Mapping Sub-Surface Geology from Magnetic Data in the Hides area, Western Papuan Fold Belt, PNG.

Irena Kivior*
Archimedes Consulting
31 Stirling St. Thebarton, SA
ikivior@archimedes-consulting.com.au

Stephen Markham
Archimedes Consulting
31 Stirling St. Thebarton, SA
smarkham@archimedes-consulting.com.au

Leslie Mellon
Archimedes Consulting
31 Stirling St. Thebarton, SA
lesliem@archimedes-consulting.com.au

**presenting author*

SUMMARY

Horizon mapping using magnetic data was conducted over a part of the Western Papuan Fold Belt, in an area of rugged terrain, where the geological structures are of relatively low complexity. Energy spectral analysis was used to detect magnetic susceptibility contrasts that were laterally merged to form magnetic interfaces corresponding to horizons derived from seismic and well data.

Numerous magnetic interfaces were detected corresponding to: magnetic layers within the Darai Limestone, top of Ieru Formation, intra-Ieru and deeper intra-sedimentary boundaries. These mapped sedimentary surfaces form an anticlinal structure which plunges towards the south-east. A major thrust fault, mapped from magnetic data using automatic curve matching, truncates the anticline in the south-west. Sedimentary magnetic layers were mapped on both sides of this fault. The results obtained from the interpretation of the magnetic data are consistent with structures mapped from seismic and well data.

Key words: Magnetic Data, Energy Spectral Analysis, Horizon Mapping, Fault Detection, Hides Gas Field

INTRODUCTION

Integration of seismic data with potential field data is valuable in the exploration for hydrocarbons in volcanic provinces, such as the Papuan Fold Belt. The rugged terrain makes the acquisition of seismic data difficult and very expensive while thick limestone covered by very thick volcanics in places, makes interpretation challenging. Use of magnetic data in this province is also challenging due to the very rugged terrain, presence of thick volcanic cover, nearby volcanoes, weak magnetic susceptibility contrasts within the sedimentary layers and very complex thrust geology.

By applying Energy Spectral Analysis (ESA) and Automatic Curve Matching (ACM) methods to high resolution aero-magnetic data, we test whether it is possible to map sedimentary horizons and faults in parts of this province where there is no volcanic cover. Whereas both methods have been used successfully in many other provinces, the Papuan Fold Belt presents a challenging area, but one where the results could add significant value in exploration. An initial project area of 114km^2 around Hides Gas Field (Figure 1), was chosen, as it was without volcanic cover and had a relatively simple anticline structure

GEOLOGICAL SETTING

The Papuan Fold Belt is 100km wide and 1000km long and in places up to 3km high and consists of complex fold and thrust structures, in places vertically overturned beds, creating thrust repeats of several formations (Hill et al, 2004). The study area covers the Hides and Karius Anticlines, and is situated centrally within the western Papuan Fold Belt. The Angore Anticline and the Tagari Syncline are north of the study area (Figure 1).

These structures lie in a region surrounded by three volcanoes, Mount Sisa, Mount Kerewa and Mount Doma. Volcanic episodes resulted in the slopes of the volcanoes and the majority of the region becoming covered in highly magnetic lavas and volcaniclastics.

The Hides Anticline generally trends northwest-southeast, plunging southeast, with fault traces in this orientation mapped at the surface. Information from four of the wells: Hides 4, Hides 3, Hides 2 and Karius-1, was used in this study. The anticlinal structure of Hides results in Darai Limestone outcrop (or subcrop) and includes thrust faulting from the southwest.

The litho-stratigraphy of the area comprises of the Miocene Darai Limestone with multiple sedimentary layers of strongly magnetic materials. The Cretaceous Ieru Formation consists of the more magnetic Upper Ieru Sandstone, and Lower Ieru, a marine siltstone mudstone. The Toro Sandstone of Lower Cretaceous age is shallow marine glauconitic sands (indicator of increased magnetic properties). The Upper Jurassic Imburu Formation consists of mudstone and siltstones.

