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Seismic Expression of Subsurface Structures in Potwar Plateau, Pakistan: A Multi-attribute Analysis Approach

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Abstract - The Potwar Plateau in Himalayan fold-and-thrust belt is a major hydrocarbon producing region of Pakistan. The Eocene carbonates are predominantly known reservoirs in the plateau which are segmented due to faulting. This article main goal is to delineate faults and fractures by testing capabilities of three types of seismically derived attributes (geometrical, instantaneous, and wavelet). Potential of attributes was also exemplified by comparing results from seismic data sets of two fields with proven hydrocarbon potential in Potwar Plateau. Since fault and fracture information derived from a single seismic attribute is not accurate, a multi-attribute approach was adopted to discuss and to compare results of integrated attribute analysis technique for subsurface structural mapping of fault zones and throw distribution. Attribute anomalies on dip variance, trace and wavelet envelope maps identified as possible fault locations, were then analyzed on additional attribute (spectral decomposition) maps. Results indicate that some attributes could suppress surrounding noises and could visualize identified faults. The application of spectral decomposition shows more convincible results than other individual attributes. The added values of proposed methodology of multi-attribute analysis are validated through applications, including mapping qualitative aspects of throw along major thrusts, tracking horizontal strata on either side of deformed zones, faults detection offsetting reflectors at various scales, and delineating main subsurface geometry of pop-up structure. After subsurface mapping and digital extraction of fault information, current work highlight importance of implementation of these automated methods in seismic interpretation to aid in reservoir modelling techniques, especially in foreland areas with complex fault system (s), *e.g.* Potwar Plateau in Pakistani Himalaya.

Keywords: seismic expression, subsurface structures, spectral decomposition, Potwar Plateau

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Introduction

The main goal of seismic exploration is to characterize geological features, such as stratigraphic and structural traps (*e.g.* faults and pop-up structures) associated with petroleum entrapment. Seismic attribute, a measure of a seismic characteristic, is one of the commonly used tools utilized to extract the desired information either directly sensitive to the geologic feature of interest, or to allow for defining the structural or depositional environment. Such attributes have been tested in diverse geological settings (*e.g.* clastics and carbonates) with different structural characteristics (*e.g*. normal and reverse faulting). Faults and fractures are the important structural features for reservoir modeling in an extensional or compressional regime. It is important to map faults/fractures as they play a significant role in controlling fluid flow in the reservoir. Seismic attribute maps provide a useful tool in interpreting these faults, particularly the ones close or below seismic resolution. Attributes derived from seismic data sets often provide a quick way to visualize the trends of faults and fractures, which are not visible in seismic amplitude information.

Several attributes have been applied for improving characterization of the reservoirs by predicting the structure of complex fault zones based on seismic data (Jones and Knipe, 1996; Chopra and Marfurt, 2005, 2006; Iacopini *et al*., 2012; Hale, 2013). For instance, NMO (Normal Move-out) velocity method provided better interval velocity estimates and more accurate subsurface geometries. Similarly, the application of bright spot techniques produced gas discoveries accompanied by some failures, which was then improved by another method AVO (amplitude versus offset). All these developments were aimed at improving understanding of the subsurface, and reducing uncertainty and risk associated with exploration practices.

Variance, parallel bedding indicator, wavelet, and trace envelopes are among the attributes, which provide information of the subsurface geometries and related physical parameters, for which amplitude is the main factor. Spectral decomposition of seismic data is one of the widely used tool(s) to evaluate the geological anomalies like channels and faults, which have different spectral contents from the surroundings. These seismic attributes have been used to derive information proven to be helpful in fault and fracture studies (Ghosh *et al*., 2014; Hamidi *et al*., 2018a, 2018b). Different seismic attributes aid in exploiting different seismic characteristics. There is no single attribute tool that may address all the questions regarding the subsurface characterization. Therefore, an integration of multi-attribute analysis was proposed for 2D reflection seismic interpretation.

In Potwar Plateau, many wells have experienced well abandonment due to structural complexities and related drilling problems in the area, for example strata dips variation, high pressure, intense faulting, and much thick seal rocks (Jadoon *et al*., 2014; Khan *et al.,* 2022, and references therein). In Potwar Plateau, the geological structures at the surface, most often, do not represent the subsurface structures. It is due to the surface distribution of Miocene Siwaliks (molasses) in the form of broad anticlines having gently dipping limbs, while in the subsurface seismic data, they are overlying the anticlines (salt-cored), duplexes, and triangle zones surrounded by steep faults (Jadoon *et al*., 1999, 2014). The thick molasse deposition caused by the Himalayan Orogeny and its uplifting has further complicated the terrain by causing the overburden load (Kadri, 1995; Shah, 2009). Within this context, a multiple attribute approach has been utilized for structural interpretation.

