several post-salt discoveries in turbidite sandstone reservoirs with either structural or stratigraphic pinch-out traps, both closely associated with salt-diapirs. The Santos South Area includes the 113 MMBOE Baúna (formerly the 2009 Tiro discovery) and the 83 MMBOE Piracaba (formerly the 2009 Sidon discovery) producing fields in block BMS-40 along with the nearby 2010 Baúna Sul (formerly Maruja) discovery in the south and the 2009 Piracucá (formerly Pialamba) discovery in the northern end.

Recently three additional discoveries have been made in the Santos South Area: the 2013 Kangaroo and Bilby discoveries in Eocene-Maastrichtian age reservoirs and the 2015 Echidna discovery in Paleocene-Maastrichtian age reservoirs.

Figure 2a shows the bathymetry of the South Santos Area along with the location of the hydrocarbon discoveries and the producing fields. The area is at the edge of the present-day continental shelf. Water depths in the central area are of the order of 200m-300m. However, 90km to the southeast water depths exceed 2,150m.

Figure 2b shows the satellite altimetric residual isostatic gravity data over the South Santos Area. Note the strong SW-NE running gravity gradient traversing the region – indicating a regional fault or lithological contact. Also note the elongated gravity low running parallel to the east, indicating a sub-basin.

Figure 2c shows the Aptian Salt Isochron as derived from seismic coverage in the area. The figure has been modified from Modica and Brush (2004). The salt thickness map clearly shows the multiple narrow and strike-trending salt ridges and diapirs of the salt diapir and mini basin province.

Figure 2d shows the first vertical derivative (1VD) filtered image of the satellite altimetric residual isostatic gravity data over the South Santos Area. The 1VD filter attenuates longer wavelengths in the data – associated with regional geology - and instead accentuates the short wavelength anomalies associated with local geological structures. Furthermore the 1VD filter accentuates short wavelength features into local highs and lows. One can observe a strong correlation between the negative lows in the vertical gravity gradient and the published locations of larger salt diapirs with a diameter exceeding 4km (outlined in white). Salt diapirs with a radius less than 2km do not appear to be resolved by the satellite altimetric gravity gradient data. Also note that most of the hydrocarbon discoveries in this area are situated on the flanks of these gravity gradients lows, associated with larger salt diapirs.

Comparison between 22 gravity gradients lows (marked by "L" in Figures 2c and 2d) and the Aptian Salt Isochron map shows that 16 gravity gradient lows are directly associated with a salt structure with a vertical amplitude exceeding 1,000ms. Hence the satellite altimetric gravity gradient lows may provide a map of the lateral extent of the larger salt-diapirs in the region, and these can be used as vectors for future exploration efforts.

Jupiter Field, Deepwater Pre-Salt Santos Basin

The 2008 Jupiter field discovery is located ~300km south of Rio de Janeiro in 2,200m water depth. The reservoirs consist of the Cretaceous Pre-salt intervals of microbial and stromatolite carbonates of the Sag-Sequence underlain by limestone coquinas of the late Syn-Rift-Sequence. The reservoir contains both gas (285m gross) and oil (65m) with an estimated original oil in place (OOIP) of 1.82 BBbl. Top of reservoir/Base of salt is at ~5,000m subsea, and the oil/water contact is at 5,435m subsea.

The depth structure mapping of the Jupiter field is largely based on 3D Pre-Stack Depth Migrated seismic data. Figure 3b shows the derived sub-sea Depth-to-Base-Salt over the Jupiter field and surrounding areas. The 567 km^2 Jupiter field is a large NE-SW trending structural high extending 40km in length and up to 20km in width. The field is located on the western margin of a prominent paleo-deep, which also marks the southeastern edge of current pre-salt discoveries and prospects.

Figure 3a shows the first vertical derivative (1VD) filtered image of the satellite altimetric residual isostatic gravity data over the Jupiter field. The paleo-deep in the eastern part is associated with a strong gravity gradient low. The Jupiter field – as well as adjacent pre-salt discoveries - is associated with positive vertical gravity gradient anomalies in the 10 - 14 Eötvös range. These positive vertical gravity gradient anomalies are partly caused by (a) the density contrast of denser carbonate/limestone structural highs (~2.6 g/cm^3) juxtaposed by lighter halite successions (2.17 g/cm^3); and partly (b) by underlying basement highs, which may have promoted and focused the carbonate build-ups.

The correlation between pre-salt prospects/discoveries and localized satellite altimetric vertical gravity gradient highs is observed throughout the Santos Pre-Salt Basin.