METHODOLOGY

Two main techniques were applied in this study:

- **Horizon Mapping Technique** applied to gridded magnetic data: ESA-MWT & ESA-MW
- **Fault Detection Method** applied to located magnetic data: ACM

Horizon Mapping

The horizon mapping technique is based on energy spectral analysis applied to magnetic or gravity data. It is well known that, based upon the decay of the energy spectrum, the depth to the causative body can be determined. The size of data window over which the spectra is calculated is crucial for correct depth estimation. If the window is too small the depth is too shallow, if too large the depth is also incorrect. Determination of the optimal data window is crucial.

To do this we applied a two stage approach

Stage 1 – Horizon Detection, ESA-MWT

The multi-window test procedure (ESA-MWT) (Kivior et al., 1993, Kivior et al., 2011) is applied to detect magnetic susceptibility contrasts at different depths that correspond to magnetic interfaces. ESA-MWT detects contrasts between stronger magnetic sediments overlaid by less magnetic material and magnetic basement covered by less magnetic sediments. This procedure detects magnetic interfaces corresponding to top of formations, intra-formational surfaces, unconformities, basement or other crustal heterogeneities. At any point of the study area, ESA-MWT allows the determination of the optimal window size to compute the depth to the magnetic interface.

The multi-window test was applied at stations covering the study area on a regular mesh. At each station, multiple spectra were computed over incrementally increasing window sizes. For each spectrum, the depth was interpreted, and plotted versus window size. When the window covers about 60% of the magnetic anomaly, the interpreted depth stabilises over a range of increasing window sizes, forming a depth-plateau. As the window further increases in size, further depth-plateaus may be detected, corresponding to deeper horizons.

The average depth from each depth-plateau was laterally merged with average depth of depth-plateaus from surrounding MWT-stations (Yates et al., 2008, Kivior et al., 2011), and integrated with faults detected using the ACM technique, thus forming a skeleton map of the magnetic interface. Each depth-plateau provided the optimal window size used for higher resolution depth mapping described in the next stage.

Each skeleton horizon was validated by forward modelling and comparison with seismic and well data. Once the quality control procedure was complete, the next stage began.

Stage 2 – Detailed Mapping, ESA-MW

On a high density mesh, optimal window sizes were extrapolated between the MWT stations, and spectra were computed at each location. For each spectra computed over the optimal window, final depth values were interpreted and a final high resolution horizon map was generated. This procedure was repeated for each mapped horizon or interface. The shallower horizons were mapped from spectra computed from relatively smaller data window sizes than the deeper horizons. The resolution of the detailed mapping depends on the depth to the horizon, the size of the area, the size of the targeted structures, and the resolution and quality of the magnetic data.

Fault Detection

To detect magnetic lineaments, at different depths within the sediments, the Automatic Curve Matching (ACM) technique was applied to located magnetic profile data. The observed line data, and profiles extracted from the TMI grid in four directions: EW, NS, NE-SW, NW-SE were analysed. Each single anomaly along a profile was interpreted in a purely automatic manner, then depth to the causative body, its geometry and magnetic susceptibility were computed. The magnetic sources detected were interpreted in a 3D cube which was sliced vertically and horizontally, and from this magnetic lineaments at different depths were delineated. Spatially correlated magnetic lineaments were traced, and fault faces were constructed in 3D. The pattern of interpreted magnetic lineaments correspond to major faults and associated structures, derived from seismic, dislocating the sediments.

GEOPHYSICAL DATA

The magnetic data used for the study was from an helicopter survey acquired in 2006 and 2007 over a large part of the Papua New Guinea Highlands. The traverse spacing for the survey was 400m with an average flight altitude of 110m but this varied greatly due to the mountainous terrain. The traverse direction was north-south while the tie-line spacing was 4km in an east-west direction.