Different researches have been conducted on seismic interpretation (mostly based on 2D seismic data) of different hydrocarbon fields (*e.g*. Meyal and Balkassar Oil Fields) of the Potwar Plateau (*e.g*. Riaz *et al*., 2019; Shakir *et al.,* 2019; Mudasir *et al.,* 2023, and references therein). Recently, seismic attribute analyses using a few seismic attributes of a seismic line of the Meyal Oil Field have been conducted, which demonstrated the presence of hydrocarbons at the Eocene stratigraphic level (Ali *et al.,* 2021). Similarly, in the case of Balkassar Oil Field seismic attribute analysis (using limited attributes) of the Eocene reservoir (*i.e.* Chorgali carbonates) revealed stratigraphic information, reservoir property (*e.g.* porosity), and the presence of hydrocarbons (Rehman and Hassan, 2013). In addition, seismic attribute analysis at the level of Permian Tobra Formation in Balkassar Oil Field was done to assess potential for deeper drilling prospects (Masood *et al.,* 2017). Moreover, Khan *et al.* (2024) did a multi-attribute analysis to assess the reservoir potential of the Paleocene carbonate reservoir (*i.e.* Lockhart Limestone) of the Balkassar Oil Field. However, a detailed subsurface interpretation using seismic attributes is not reported to the best of our knowledge. The earlier studies are based on a single oil field, a single stratigraphic level, and limited seismic attributes, but the present study is based on two oil fields (*i.e.* Meyal and Balkassar Oil Fields) where reservoirs are bounded by varying structural features. The current work presents the first attempt by applying seismic attributes to discuss the structural details of Eocene strata (in particular) of the Potwar Plateau, Pakistan, by mapping structural features, as well as their importance in inferring the growth and evolution of faults, and of the adjacent geologic strata over a large geological time period.

Geological Setting

The Salt Range and Potwar Plateau are part of the foreland zone of the northwestern Himalayan Fold-and-Thrust Belt (Jaume and Lillie, 1988). The structural deformation is caused by a collision between the Indian and Eurasian Plates. The rocks of Potwar Plateau represent thin-skinned compressional deformation (Lillie *et al*., 1987).

The Potwar Plateau is the former oil producing province of Pakistan (Kadri, 1995). The hydrocarbon potential of the Potwar Plateau was established by the discovery of Dhulian, Joya Mair, Balkassar, Toot, Meyal Oil Fields, and many others (Kadri, 1995). Most hydrocarbon discoveries are associated with subsurface anticlines (mostly salt-cored anticlines), reverse faults, and duplexes (Jadoon *et al*., 2014). The Northern Potwar Deformed Zone (NPDZ) contains the Meyal Oil Field, while the Balkassar Oil Field lies in the central part of Potwar Plateau (Figure 1). Meyal Oil Field is developed on a structural trap (Meyal Kharpa Anticline), which is a narrow, steep, faulted anticline striking in the east–west direction having two main thrust faults intersecting the structure longitudinally (Hasany and Saleem, 2012). At Eocene level, the structure in the subsurface is a pop-up, salt cored, doubly plunging, gently dipping anticline bounded by thrusts in the north and south (Hasany and Saleem, 2012). Balkassar Oil Field has been established on the Balkassar Anticline (four-way closure pop-up anticlinal structure) which is bounded by thrust faults (Rehman and Hassan, 2013; Iqbal *et al.,* 2015; Mudasir *et al.,* 2023). Seismic sections of the Balkassar Oil Field demonstrate the presence of reverse faults in the cover sequence (Precambrian–Recent), while the basement shows normal faults, which are also obvious on the seismic data (Lillie *et al*. 1987; Pennock *et al*. 1989; Moghal *et al*. 2007).

The Potwar Plateau is composed of platform rocks of Cambrian to Eocene age, underlain by Precambrian evaporites and overlain by Miocene-Pliocene molasses (Figure 2) (Shah, 2009; Moghal *et al.,* 2007).

Materials and Methods

The seismic reflection data was loaded, and quality checked into the Kingdom software. For seismic data interpretation, firstly marker horizons were marked throughout the section and based on discontinuities, and changes in the dip behaviour of reflectors, faults, and structural traps (Meyal anticline) were identified and interpreted. Correct fault mapping in the subsurface can be crucial for the success of a petroleum exploration project. To achieve a fault visualization, seismic attributes have been proved to be an effective tool. Literature shows that there is not a single best tool available for providing all stratigraphic or structural details on the target reservoir in a sedimentary basin. Therefore, the multi-attribute approach is adopted to enhance visualization of faults. Three types of seismically driven attributes have been computed including the ones which are fault-sensitive, their dip, and other related discontinuities. The seismic attribute analyses were done using Kingdom software. The deployed seismic attributes include geometrical (dip variance, parallel bedding indicator), instantaneous (trace envelope/reflection strength) and wavelet (wavelet envelope) attributes. A seismic multi-attribute analysis was used to test the performance of each attribute in detecting the faults and fractures. Integrating dip variance (geometrical, instantaneous, wavelet) attributes highly improved the results of the fault and fracture analysis in the studied area.