Conclusions

The satellite altimetric residual isostatic gravity data indicates the presence of a NE-SW striking sub-basin in the South Area of the Santos Basin.

The first vertical derivative (1VD) of the satellite altimetric residual isostatic gravity data shows a strong correlation between the location of larger salt diapirs (>4km width) and gravity gradient lows. Smaller salt-features (<2km width) are not resolvable in the satellite altimetric residual isostatic gravity data.

The satellite altimetric gravity gradient lows may provide a map of the lateral extent of the larger salt-diapirs in the region. Many of the oil discoveries in the area are situated on the flanks of salt diapirs.

The inferred locations of larger salt diapirs can be used as vectors for future exploration efforts.

Further 3D gravity gradient modelling may provide more information about the distribution of halites and clastic sediments in the sub-basin.

Furthermore we have established that there is a strong association between the structural highs in the pre-salt formations and basement architecture.

Most pre-salt discoveries appear to be associated with positive satellite altimetric gravity gradient anomalies, which may reflect the combined gravitational effects of the structural highs in the pre-salt and the underlying basement

Salt diapirs in the deep water Santos Basin appear to be less well imaged by the satellite altimetric gravity gradients, than is the case in slat diapir and mini basin region in the South Santos Area. This is possibly due to relatively smaller size, lesser density contrast, large water depth, and the thickness of post-salt sediments

The inferred locations of pre-salt structural highs from positive satellite altimetric gravity gradient anomalies can be used as vectors for future exploration efforts.

Further 3D gravity gradient modelling may provide more information about the distribution of carbonates, pre-salt sediments and the basement architecture in the pre-salt.

I have demonstrated that satellite altimetric gravity data now have sufficient accuracy and resolution to (a) locate and identify individual larger salt domes in the Santos South Area, and (b) locate and identify the Jupiter and other discoveries in the pre-salt deep water Santos Basin

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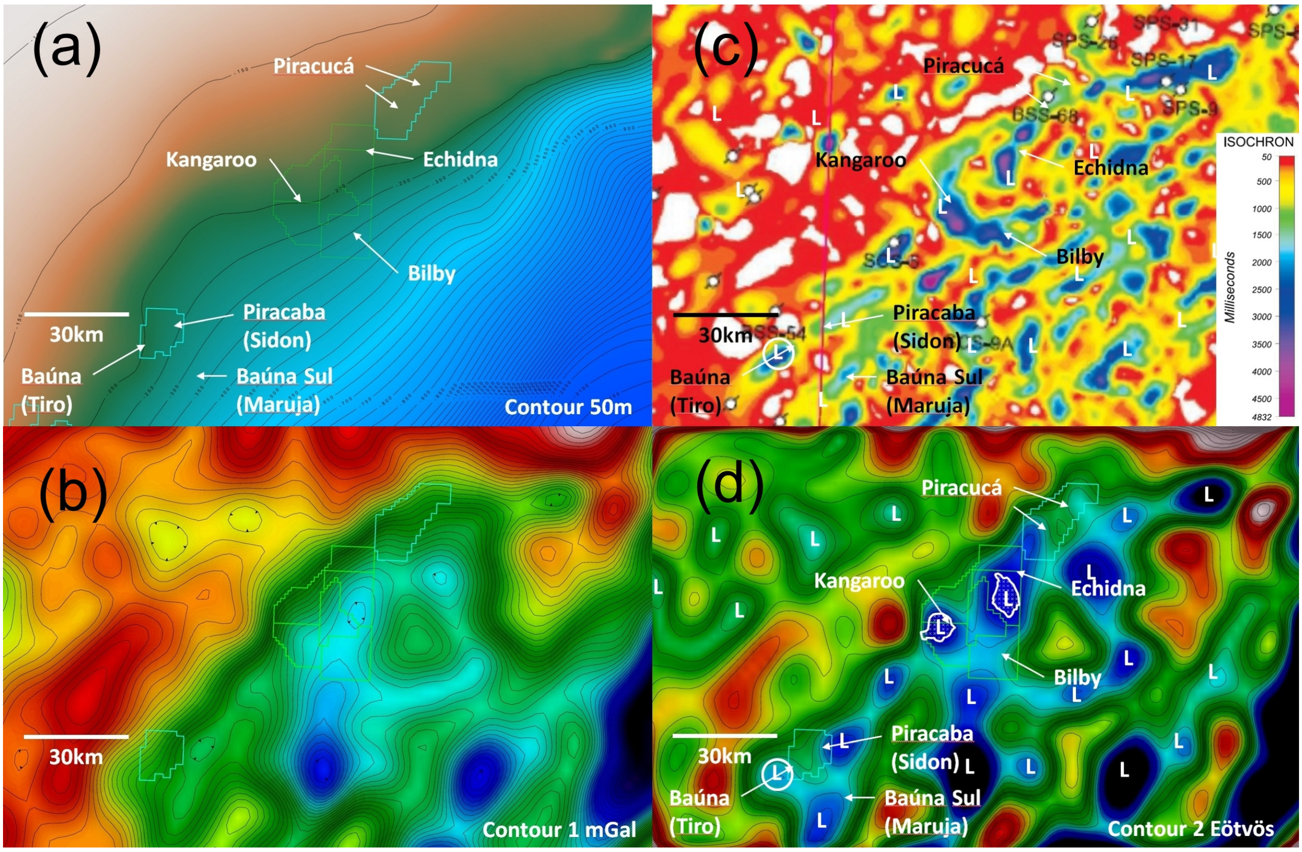