The Total Magnetic Intensity (TMI) data was gridded with a 100x100m mesh. The TMI data was Reduced To Pole (RTP) using an inclination of -27.5°and a declination of 4.86° (Figure 2). Derivative maps and a full suite of filters (such as matched filters and upward continuation) were applied to understand the distribution of the magnetic anomalies. As the survey was draped and over rugged terrain, the magnetic data was recalculated to a common datum.

Existing down-the-hole magnetic susceptibility logs from the four wells showed that there are multiple magnetic markers within the Darai Limestone. Susceptibility values from Hides 2 averaged around 0.0025 SI units in the Darai Limestone but the values measured in Karius 1, which is on the south-western flank of the Hides Anticline, were typically less than 0.0001 SI units, although they increase at depth around the Ieru Formation. The latter value is a more typical value for limestones and sandstones. Hides 1, just to the north of the Hides Anticline, has layers near the top of Darai with magnetic susceptibilities of 0.01 SI units, suggesting the presence of volcaniclastic units within the Darai Limestone. The Ieru Formation has relatively higher magnetic susceptibilities in the upper section close to the Base Darai.

The magnetic anomalies within most of the study area are of relatively low amplitude, except for those along the north-eastern margin and around the Hides 4 well on the eastern edge, where they indicate the probable presence of volcanic layers.

MAPPING FAULT STRUCTURES

The ACM method was applied to flight line data spaced every 400m, and to profile data extracted every 100m from the TMI grid, in EW, NS, NE-SW and NW-SE directions. Several different geophysical models were used to analyse and interpret single magnetic anomalies from the TMI and vertical gradient of TMI data in a purely automatic manner. The detected magnetic sources were interpreted in a 3D cube using horizontal and vertical crustal depth slices. The magnetisation of the rocks, when depicted in vertical slices, provided a guide to understanding the structural model of the study area, as the magnetic markers within the sediments can be seen dislocated by the thrust faults (Figure 3).

The major thrust faults, as well as smaller associated structures were interpreted. There is a major fault, trending northwest-southeast, thrusting the Hides Anticline towards the southwest. This main thrust fault in the study area appears to have several kilometres of displacement. The Hides anticline strata on the northeastern side do not coincide with those on the opposite side of the thrust fault (Figure 3). This complex thrust structure, interpreted from magnetic data, corresponds to the structure derived from seismic and well data.

MAPPING MAGNETIC CONTRASTS

The magnetic data was transformed to a common datum and was processed to detect magnetic susceptibility contrasts within the sediments. The horizon mapping technique was applied to detect these contrasts between strongly magnetic sediments overlaid by less magnetic strata and next, map the top of these magnetic heterogeneities. They are referred to as horizons or interfaces.

The Horizon Mapping Technique was applied in two stages:

Stage 1 - Horizon Detection

ESA-MWT was conducted over the whole area at stations located on a mesh of 1 x 1km, with additional stations placed around the wells and on a 700m x 700m mesh along the axis of the Hides Anticline. The additional stations were needed in areas where the original 1x1km mesh was too sparse to laterally correlate the detected magnetic contrasts, and to clearly resolve which horizon or interface they represent. At each MWT-station, numerous depth-plateaus were detected, which were laterally merged and skeletons of magnetic horizons or interfaces were constructed. In total, 15 skeleton horizons and interfaces were interpreted.

Nine horizons were detected on the northern side of the major thrust fault dislocating the Karius and Hides Anticlines (Horizons-1 to Horizon-7) and six interfaces (Interfaces-1 to Interface-6) were detected on the southern side of the thrust fault, as depicted in Figure 3. Horizon-1 (H1) coincides with the top of a swarm of magnetic markers near the top of the Darai Limestone, intersected in the Hides 1 well. These magnetic markers are layers of volcaniclastics deposited over the whole study area which were intersected in Hides-2, Hides-3, Hides-4 and Karius-1.