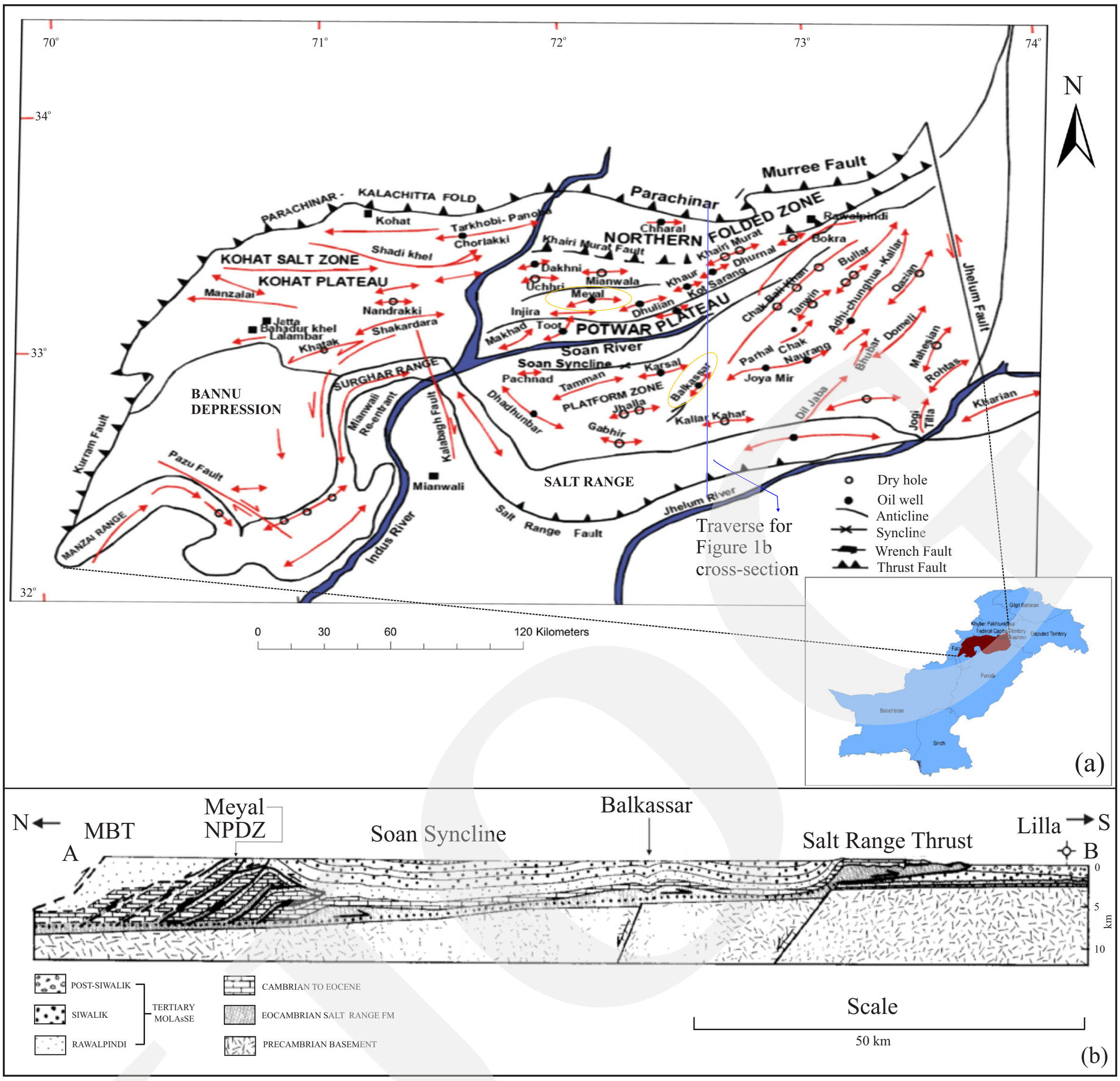

Figure 1. Tectonic map and cross-section showing certain parts of Upper Indus Basin. (a) Tectonic map of the Kohat-Potwar Plateaus (modified from Kazmi and Rana 1982; Khan *et al.,* 1986). Meyal and Balkassar Oil Fields are shown by orange ellipses. (b) Structural cross-section of Potwar Plateau and Salt Range showing different structural zones in the Potwar Plateau, Main Boundary Thrust (MBT), Northern Potwar Deformed Zone (NPDZ) (after Baker, 1987; Lillie *et al.*, 1987; Baker *et al.,* 1988).

The Potwar Plateau experienced severe deformation during the Himalayan Orogeny in Pliocene to Middle Pleistocene (Moghal *et al*., 2007). The severity is documented by regional unconformities, uneven distribution of salt, and the occurrence of decollement at different levels. Thus, different parts (northern and central) of the plateau manifest distinct structural style. To analyze the structural architecture in such type of tectonic setting, several seismic attributes were combined by using two 2D time-migrated seismic profiles each from Meyal (MYL-X1) and Balkassar (BLK-X1) Oil Fields of the Potwar Plateau (Upper Indus Basin, Pakistan).

Results and Discussion

This paper investigated the faults offsetting Cenozoic nonclastic (carbonates) rocks that developed into the anticlines and clastic rocks that overlie anticlines using high quality 2D seismic data from foreland basin of Pakistan. Geometrical, instantaneous and wavelet attributes were

