Mapping Sub-Surface Geology from Magnetic Data in the Hides Area, Western Papuan Fold Belt, Papua New Guinea*

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Abstract

Integration of seismic data with potential field data is valuable in the exploration for hydrocarbons in volcanic provinces, like the Papuan Fold Belt. Use of magnetic data in this area is 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 the possibility of mapping sedimentary horizons and faults in this region where there are no surface volcanics. An initial project area of 114 km^2 in the vicinity of Hides, was chosen, as it was without volcanic cover and had a relatively simple anticline structure. The horizon mapping technique, developed from ESA, was used to detect magnetic susceptibility contrasts that were laterally merged to form magnetic interfaces corresponding to geological horizons derived from seismic and well data. The ACM technique was used to delineate structures such as major faults. The magnetic data was used to successfully detect and map generally shallow-dipping magnetic horizons in the Hides Anticline structure and to define steep-dipping magnetic discontinuities in 3D interpreted as major faults, along with smaller associated structures. The combination of folded shallow horizons and steep faults was used to suggest an interpretation of the very complex overthrust structure, intersected at the Karius 1 well. The magnetic horizons could broadly be correlated to sedimentary interfaces, including magnetic markers (volcanic layers) within the weakly magnetic Darai Limestone. The base of the Darai Limestone/Top of the Ieru Formation correlated well with one magnetic horizon, the morphology of which was consistent with structures mapped from seismic and well data. Other horizons loosely correlated to the Top of Toro Formation, which contains magnetic sediments, and five deeper sedimentary interfaces within the Imburu Formation or below. Using very limited geological information and constraints with magnetic data, we built a 3D structural model of the Hides Anticline that is overthrust to the southwest. This project has been a successful proof of concept and we propose, therefore that a similar approach may be applied with some confidence to more complex geology underlying thick volcanic cover, however, attenuating the influence of volcanics requires great care.

Introduction

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.

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, in places, very thick volcanics makes interpretation challenging. However, use of magnetic data in this area 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 this region 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, yet one where the results could add significant value in exploration. An initial project area of 114 km^2 around Hides (Figure 1), was chosen, as it was without volcanic cover and had a relatively simple anticline structure. This is in comparison to the complexity of the thrust geology of the rest of the Papuan Fold Belt. This work should be followed with similar studies in adjacent areas where there is thick volcanic cover and more complex geology.

Geological Setting

The Papuan Fold Belt is 100 km wide and 1000 km long and in places up to 3 km high. The oblique convergence of the north-moving Australian Plate and WNW moving Pacific Plate beginning in Early Miocene and continuing through to the present, is resulting in the deformation of the Papuan Thrust Belt (Smith, 1990).The Papuan Fold Belt consists of complex fold and thrust structures, in places vertically overturned beds, creating thrust repeats of Miocene Formations (Hill et al., 2004).

The study area covers the Hides Anticline, and is situated centrally within the western Papuan Fold Belt. To the east lies the Angore and Huria Anticlines, and the Tagari Syncline (Figure 1).

These structures lie in a region surrounded by three volcanoes, Mount Sisa to the south-west, and Mount Kerewa and Doma to the east. The latter volcanoes are of Pleistocene to Recent age. Volcanic activities resulted in the slopes of the volcanoes and the majority of the region becoming covered in highly magnetic lavas and volcaniclastics.

Located in a mountainous part of the belt, the topography of the study area ranges from 2800 m in the centre, to 1200 m along the north-eastern margin (Figure 1). The Hides Anticline generally trends north-west to south-east, plunging to the south-east, with fault traces in this orientation mapped at the surface. Four wells have been drilled within the region: Hides-4, Hides 3, Hides 2, and Karius-1. The anticlinal structure of Hides results in Darai Limestone outcrop (or subcrop) and includes thrust faulting from the southwest (Figure 2).

The litho-stratigraphy of the area comprises of (Figure 3):

- **Darai Limestone** of Miocene age. Karsted, marine shelf bioclastic limestone that is highly fractured and can vary in thickness from 900 m to 1500 m. Minor intervals of mudstone and chert are present, with limestones that include multiple sedimentary layers containing strongly magnetic materials.
- **Ieru Formation** of Cretaceous age. Upper Ieru is mainly sandstone, whilst the lower Ieru is mainly marine siltstone and mudstone with minor sandstone; upper Ieru sandstones are relatively more magnetic than the lower Ieru strata.
- **Toro Sandstone** of Lower Cretaceous age. Shallow marine, with fine to medium grained glauconitic sands, which is an indicator of increased magnetic properties. This is a targeted reservoir formation.
- **Imburu Formation** of Upper Jurassic age. Marine, open shelf, mudstone, and siltstones grading upwards, with sandstones at the top.

