Introduction

Within areas of complex geology such as fold-thrust belts, the subsurface understanding is challenged by several factors through acquisition, processing, and interpretation of seismic data. Acquisition setup can be sub-optimal in rugged terrains and topography with high elevation changes reducing the signal-to-noise ratio of the seismic reflections, making exploration and development plans more expensive and less certain. In those circumstances, because seismic imaging techniques could not be used as the unique interpretation tool, ground acquisition of potential field data provides additional and relatively detailed information to be successfully integrated with seismic data, thus helping to fill gaps in geological understanding.

In this work, we present a case study from a thrust belt area where potential field (PF) methods proved to be a valid complementary discipline for exploration purposes.

Geological setting

The study area is located within the Kirthar Fold Belt, part of the Pakistani mountain belts linking the Himalayan orogeny with the Makran accretionary wedge (Figure 1). This is a highly complex portion of the earth’s crust, where left-lateral movements follow, and partially override, regional N-S strain trends, still active today at a rate of 4 mm per year. More precisely, the study area is on the Kalat Plateau in a region that is deforming very obliquely, nearly parallel to the regional plate motion vector.

![Figure 1](image)

Figure 1  Left: Study area location (black rectangle) with major faults in red and direction of the plate vector. Right: Stratigraphic column valid for the Kalat Plateau and Central Kirthar Range.

The Chaman fault, a large-scale strike-slip fault, is considered to represent the lithospheric plate boundary (transform fault) in this lateral collision zone. East of the plate boundary, a 150- to 200-km-wide deformation zone is present (Bannert et al. 1992). Due to the highly oblique orientation to the plate vector, strain partitioning is ongoing in this lateral deformation zone (i.e., dividing overall displacement into components of shortening and strike-slip deformation). For the frontal part of this deformation belt, neither the deep structural architecture nor many aspects of the complex deformation are well understood.

Existing structural concepts for the area were developed for the northern Kirthar Fold Belt and the Sulaiman Fold Thrust Belt. For the southern Kirthar Fold Belt, a model of basement inversion with folds in the sedimentary cover was put forward (Fowler et al. 2004). However, detailed kinematics about thick-skinned versus thin-skinned structural connection is not obvious.
The sedimentary sequence (Figure 1) is the result of all the geologic processes that occurred on the northeastern margin of the Indo-Pakistani plate, which developed as part of the northern margin of Gondwana until Triassic/Early Jurassic (Kadri, 1995).

The first exploratory well within the study area had as primary targets, the Dunghan Limestone and Chiltan Limestone levels. Due to greater-than-prognosed encountered thickness for Kirthar Limestone, Top Ghazij shale was encountered around 1800 m, much deeper than expected. Thus, despite the drilling reaching over 3700 m, the primary reservoir targets were not encountered.

Following completion of the well, all existing interpretations along seismic lines were updated to reflect the direct measurements from the field. Moreover, the well corroborated the high uncertainty level in the area. Land-based gravity and magnetic data were acquired to improve the geological understanding of this challenging area.

Workflow

Gravity and magnetic measurements were used to investigate deep tectonic structures as part of regional syntheses, depth-to-basement estimation, and local identification of buried bodies. The data processing sequence consisted of three main phases: i) a qualitative interpretation phase with spectral analysis to characterize the energy content and identify the presence of any directionality in the input data grids; ii) then, an approximated depth-to-source evaluation and cut-off frequency definition to properly isolate the contributions of signal sources at shallow and deep levels; iii) finally, a scenario testing and validation phase allowing us to exploit the most plausible geological scenario, jointly leveraging all available information.

Qualitative interpretation of potential field data

Anomalous surface gravity and magnetic observations occur wherever there are density contrasts and magnetization variations in the earth due to lithological or structural changes. Gravity and magnetic surveys are, thus, useful to delineate structural basin configuration and sedimentary package thickness to map likely faulted trends and to determine the strike direction of prevailing geologic features, aiding further exploration strategy. From an exploration point of view, the main areas of interest are usually characterized, for a working petroleum system, by transform faults being in interference with other tectonic structures and producing secondary porosity and sealing for potential oil and gas accumulation. For this reason, the surface expression of geological structures such as fractures (faults and joints), shear zones, and foliations were initially analysed as lineaments (edges) traced on a topography map from a high-resolution digital-elevation model. Then, to develop a comprehensive picture of the structural trend, regional tectonics, sediment thickness and basement architecture in the area, the lineaments were validated and compared against public-domain information and literature. The full set of lineaments was successively expanded through the addition of new lineaments traced by analyzing potential field maps specifically filtered and enhanced (Figure 2).