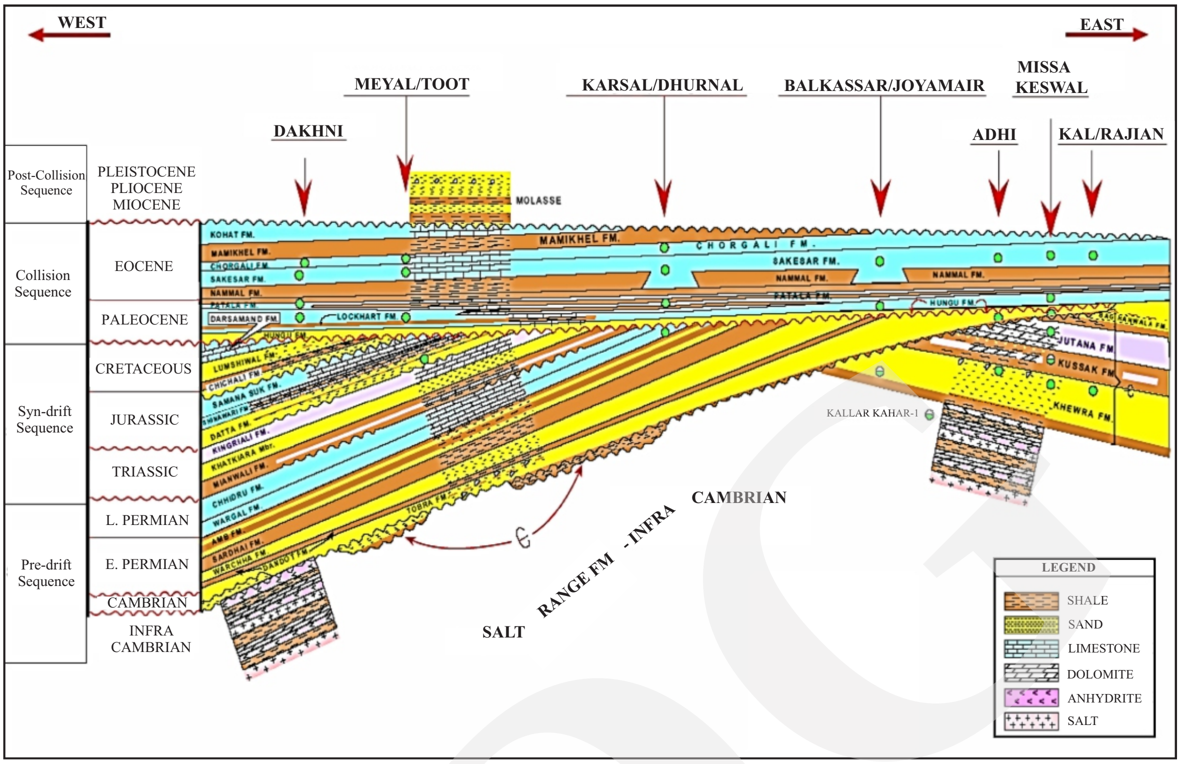

Figure 2. Generalized stratigraphic chart of the Potwar Plateau (modified after Moghal *et al*., 2007).

presented as evidence to demonstrate thrust faulting and related deformational features responsible for structural traps for proven reservoirs in the Meyal and Balkassar Oil Fields.

A seismic attribute analysis has been carried out along MYL-X1 and BLK-X1 seismic lines separately (Figures 3 - 6). The uninterpreted, interpreted, and seismically derived attributes have been shown (*i.e.* dip variance, parallel bedding indicator, wavelet, trace envelope, and spectral decomposition) in Figures 3 - 6. After analyzing 2D seismic data of Meyal Oil Field in the northern part, seismic attribute tests on 2D seismic data from Balkassar Oil Field were conducted in the Central Potwar Plateau to compare the computed results. As both northern and central parts manifest differences in the structural style and deformation (Figures 1, 3 - 6). It was expected that remarkable difference(s) would be observed after comparing seismic attributes from each data set.

Interpreted seismic attributes of seismic line MYL-X1 of Meyal Oil Field clearly indicate the main geological structure in the subsurface (Figure 4). The result demonstrates the presence of anticline structure bounded by faults on both sides. The reflectors at the limbs of anticlinal (pop up) structure are cut by clear discontinuities that can be readily interpreted as thrust faults (Figures 4c - e). Higher values of dip variance are associated with thrust faults on either side of the Meyal anticline, clearly showing that the attribute is sensitive to the anomalous dip variations across the faults (Figure 4a). On the other hand, lower values represent the relatively flat strata disrupted by thrust faults.

An attribute analysis has also been carried out, which may not provide direct information regarding geological structure in the area. However, such attributes provide indirect evidence, *e.g.* a geometrical attribute (parallel bedding indicator; PBI) has been applied that aided in identification of the structural features (Figure 4b). Low and higher values of the PBI attribute are related to the presence of almost horizontal beds of Eocene carbonates (at 1-60 and 100-110 SP) and faults respectively, thereby helped in tracking faults (Figure 4b). Lateral continuity of