Volcanics surrounding Hides are classified into two types:

- **Pleistocene Volcanics**, sub-classified into the Mount Sisa series and Mount Kerewa series, both appear shallowly dipping and only moderately deformed.
- **Pliocene Volcaniclastics**, comprised of conglomerates, sands, tuffs, and mudstones with minor lignite seams. In some areas, grade into calcareous mudstones and shales. Not present in all areas.

Methodology

Two main techniques were applied in this study:

- ESA - Horizon mapping technique based on spectral analysis applied to gridded magnetic data
- ACM - Fault detection technique applied to located profile data

Horizon Mapping

The horizon mapping technique is based upon 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.

The horizon mapping technique was applied in two stages:

- Stage 1: Horizon detection/skeleton
- Stage 2: Detailed mapping

Stage 1 Horizon Detection – Energy Spectral Analysis – Multi-Window Test

The multi-window test procedure (ESA-MWT) (Kivior et al., 1993; Kivior et al., 2011) allows the determination of the optimal window size to compute the depth to the horizon at any point of the study area.

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 or gravity 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 those of depth-plateaus from surrounding MWT-stations, and integrated with faults detected using the ACM technique, thus forming a skeleton map of the magnetic, or density, interface. Such interfaces correspond to unconformities, basement, sedimentary horizons, or other crustal inhomogeneities. Each depth-plateau provided the optimal window size for higher resolution depth mapping described in the next stage.

Each skeleton horizon was validated by forward modelling, 3D inversion, and comparison with seismic and well data. Once the quality control procedure was complete, the next stage began.

Stage 2 – Detailed Mapping

On a high density mesh, optimal window sizes were extrapolated between the MWT stations, and spectra are computed at each location. Final depth values were interpreted and a final high resolution horizon map was generated. Using this technique, several sedimentary surface interfaces as well as the basement configuration can be mapped by laterally merging depth plateaus at different depths (Yates et al., 2008; Kivior et al., 2011). If the data coverage is large enough deep crustal features including the Curie Isotherm and Moho can be detected.

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 and depth to the causative body, its geometry and magnetic susceptibility were computed. The magnetic sources detected were visualised in a 3D cube which is either sliced vertically or horizontally and magnetic lineaments at different depths were delineated. Spatially correlated magnetic lineaments were traced, and fault faces were constructed in 3D. The pattern of magnetic lineaments correspond to major faults and associated structures dislocating the sediments.

Geophysical Data Description

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

The Total Magnetic Intensity (TMI) data was gridded with a 100x100 m mesh. The TMI data was Reduced To Pole (RTP) using an inclination of -27.5º and a declination of 4.86º (Figure 4). Derivative maps and a full suite of filters (such as matched filters, upward continuation, and spatial filters) 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.

Based upon existing down-the-hole magnetic susceptibility logs from the four wells, it is apparent 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. This suggests that there are likely volcaniclastic units within the Darai Limestone. The Ieru Formation has relatively higher magnetic susceptibility in the upper section close to the Base Darai.

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

Mapping Structures

The ACM method was applied to flight line data spaced every 400 m, and to profile data extracted from the TMI grid, in EW & NS directions every 100 m, and the NE-SW & NW-SE directions every 71 m. Multiple filters were applied to the profile and line data to remove high frequency noise. Several different geophysical models were used to analyse and interpret single anomalies using the TMI and vertical gradient of TMI data in a purely automatic manner. Several hundred thousand magnetic sources were detected, at different depths, showing the

magnetisation of the sediments. For each single anomaly, ACM determined the depth to the magnetic source, and the susceptibility and geometry of the source body. 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 5).

The major thrust faults, as well as smaller associated structures were interpreted. There is a major fault, trending northwest-southeast, thrusting the Hides Anticline from the southwest. This is the main thrust fault in this study area, where the sediments on the south-western side are downthrown a few kilometres. The Hides Anticline strata on the north-eastern side do not coincide with those on the other side of the thrust fault.

Mapping Magnetic Interfaces

The magnetic data that had been transformed to a common datum, was further processed to detect magnetic susceptibility contrasts within the sediments. The horizon detection 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 km x 1 km, with additional stations placed around the wells and on a 700 m x 700 m mesh along the axis of the anticline. The additional stations were needed in areas where the original 1x1 km mesh was too sparse to resolve the horizons clearly.