Figure 2 Left: Lineaments extracted from first vertical derivative applied to filtered Bouguer anomaly grid and rose diagram with major NE-SW strike. Right: Results of three depth-to-magnetic source methodologies and their relative positioning of the basement depth.
By comparing the resulting rose diagrams, the presence of two main strike directions was highlighted: NE-SW and NNW-SSE (Figure 2). The resultant structural configuration was clearly dominated by the NE-SW striking lineaments, representing the consequences of the Indian plate’s pushing against the Eurasian plate. This deformation appeared to be very pervasive; therefore, involving the more ductile sedimentary sequence and possibly portions of the basement as well. Conversely, the less pervasive NNW-SSE striking direction seemed to be more related to episodic accommodation of the energy coming from the above-mentioned stress direction. These discrete structures, likely involving the basement and the full sedimentary sequence, can be described as sinistral strike-slip transpressional fault zones, helping the north-northwestern-verging indentation of India against Eurasia.

It was not possible to identify a clear and precise temporal subdivision of the two main strike directions, suggesting that they could correspond to two different deformation styles working as a consequence of the same geodynamical phenomenon. Interpreting gravity filtered maps allowed us to detect deep and continuous plastic deformation, first-order sedimentary structures, and deep-rooted structures. Analysing the magnetic filtered data helped mainly in extracting geological attributes related to deep-rooted structures.

**Depth to magnetic sources**

As a second phase, three methodologies were applied to the PF data to further unravel the structural complexity of the study area:

- **Extended Euler deconvolution**: an expanded implementation of Euler deconvolution that utilizes an additional constraint to Euler’s original homogeneity equation that aims at improving the source location determination and allowing the definition of dips and susceptibility contrasts of dyke and contact source models (Mushayandebvu et al. 2001).
- **Source parameter imaging (SPI)**: an algorithm that estimates the magnetic source depth from the local analytic signal wavenumber and can be used for depth-to-basement estimation (Thurston et al. 1997).
- **Layered gravity inversion (LGI)**: the depth-to-basement solution is computed through the Parker–Oldenburg iterative method that provides a full 3D depth relief. The pseudo-gravity functional transformation enhances the anomalies associated with deep magnetic sources, providing a good input for depth-to-basement estimation (Panepinto et al. 2014).

The outcomes of each method (Figure 2) were then integrated and combined in the scenario testing and validation phase to produce a unified structural interpretation. Current SPI results were used as a reliable guidance for the interpretation of magnetized lithological contacts and localized features of interest, while LGI analytic results provided starting bounds for top and base discontinuities placed between 2.5 and 7 km of depth.

**Scenario testing and validation**
Aiming to achieve a better geological understanding of the area, the available interpretations were tested though gravity and magnetic 2.5D forward modelling along several 2D profiles. The outcomes of the previous phase were significantly leveraged during magnetic data fit analysis. This scenario testing was preliminary tailored to analysing the sedimentary package. To achieve this, the contribution of the deeper geological formations was stripped off from the gravity data, allowing focus on the shallow depth section. During this final phase, all the valuable information obtained through the entire workflow was revisited. In particular, lineaments were found to have the most meaningful association of the wavelength contribution from different portions of the spectrum (Figure 3). The outcome of the full study was a comprehensive and conclusive scenario with meaningful geology that explained the geophysical outcomes.

Conclusions

Gravity and magnetic data have proven to be crucial in constraining crustal structures related to the regional tectonic framework. The geophysical information was combined to model realistic and complex geometries by leveraging the ability of gravity and magnetics to map lateral variations of rock-physics properties (density and susceptibility) related to structural and/or lithological contacts. The interpretation and modelling process produced different outcomes at the different scale level: at the regional scale, the edge detection and lineament extraction allowed discriminating different tectonic styles and comparing the significance of crustal-scale structures. At district to prospect scale, the interpretation and modelling were used for geologic framework definition to identify subtle changes in sedimentary sequences and to constrain basement geometries at depth. Finally, the possibility to infer information and extend the interpretation below the effective level of seismic penetration was key for predicting and ranking hydrocarbon potential areas for future exploration.

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References