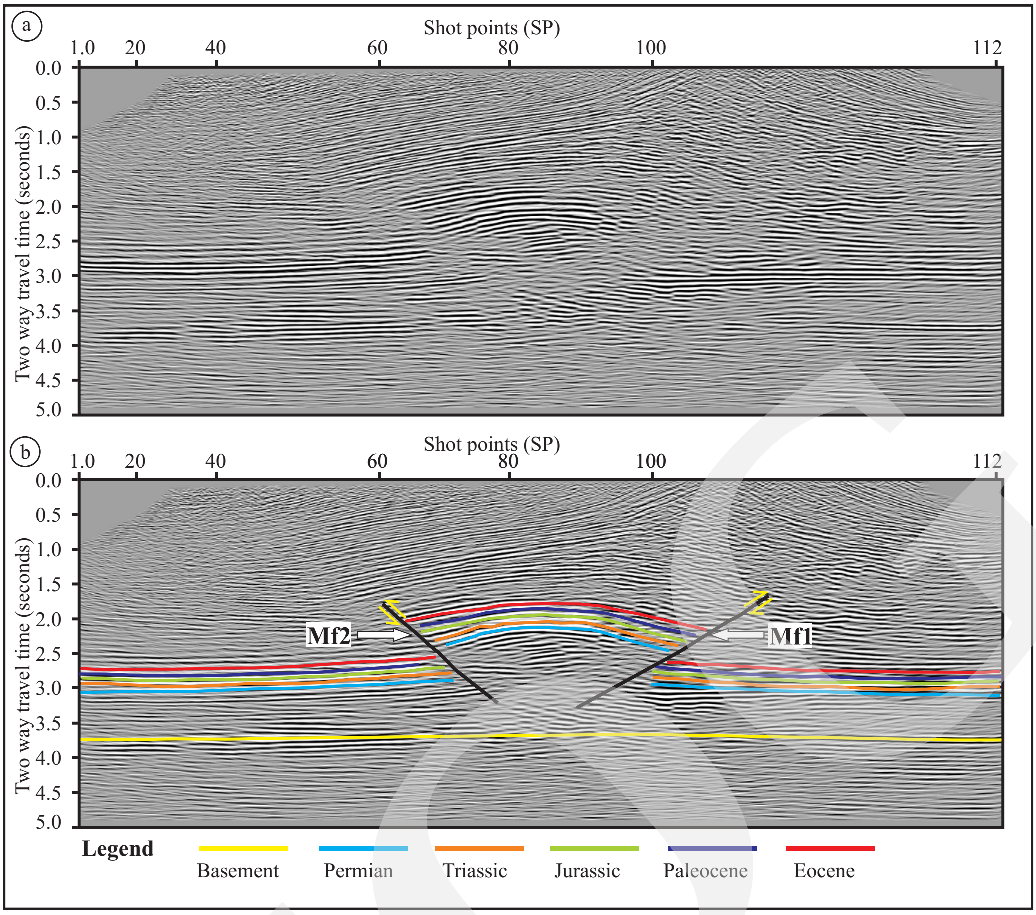

Figure 3. Seismic section of seismic line MYL-X1, Meyal Oil Field. (a) Uninterpreted section and (b) Interpreted section.

horizontal strata based on parallel bedding attribute information led to demarcate the principal faults disrupting bedding upon which much of the displacement has been accommodated. The main structure (Meyal anticline) generally has other deformation(s) in sandstone-shale multilayers as can be seen in the upper and lower parts of the map (Figures 3 and 4). Thus, PBI attribute provided an indirect indication of fault zones by clearly mapping geometrical configuration and lateral continuity of horizontal beds (Figure 4b).

Apart from the attributes closely related to the geometry of the subsurface structure, instantaneous attribute was tested to map the main faults responsible for generating pop-up structure (Figure 4c). The instantaneous attribute (trace envelope) indicated two faults with very lower values. In addition, it captured the overall shape of the main structural trap in the area (Figures 3 and 4c). Underneath SP-100, a down thrown block is clearly observed at 2.2−2.9 sec (Figure 4c). Finally, wavelet attribute analysis was conducted by constructing wavelet envelope and spectral decomposition maps (Figures 4d and 4e). The wavelet envelope attribute demonstrated enhanced subsurface structure by preserving the anticlinal shape as well as clearly showing relatively large throw below 100-SP of Meyal fault-1 (Mf1), while less separation was observed along Meyal fault-2 (Mf2) (Figures 3 and 4d). Low envelope values correspond to the region where the seismic signal has been strongly perturbed, and the amplitude damaged. The energy distribution is more compacted on the wavelet envelope map, which helps in thorough tracking both the geometry of anticline and thrust faults bounding the structure. Overall, wavelet envelope attribute better resolved geological features of interest than trace envelope (Figures 4c and d). A broad Meyal doubly plunging anticline bounded by faults *(i.e.*