Numerous depth-plateaus were detected at each MWT-station, which were laterally merged into probable magnetic interfaces called skeleton horizons. In total, 15 skeleton horizons were built. Nine were detected on the northern side of the major thrust fault dislocating the Hides Anticline (horizons 1 to 7) while a further six (interfaces 1 to 6) were detected on the southern side of the thrust fault, as depicted in Figure 5.

Horizon 1 (H1) corresponds to magnetic markers of high magnetic susceptibility (0.01 SI units) as measured in the Hides 1 well, near the top of the Dari Limestone. Horizon 2 (H2) corresponds to the top of the Ieru Formation underlying the Dari Limestone. Horizon 3 (H3) represents an intra-sedimentary layer within the Upper Ieru Formation. It appears that Horizon 4 (H4) corresponds to the top of the Toro Formation underlying the Ieru Formation. Deeper horizons are at the base of the Imburu Formation and deeper Jurassic sedimentary surfaces. The magnetic interfaces on the south-western side of the major thrust fault were also mapped. Interface 1 presumably belongs to the Oribudi Beds overlying the Dari Limestone. Interface 2 and deeper represent the underlying stratigraphy offset by faulting (Figure 5).

The skeleton of Horizon 2 (H2) was constructed from the depth-plateaus. When compared to well data it corresponded to the top of the Ieru Formation. Following checking of the skeletons of H2 and H4, additional MWT stations were interpreted and these surfaces were then validated using a grid of Top Ieru and a partial Top Toro grid newly derived from seismic. Figure 6c depicts the map of differences between top of Ieru as derived from magnetic data and the top of Ieru Formation as derived from seismic data, which shows a very close correspondence.

The optimal window size at each MWT-station for two horizons (H2: Top of Ieru Formation and H4: Top of Toro) were selected. In addition, interface 3 and interface 4 were selected for detailed mapping.

Numerous plateaus were detected at greater depths forming sedimentary strata that conform to the anticline structure at depths exceeding 9 km. In this study area, basement is much deeper, however mapping basement was beyond the scope of this study.

Stage 2 Detailed Mapping

ESA MW was applied to compute and interpret the spectra over the optimal windows on a regular mesh of 500 m x 500 m to generate high resolution maps as depicted in Figure 6e and Figure 6f.

Conclusions and Further Work

Using high resolution magnetic data in the rugged terrain of the Western Papua Fold Belt, in areas with little or no volcanic cover, by applying an energy spectral horizon detection technique (ESA-MWT) and an automatic curve matching technique (ACM), it is possible to successfully detect and map:

- The relatively simple Hides Anticline structure.
- Major thrust faults, mapped in 3D, as well as smaller associated structures.
- Very complex overthrust structure, intersected at the Karius 1 well.
- Numerous sedimentary interfaces, such as magnetic markers within the weakly magnetic Dari Limestone; the shallower magnetic marker being close to the top of the formation, possibly allowing the mapping of the top of the Dari.
- Top of Ieru Formation, which contains magnetic sediments.
- Top of Toro Formation, which contains magnetic material, such as glauconitic sandstones.
- Five deeper sedimentary interfaces within the Imburu Formation or below.
- Structural model of the overthrust area.

Using very limited geological information and constraints, with purely magnetic data, we were able to build 3D structural model of the Hides Anticline that is overthrust to the southwest.

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, however, attenuating the influence of volcanics must be performed with great care.