Horizon-2 (H2), when compared to well data in Hides-2, Hides-3, Hides-4 and Karius-1, corresponds to the Top of the Ieru Formation underlying the Darai Limestone. The upper Ieru Formation is relatively more magnetic than the overlying basal Darai Limestone therefore the magnetic contrast was detected by MWT. The skeleton map of Horizon-2 (Figure 4A) was validated by a comparison with a map of Top Ieru derived from seismic and well data (Figure 4B) which shows a close correspondence..

Horizon-3 (H3), represents an intra-sedimentary layer within the Upper Ieru Formation. Downhole magnetic susceptibility logs at the Hides-1 well show a significant increase in magnetic susceptibilities within the sediments at depths corresponding to the H3 depth-plateaus. It is very likely due to volcaniclastic layers forming magnetic markers and was also intersected in the other wells: Karius-1, Hides 2, Hides-3 and Hides 4.

It appears that Horizon-4 (H4) corresponds to the top of the Toro Sandstone which underlies the Ieru Fm. This is based on comparison between detected depth-plateaus and lithology from the wells used in this study; Hides 2, Hides 3, Hides 4, where the Top of the Toro Sandstone is intersected.

Several magnetic interfaces on the south-western side of the major thrust fault were mapped. Interface-1 presumably belongs to the Oribudi Beds overlying the Darai Limestone. The magnetic contrast detected as depth-plateaus, is due to the magnetic susceptibility differences between the very weakly magnetic Oribudi Beds and the multiple magnetic layers deposited within the upper section of the Darai Limestone. Interface-2 and deeper mapped interfaces (Interfaces-3 & 4) represent the underlying stratigraphy offset by faulting (Figure 3).

The complex overthrust structure, intersected at the Karius 1 well, was interpreted as Horizon-1, Horizon-2 and Horizon-3 overthrusting Interface-1 and Interface-2 to the southwest. As discussed above, the large thrust fault intersecting the Karius and Hides Anticlines was detected using ACM and mapped in 3D. The complexity of the thrust structure below the fault was demonstrated when it was discovered in the Karius 1 well that the Darai Limestone is not only repeated in the sequence but is, in part, vertical, demonstrating that there is a major fold/fault element (Hill et al., 2004) (Figure 3).

Numerous depth-plateaus were detected at greater depths than the deepest mapped horizon or interface. These depth-plateaus form surfaces corresponding to sedimentary strata that conform to the anticline structure at depths exceeding 9km. In this study area, basement is much deeper but mapping basement was not of interest as it was beyond the scope of this project.

Stage 2 - Detailed Mapping

Detailed mapping was conducted for two selected surfaces: Horizon-2 corresponding to Top of Ieru Fm and Interface-4 corresponding to the Top of Toro Sandstone southwest of the thrust fault. For both Horizon-2 and Interface-4, the optimal window size at each MWT-station was determined based on the depth-plateaus used to produce the skeleton maps. The shallower depths of Horizon-2 and Interface-4 were mapped from the higher frequency/shorter wavelength component while for the deeper parts, the longer wavelength component was used. ESA-MW was applied to compute and interpret the spectra over the selected optimal windows for Horizon-2 and Interface-4, on a regular mesh of 500m x 500m to generate the high resolution maps depicted in Figures 5A and 5B.

CONCLUSIONS

We demonstrated in this paper that it is possible to map sub-surface geology from magnetic data, by comparison with well and seismic data, in the rugged terrain of the Western Papua Fold Belt. Application of the Horizon Mapping and Fault Detection techniques allowed the detection and mapping of complex overthrust structures.

The following can be concluded: Magnetic contrasts within the sedimentary section were detected at different depths and comparison with well data shows that the detected magnetic contrasts correspond to the top of formations or inter-formational markers. In total, 15 magnetic heterogeneities were detected and laterally mapped (9 horizons and 6 interfaces). The mapped magnetic heterogeneities correspond to the Karius and Hides Anticline structures interpreted from seismic.