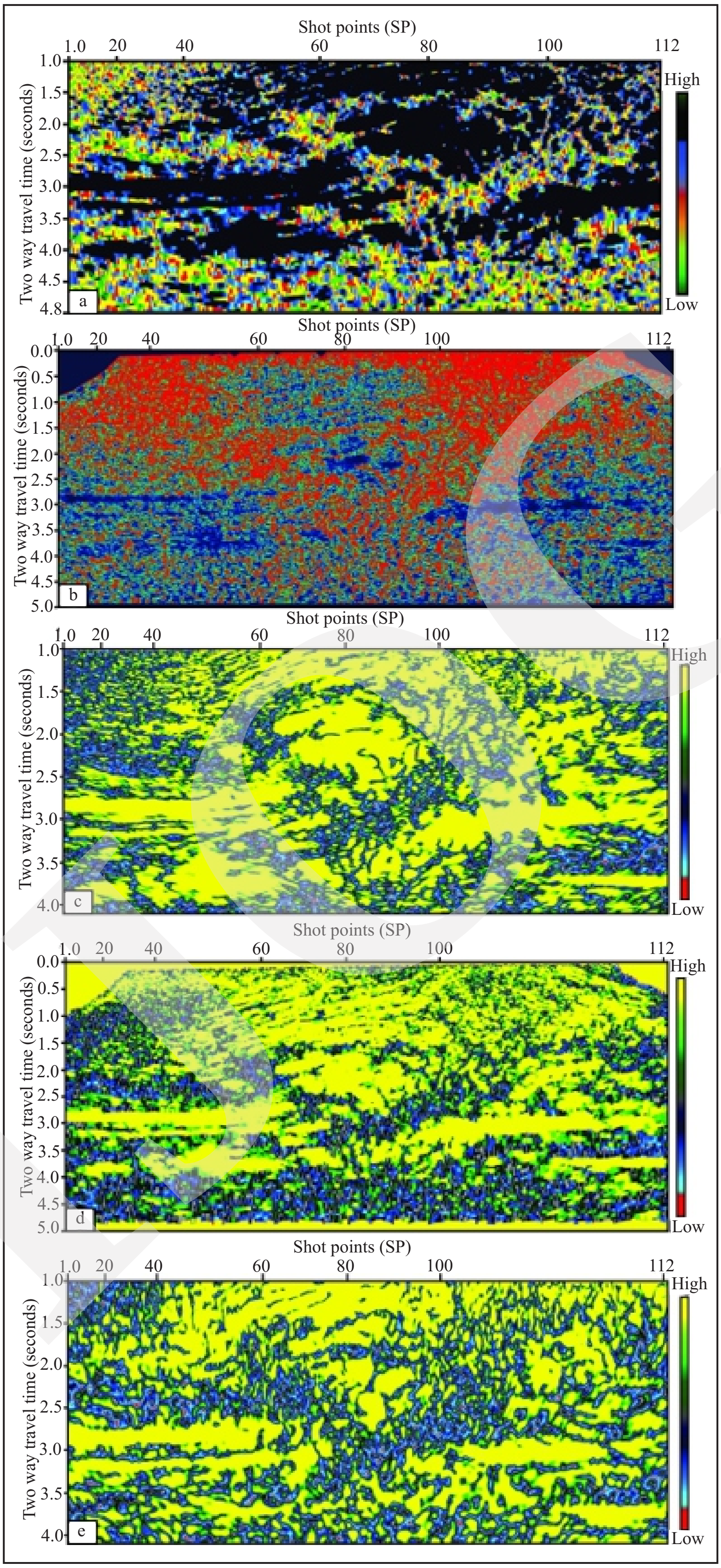

Figure 4. Seismic attribute maps of seismic line MYL-X1, Meyal Oil Field. (a) Dip variance, (b) Parallel bedding indicator, (c) Instantaneous trace envelope, (d) Wavelet envelope, (e) Spectral decomposition envelope.