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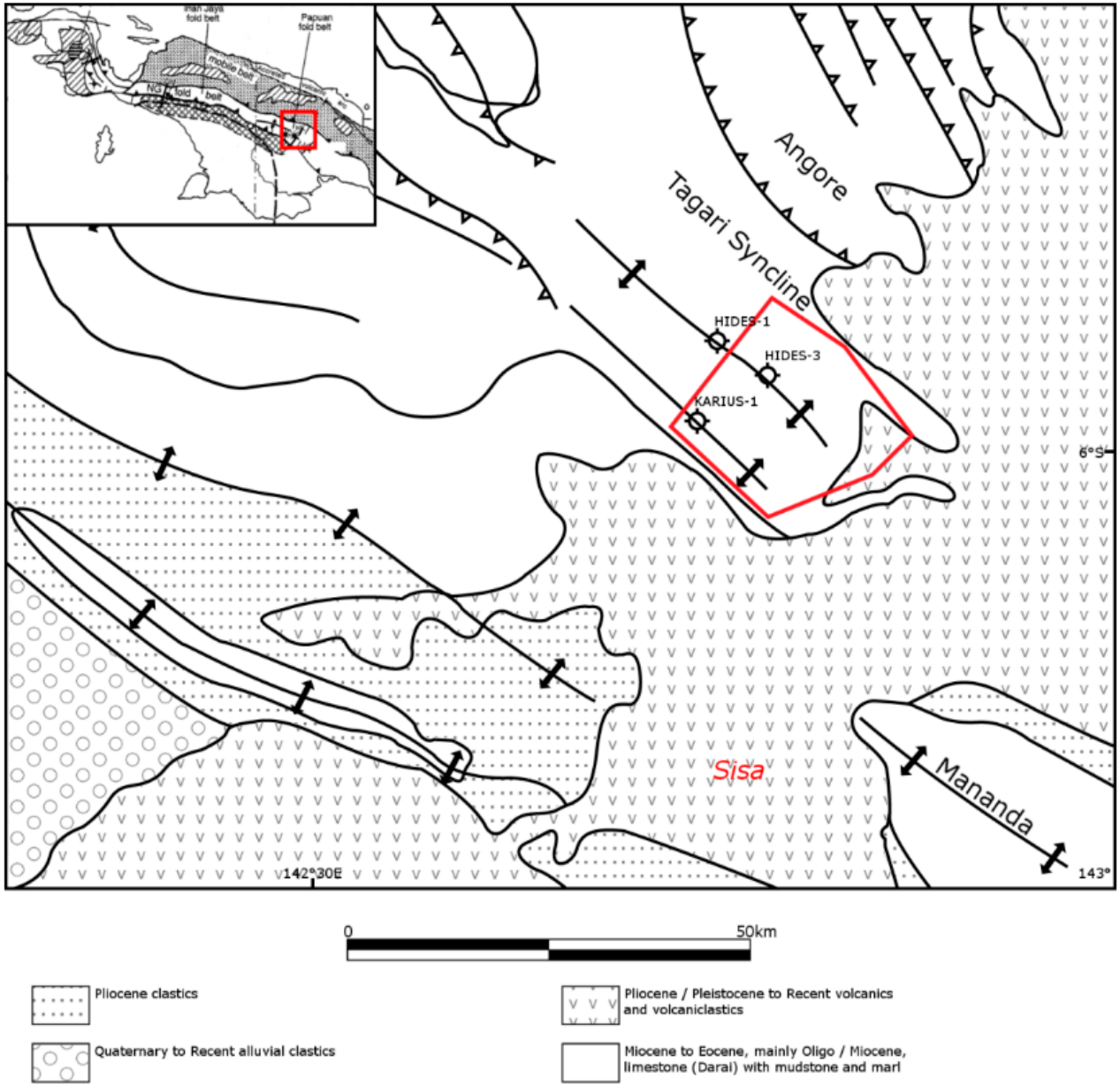

Figure 1. Location of study area, Hides, Western Papuan Fold Belt, PNG. (Image and insert modified after Hill et al 2004.)