The near-top of the Darai Limestone was mapped as Horizon-1 and the Top of Ieru Fm, which contains magnetic sediments, was mapped as Horizon-2. Horizon-3 represents a lateral extension of the strongly magnetic volcaniclastic layers within the Upper Ieru Fm. (Davies 2012). The Top of Toro Sandstone, which contains magnetic material, such as glauconitic sandstones, was mapped as Horizon-4 while the Oribudi Beds, overlying the Darai Limestone, were mapped as Interface-1. Five deeper sedimentary interfaces within the Upper Jurassic Imburu Fm and deeper sediments were also mapped.

Major thrust faults, as well as associated structures were mapped in 3D, especially the complex overthrust structure, intersected at the Karius-1 well, where Horizon-1, Horizon-2 and Horizon-3 overthrust Interface-1 and Interface-2 to the southwest.

Using very limited geological information and constraints, with purely magnetic data, we were able to build 3D structural model of the complex overthrusted Karius and Hides Anticlines.
This project has been a successful proof of concept, therefore a similar approach may be applied with some confidence to more complex geology underlying thick volcanic cover.

ACKNOWLEDGMENTS

The authors would like to thank Oil Search and Archimedes Consulting for permission to publish this paper and Archimedes for providing the facilities for the interpretation.

REFERENCES

Davies, H., 2012 The Geology of New Guinea- the cordilleran margin of the Australian Continent, Episodes, Vol. 35, no. 1. 87

Gant, N.J., 1996, An interpretation of a High Resolution Aeromagnetic Survey over the Kutubu Area, PNG, for South Pacific Chevron Company, Brisbane, Qld.

Hill, K.C., Keetly, J.T., Kendrick, R.D. and Sutriyono, E., 2004, Structure and Hydrocarbon Potential of the New Guinea Fold Belt, in McClay K.R. (ed), Thrust Tectonics and Hydrocarbon systems: AAPG Memoir 82, pp. 494-514.

Kivior, I., Shi, Z., Boyd, D. and McClay, K.R., 1993, Crustal studies of South Australia based on energy spectral analysis of regional magnetic data. Exploration Geophysics, 24, pp 603608.

Kivior, I., Markham, S., Damte, S., Randle, S., Shimada, M., Jong, J., Kusaka, H. and Tran Quoc Tan, 2011, Mapping regional sedimentary horizons in the onshore Baram Delta, Sarawak, from magnetic and gravity data using Energy Spectral Analysis. Petroleum Geology Conference and Exhibition (PGCE), Kuala Lumpur, Malaysia, 2011.

Smith, R.I., 1990, Tertiary Plate Tectonic Setting and Evolution of Papua New Guinea, in Carmen, G.J and Z (eds), Petroleum Exploration in Papua New Guinea: Proceedings of the first PNG Petroleum Convention, Port Moresby, pp 229-244.

Yates, S., Kivior, I., Damte, S., Markham, S., and Vaughan, F., 2008, Imaging multiple horizons with spectral techniques in the Sirt Basin, Libya. EAGE Non-Seismic Methods Workshop Bahrain.