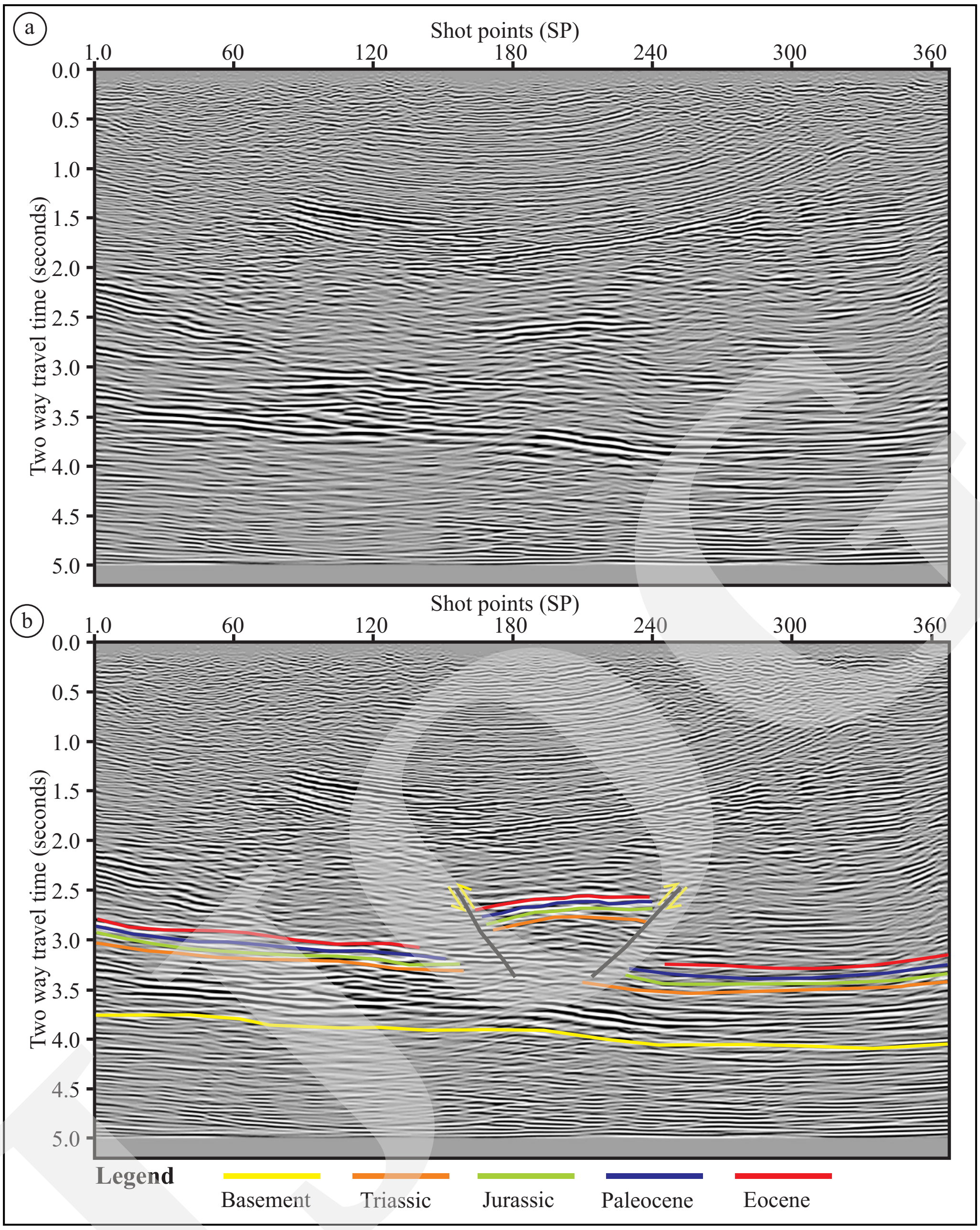

Figure 5. Seismic section of seismic line BLK-X1, Balkassar Oil Field. (a) Uninterpreted section and (b) Interpreted section.

Mf1 and Mf2) at SP 80 can clearly be seen on wavelet envelope map (Figure 4d). Thrust faults are conventionally defined based on the apparent offsets of seismic reflectors, *e.g.* Shaw *et al.* (2005). Yet, this may not be sufficient to identify the position of thrusts as well as their damaged zones in a complex tectonic setting like Potwar deformed zone. For the subsurface structure shown in Figure 3, deformation includes faults with variable dipping orientations are responsible for offsetting strata at various scales, so that the bedding is gently folded which is inferred as Meyal anticline in the studied area.

The spectral decomposition attribute was used to identify small and large-offset faults in compressional environment in the Himalayan foreland basin. The studied area experienced severe deformation, therefore, apart from major thrust faults, pop-up structure is disrupted by several minor faults (Figure 4e). The spectral decomposition results demonstrate that the applied tool has the potential to detect these minor small faults (Figure 4e).