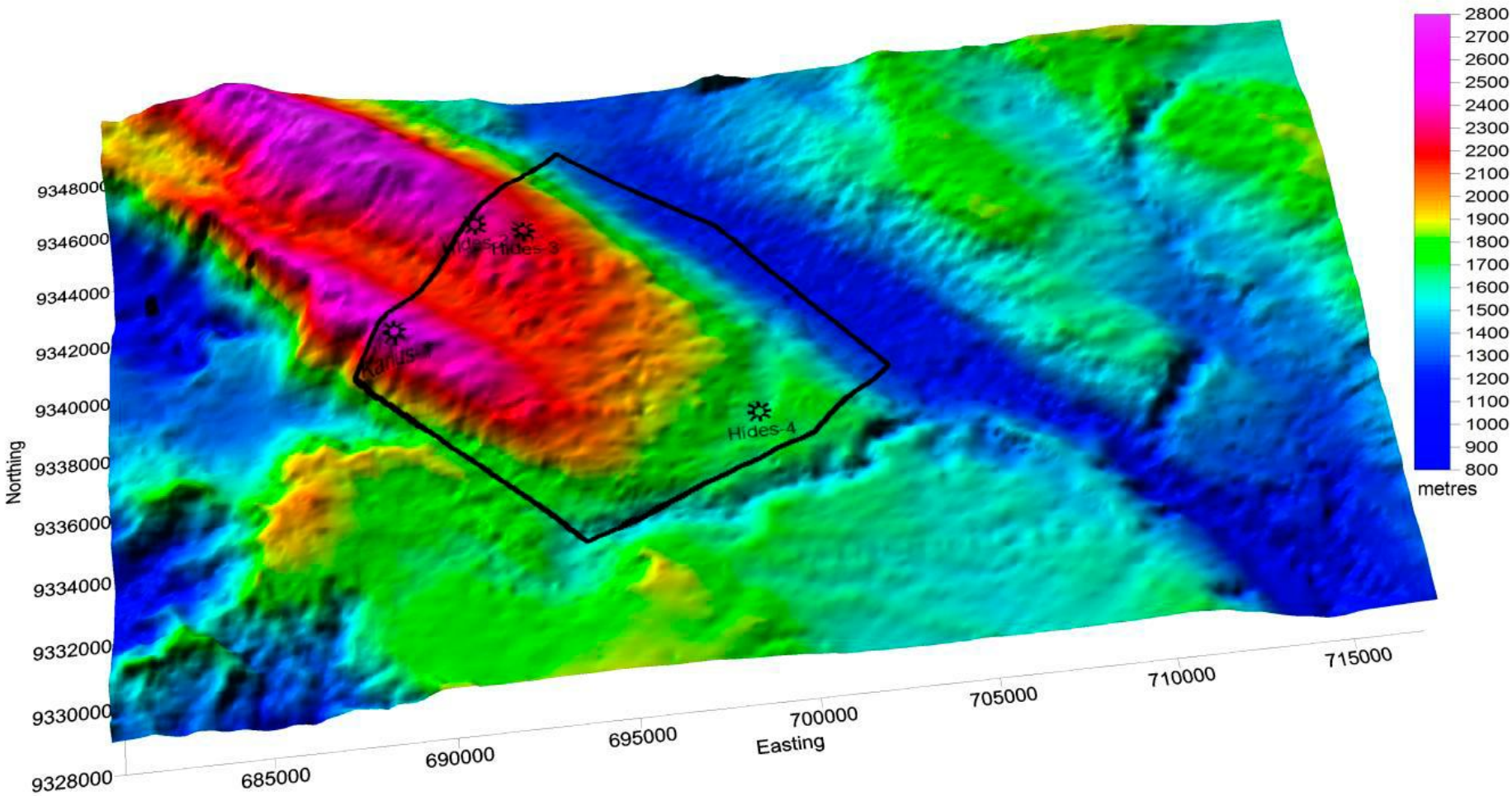

Figure 2. Hides Topography in 3D with study area and wells

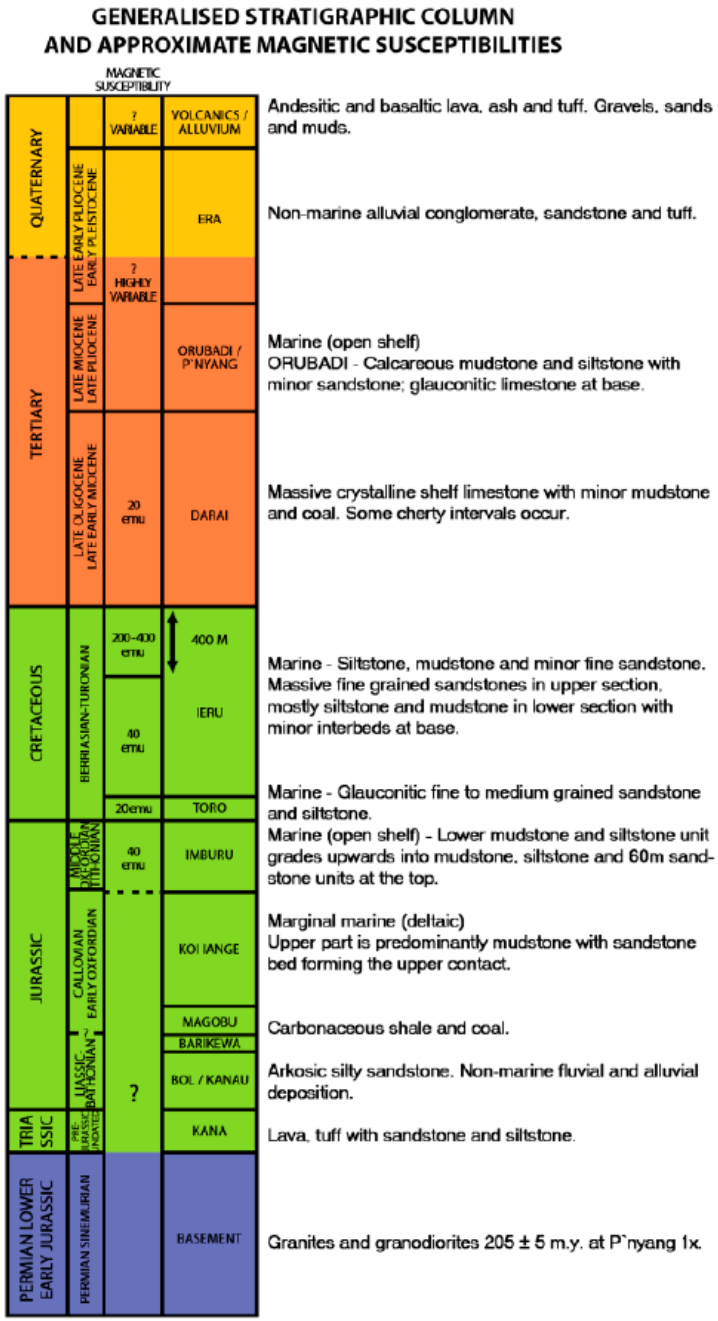

Figure 3. Litho-stratigraphy of the Hides Anticline.