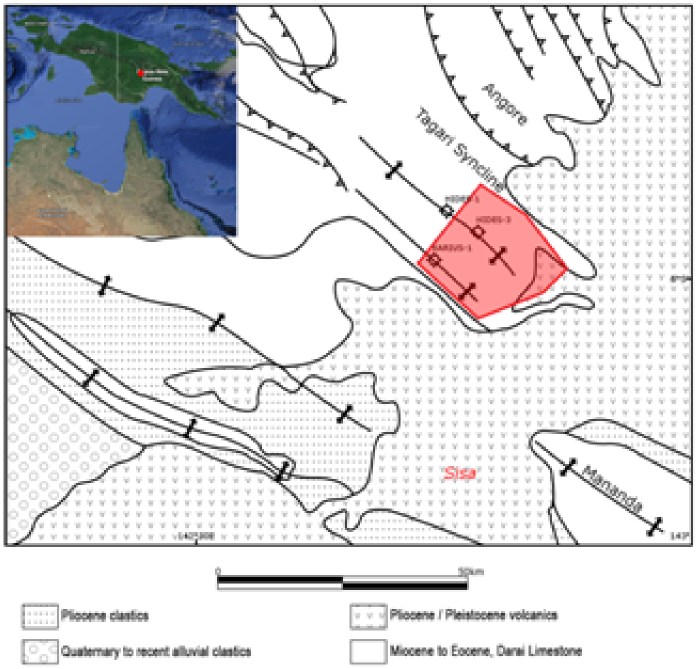

Figure 1 Location of Study Area, Hides Gas Field, Western Papuan Fold Belt, PNG (after Hill et al., 2004)

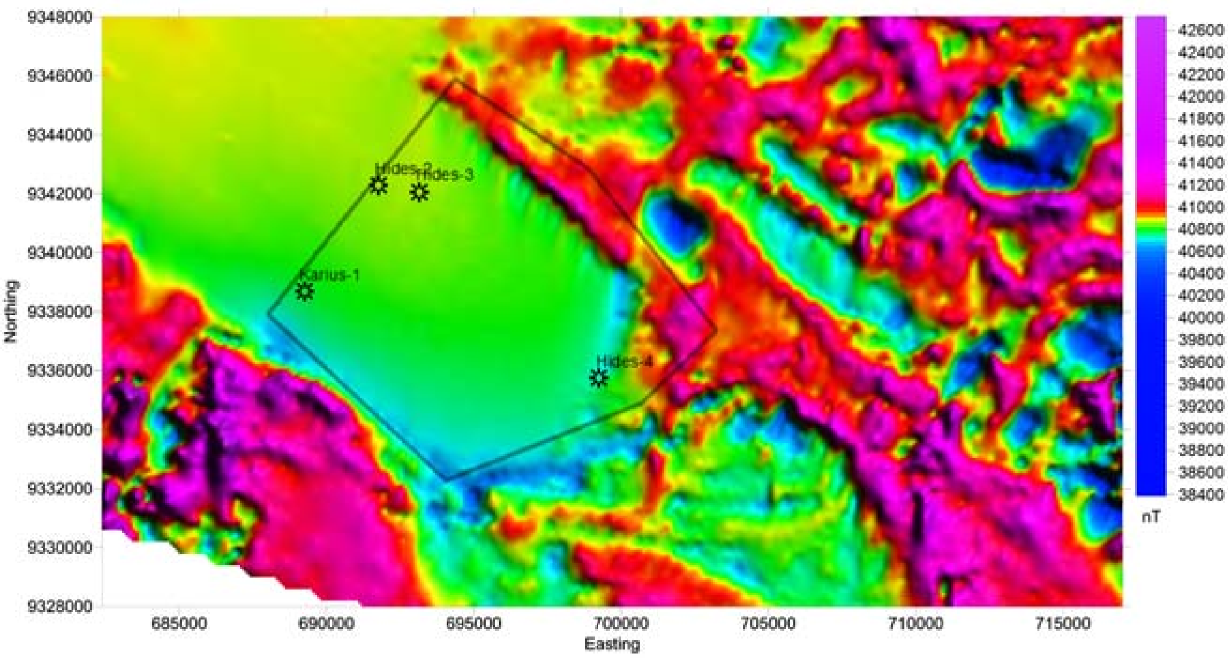

Figure 2 Total Magnetic Intensity, Reduced To Pole (RTP)