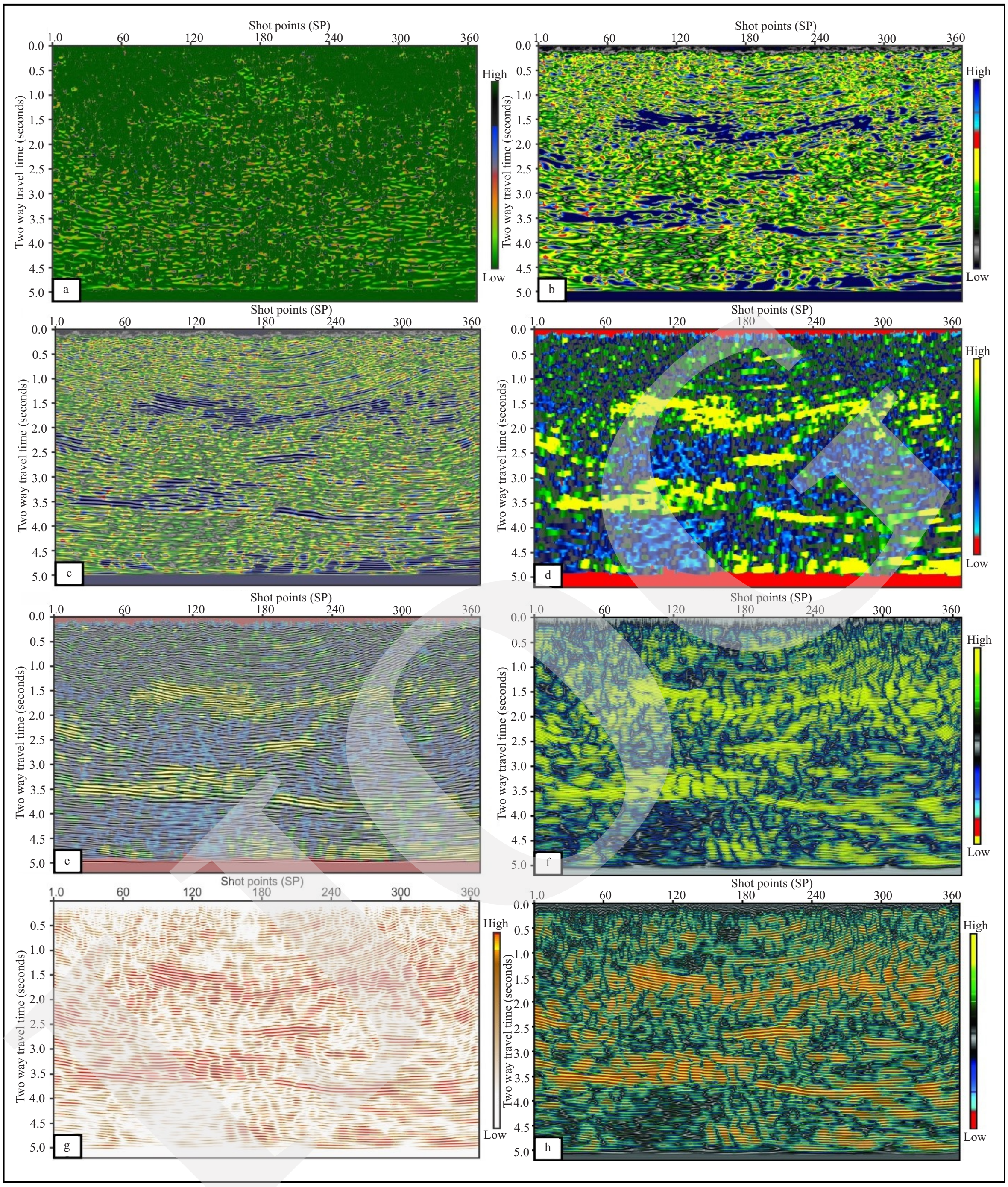

Figure 6. Seismic attribute maps of seismic line BLK-X1, Balkassar Oil Field. (a) Dip variance, (b) Trace envelope, (c) Overlay of trace envelope on uninterpreted seismic section, (d) Wavelet envelope, (e) Overlay of wavelet envelope on uninterpreted seismic section, (f) and (g) Spectral decomposition envelope, and (h) Spectral decomposition trace.

In the case of Balkassar Oil Field, the parallel bedding attribute result indicated no response, which means it could not detect beds or zones having zero or close to zero variance. It clearly confirms the intensity of deformation in the central part of the Potwar Plateau. Thus, it can be concluded on the complexity of subsurface structure in the central region of the plateau as compared to the northern deformed zone. The dip variance result demonstrates that the derived attribute did not provide detailed structural information like Meyal area (Figure 6a). The reason behind not getting a clearer subsurface picture from dip variance attests to the drastic variations in local dip of seismic events in the studied area. However, the trace envelope map indicated a broad anticline underneath SP 210, but unable to track thrust faults on either side of the structure (Figures 6b and c). From wavelet envelope attribute, sub-surface geometry of the same structural feature can be seen with relatively better resolution (Figures 6d and e).

Spectral decomposition method overperformed trace and wave envelope, and dip variance attributes by resolving the target of interest in detail (Figure 6f). The subsurface configuration as well as major thrusts bounding the anticline can be observed on the attribute map. While interpreting seismic section, the use of a good colour scheme may help detect small changes in reflectivity, and hence enhances seismically derived attribute response. Thus, keeping in mind that idea, the same attribute was reproduced (*i.e.* spectral decomposition) response (Figure 6g) which predominantly reduced the effect of seismic amplitude variations in the surrounding of the main structural trap, thereby detecting pop-up structure with enhanced visualization.

Spectral decomposition trace shows the best possible attribute map detailing the geometry as well as clearly tracking the fault zones in the area of interest (Figure 6h). The improved result demonstrated not only the main target, but also mapped the lower and upper parts of the seismic section exhibiting prominent amplitude changes. Therefore, the aforementioned method(s) reacted to small and large changes in reflectivity patterns.

It becomes increasingly difficult to discriminate features of small scale in a certain tectonic framework exhibiting increasing complexity. Depending on the complexity of the fault system in a geological setting, different attribute analyses had varying success for characterizing structural features. Therefore, it is important to combine various attributes, thereby taking advantage of the potential of each individual attribute, to better discriminate structural elements as fully as possible. The present results demonstrate that the application of seismic attribute analysis enhances the understanding of thrust zones from a single case study in the hope that the methods will be applied to other areas of fold-and-thrust belts which experienced severe tectonics.

Based on the results, some of the computed attributes failed to give a clearer indication of thrust faults in the compressional regime. After carrying out multi-attribute analysis techniques, it was expected to capture small and large-scale changes like Meyal Oil Field. However, the subsurface geometry as well as individual major faults were not identified on all maps which could be associated to poor quality seismic information upon which attribute result is dependent, intense tectonic deformation and unavailability of 3D seismic data. Thus, it is inferred that the availability of quality seismic data and less deformed strata can play a significant role in deriving detailed and enhanced subsurface characterization of structural features using attribute maps in foreland fold-and-thrust belt.

Conclusions

In order to display the seismic expression of the main structural trap of the Meyal Oil Field in NPDZ, three types of seismic attributes were analyzed and compared (*i.e.* geometrical, instantaneous, and wavelet). The attributes demonstrated their capabilities in enhancing different seismic aspects of the NPDZ by detecting deformation related features. Multiple attributes provided important information. The attribute results delineate reflectors defining anticlinal feature, and the deformed strata overlying the fold is differentiated based on the response obtained from wavelet envelope attribute analysis. Spectral decomposition revealed subtle faults, especially the ones related to the main pop-up structure in Meyal Oil Field. Wavelet envelope attribute indicated the overall subsurface geometry of the structural trap with relatively better resolution. Qualitatively, the movement along fault planes and associated discontinuities were analyzed through parallel bedding and dip variance attribute analyses. Very poor performance of the aforementioned attributes concludes on the drastic variations in local dip of seismic events which are subsequently associated with structural complexity and/or high deformation structural styles of the studied area.

Comparing results of both Meyal and Balkassar Oil Fields, it can be concluded that seismic attributes capture fault-related important small-scale structural information on deformation distributed around those larger scale structures, which may not be readily and easily interpreted in conventional amplitude displays of seismic data in a tectonically complex environment. The potential of using 2D seismic data has been demonstrated for characterizing fault zone properties and its direct application for subsurface exploration.

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