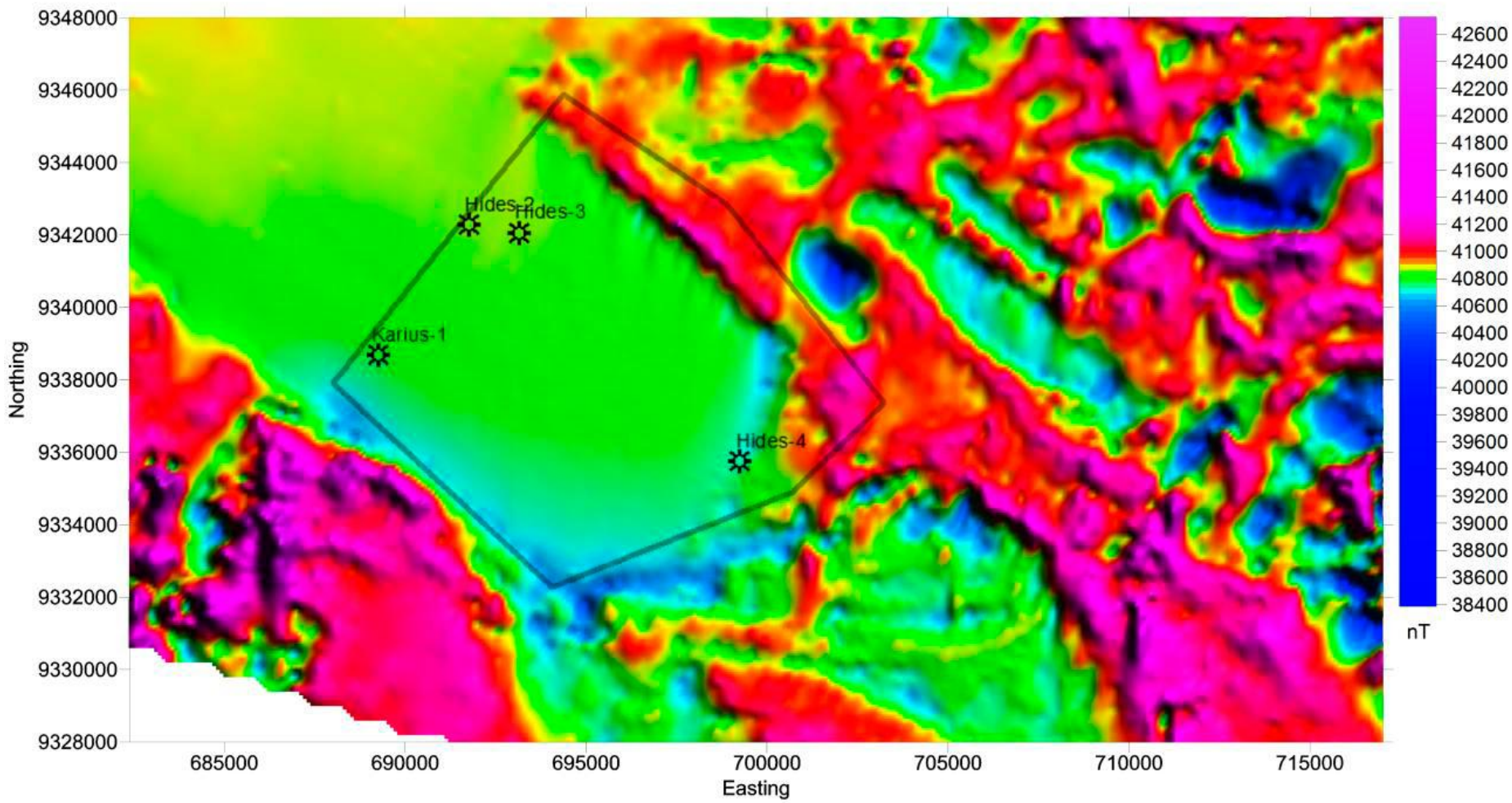

Figure 4. Total Magnetic Intensity, Reduced To Pole (RTP) data