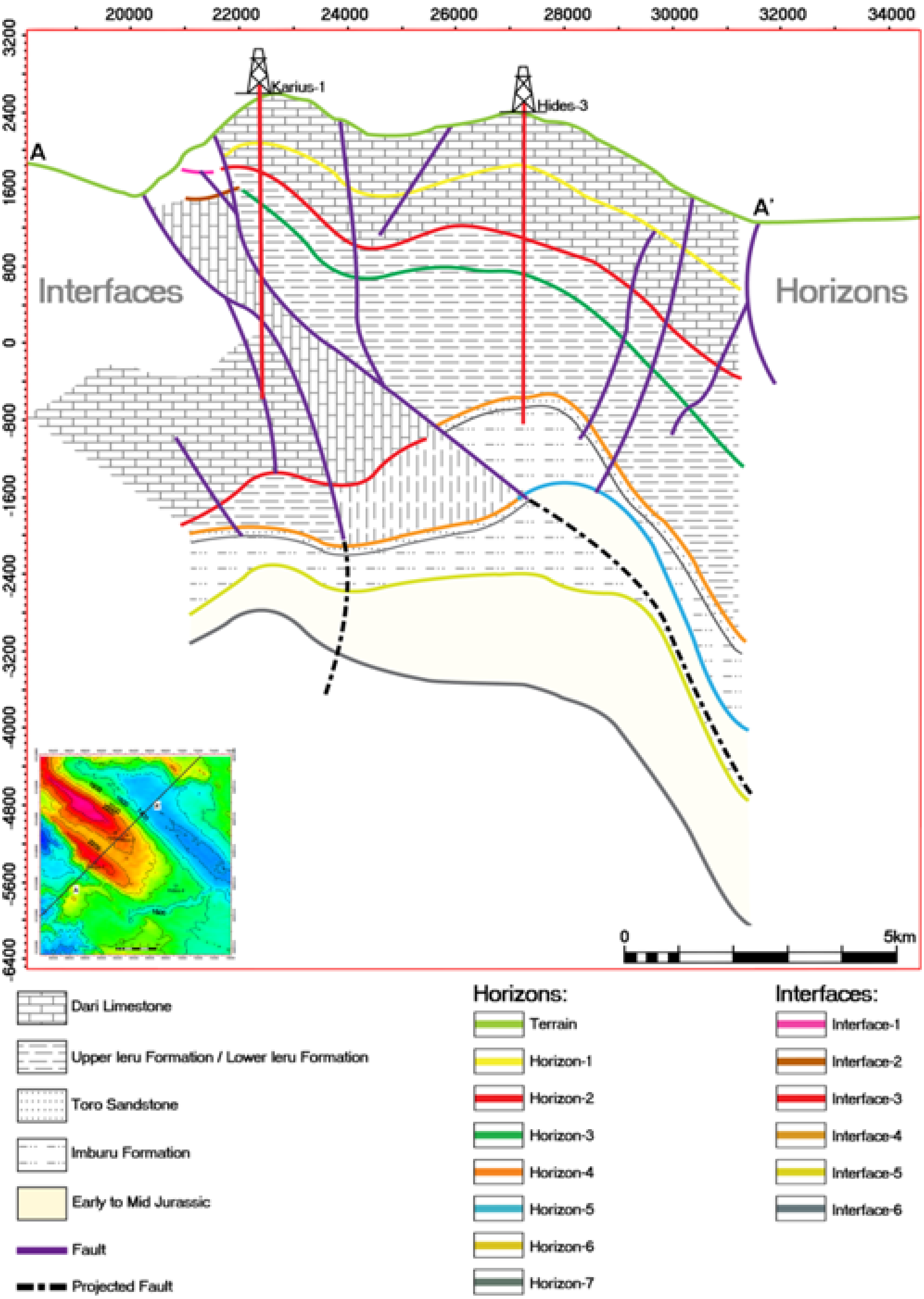

Figure 3 Faults, Horizon and Interfaces interpreted from magnetic data, shown in cross-section