Figure 2 South Santos Area (a) Bathymetry with discoveries and producing fields, (b) Satellite Altimetric Residual Isostatic Gravity, (c) Aptian Salt Isochron, modified from Modica and Brush (2004) (d) Satellite Altimetric Residual Isostatic Gravity – First Vertical Derivative (1VD) filtered.

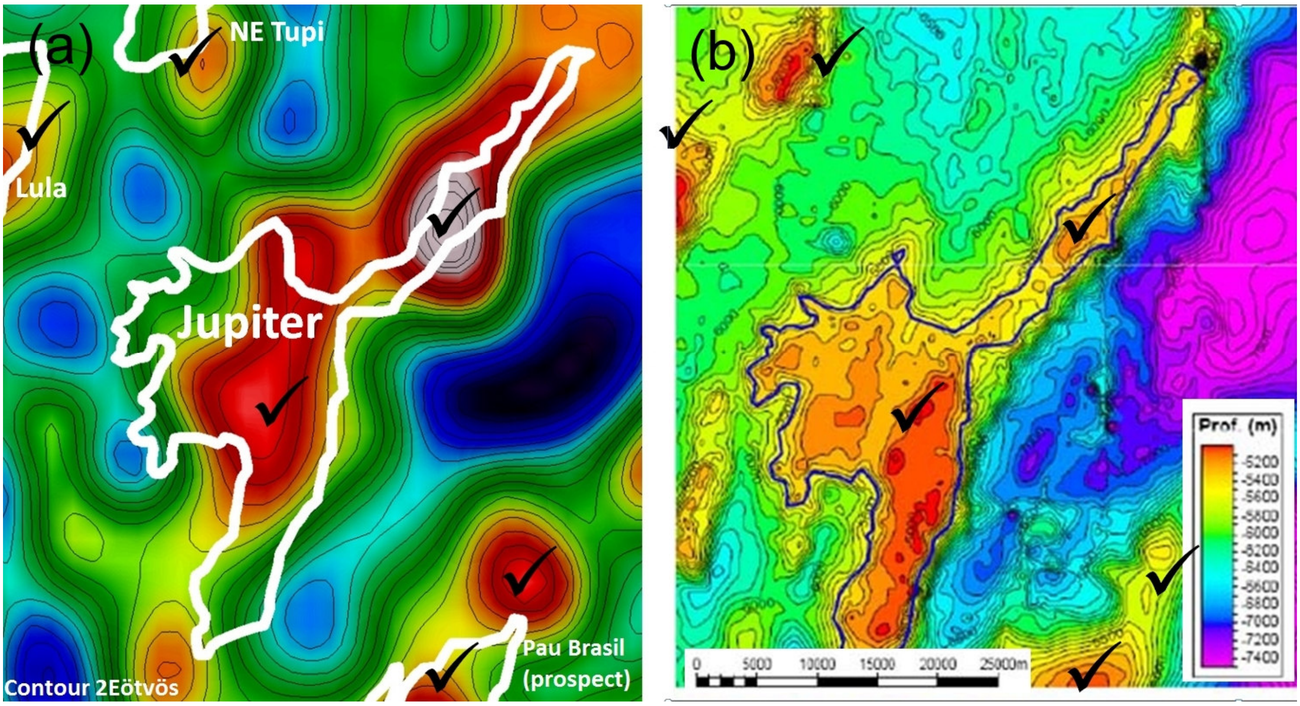

Figure 3 Jupiter field, deepwater Santos Pre-salt (a) Satellite Altimetric Residual Isostatic Gravity – First Vertical Derivative (1VD) filtered (b) Base-of-Salt depth structure map (ANP, 2010).