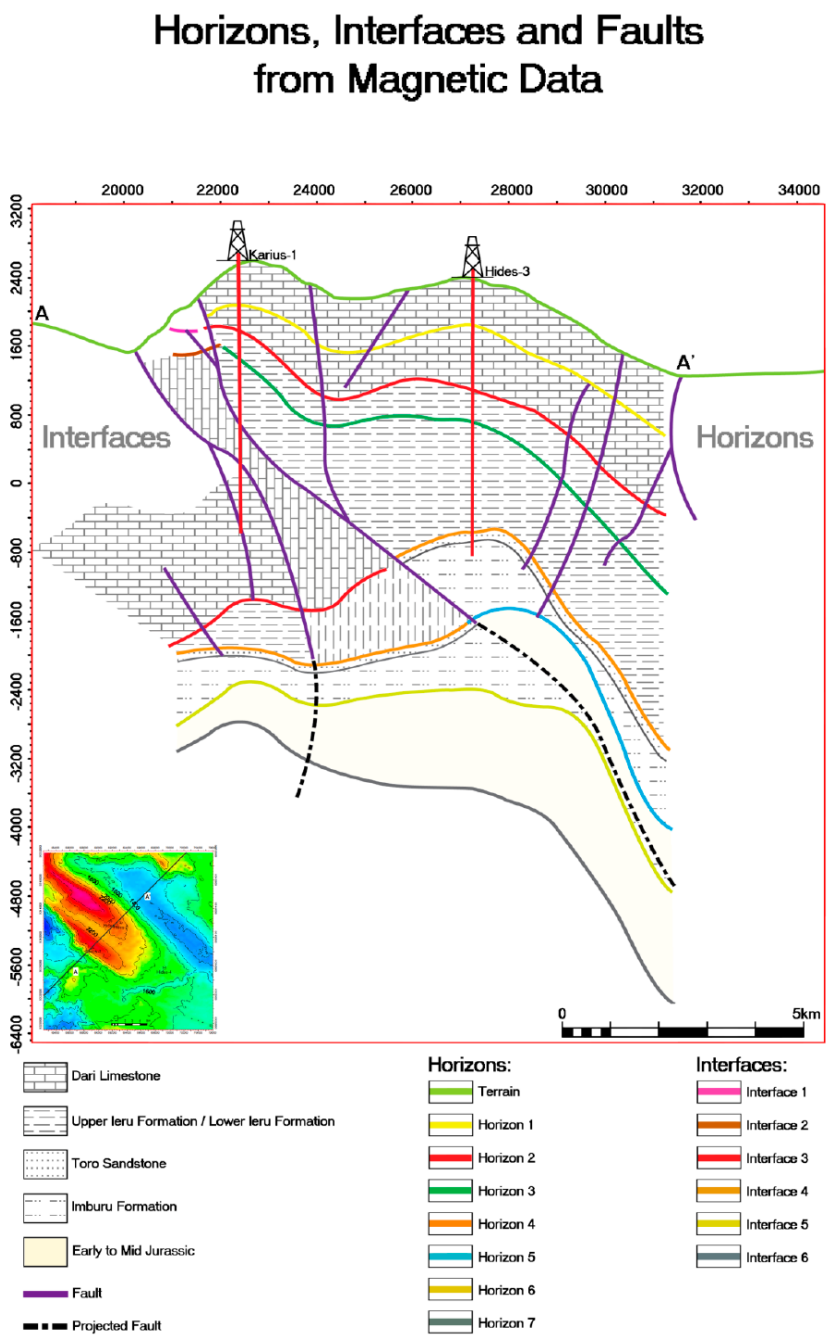

Figure 5. Horizons, interfaces and faults mapped from magnetic data.