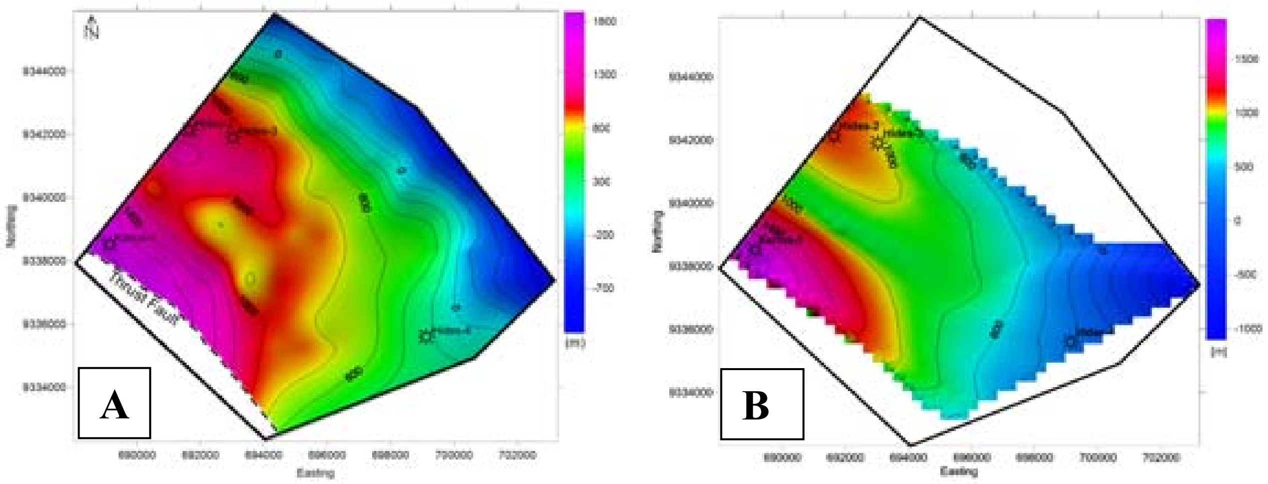

Figure 4A & B Skeleton Map of Horizon 2, Top of Ieru Fm (A) Top of Ieru Fm derived from seismic and well data (B)

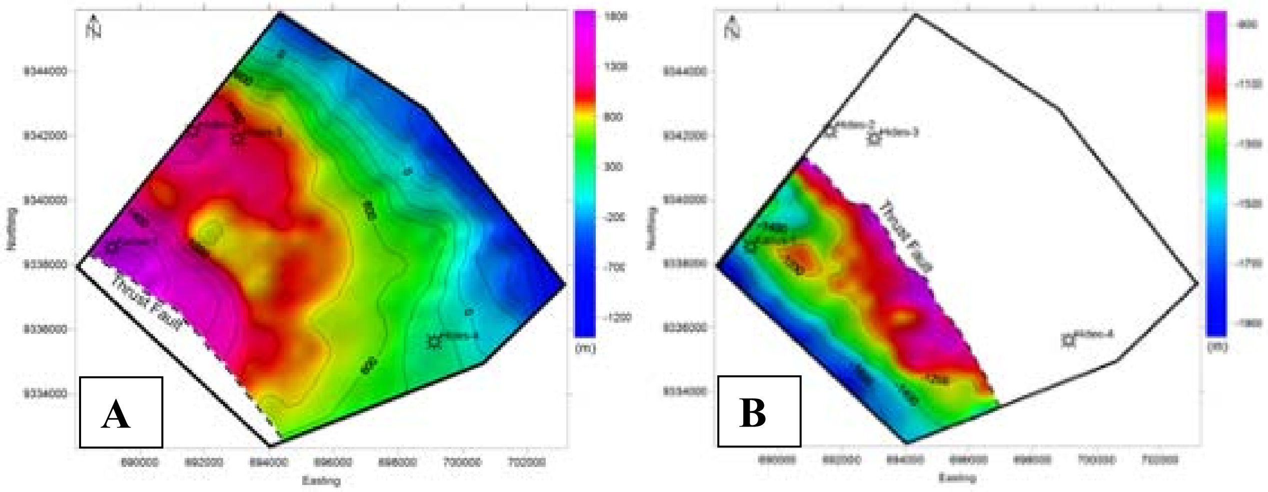

Figure 5A & B Detailed Map of Horizon 2, Top of Ieru Fm (A) Detailed Map of Interface 4, Top of Toro SST (B)