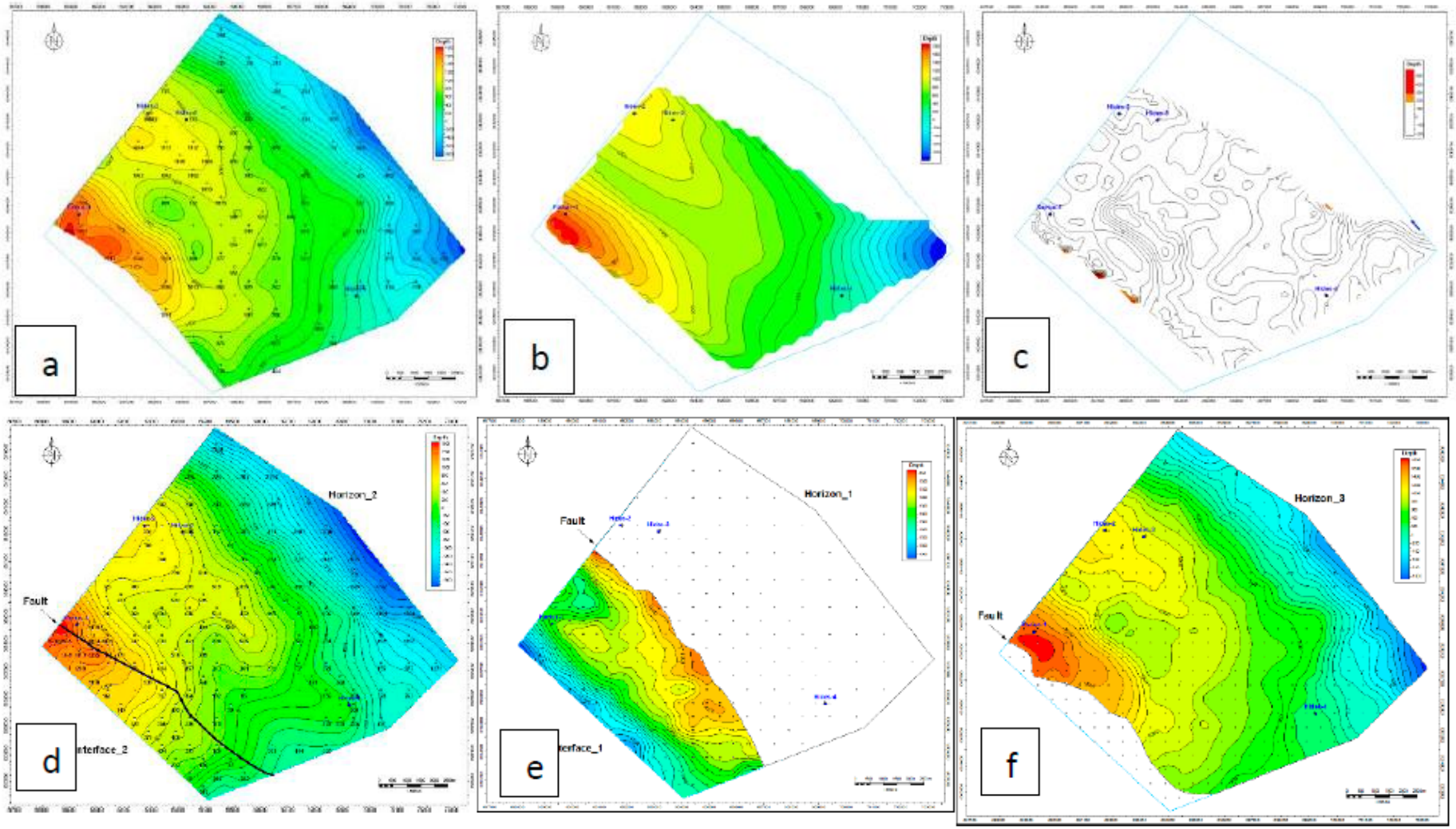

Figure 6. (a): Skeleton Magnetic Horizon Top Ieru (H2) ; (b): Top Ieru derived from seismic and well data; (c): Map of differences between (a) magnetics and (b) seismic and wells; (d): Magnetic H2 Top Upper Ieru and Interface 2; (e): Detailed Magnetic Interface 1; (f): Detailed Magnetic Horizon H3, possibly Top Lower Ieru