ORIGINAL PAPER-EXPLORATION GEOLOGY

Assessing the hydrocarbon potential of the Kadanwari gas field using integrated seismic and petrophysical data

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Abstract

Kadanwari is a major gas-producing field in Pakistan's Lower Indus Basin (LIB), extensively explored for optimized production. However, the reservoir sands of the Lower Goru Formation (LGF), deposited in a complex river-dominated delta, bear severe variability and hinder accurate facies approximation for optimal production. Furthermore, the regionally extended NNW-SSE directed horst and graben structures significantly compartmentalized these reservoir facies. The main E-sand interval is analyzed for its geological properties, depositional environment, and distribution. The integration of various approaches, including seismic interpretation, attribute extraction, well-based facies modeling, and petrophysical evaluation, proved significant in evaluating the heterogeneous and tectonically influenced E-sands. The discontinuity attribute substantially highlighted the structural style and aided in analyzing the geometries of faults. The low values of the frequency attribute (< 10 Hz) signified the entrapped gas-bearing sands along the faulted zones. The high responses of instantaneous amplitude and sweetness profoundly illuminated the gas-significant deposits throughout the field in association with the well-identified gas-prone sand facies. The outcomes of the neutron-density crossplot depicted gas-bearing sands having low density (< 2.3 g/cc) and good porosity (12%) with the assessment of various cements. The facies modeling distinguished between clean and intermixed sand-shale reservoir zones. Petrophysical analysis revealed a net pay of 14 m within E-sand having gas saturation of about 68%. The adopted approach is robust and efficient, employing a limited data set for developing well-associated seismic responses for potential zone delineation within structural arrangements. The techniques can be optimistic about the LGF's complex potential sands demarcation throughout the Indus Basin.

Keywords Sand lithologies · Seismic attributes · Petrophysical analysis · Reservoir characterization · Facies modeling

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Abbreviations

3D	Three dimension
AVO	Amplitude variation with offset
E&P	Exploration and production
ENI	Ente Nazionale Idrocarburi
LGF	Lower Goru formation
LIB	Lower Indus Basin
LLD	Laterolog deep
LLS	Laterolog shallow
MSFL	Micro spherically focused log
NNW-SSE	NorthNorthWest-SouthSouthEast
OGDCL	Oil and Gas Development Company Limited
PSTM	Pre-stack time migration
TOC	Total organic carbon
UEPL	United Energy Pakistan Limited
UTP	Union Texas Pakistan

Introduction

The Kadanwari gas field is Pakistan's most important hydrocarbon-producing region and lies in a zone that is geologically associated with the LIB. The main reservoirs of the basin comprise the potential sands present in the LGF of Early Cretaceous age (Khan and Khan 2018). These sands are normally compartmentalized by the horst and graben structural mechanisms, having a NNW-SSE orientation and being widely distributed in the LIB (Ali et al. 2022). This widespread distribution caused by the diversified clastic fluvial system creates challenges in the characterization of the Lower Goru's potential sands in the basin (Munir et al. 2011). The complications included the heterogeneities, such as porosity, shale, saturations, cementation, of potential facies in the complex depositional environment. Therefore, the varied reservoir intervals, i.e., B-sands, C-sands, E-sand, and G-sands of LGF, with interbedded shales, in complex structural geometries need to be thoroughly assessed for optimized field production. The variability of sand deposition accompanying the structural features is alleviated by employing the three-dimensional pre-stack time migration (PSTM) seismic features along with the parameterization of well-based petrophysics and rock physics approaches. The integrated techniques are implemented to identify the characteristics of the key reservoir, i.e., the E-sand facies of the LGF, with the benefit of optimizing production in the field that is now declining.

The seismic attributes can be used to identify pore fluid immersion and delineate the in situ conditions of reservoirs, especially fluvial potential sand deposits (Marfurt et al. 1998; Hampson et al. 2001; Chopra and Marfurt 2005; Ismail et al. 2022; MonaLisa et al. 2023b). Seismic attributes are organized by partitioning the properties physically and geometrically and they can be used to highlight prospects within structural pockets (Taner et al. 1979; Bodine 1984, 1986; Taner 2001; MonaLisa et al. 2023a). With the advent of new technologies, the seismic amplitude types have been greatly upgraded and extensively utilized to demarcate depositional environments (Chopra and Marfurt 2005; Løseth et al. 2009; Raef et al. 2015). Similarly, the petrophysical interpretation based on the utilization of well logs provides details regarding reservoir characteristics, including shales, porosity, saturations, (Khan et al. 2022a, b; Hussain et al. 2023). The outcomes of the petrophysical interpretation assess heterogeneities of multiple lithofacies present in the thin reservoir (Khan et al. 2023). The facies modeling clarifies the facies presence and aids in the depositional environment assessments in accordance with petrophysical-elastic properties crossplots (Khalid et al. 2022).

Previously, many studies have been performed, including the seismic characterization, amplitude variation with offset (AVO) analysis, and porosity prediction which have differentiated conventional and unconventional porous reservoir facies of the Indus Basin (Naseer and Asim 2017a, b). Specifically, in the Kadanwari gas field, research has been conducted regarding potential facies demarcation through petrophysical assessment using well logs (Khan and Khan 2018; Ali et al. 2022), seismic inversion techniques (Zhang et al. 2022), and 3D volumetrics approximation of key geological properties, i.e., water saturation and effective porosity (MonaLisa et al. 2023a). However, in the present study, an integrated approach including structural demarcation, seismic attributes, petrophysical evaluation, and lithofacies modeling is employed to delineate the most promising zones in complex structures, along with heterogeneity assessment in the lithofacies. The study is helpful in classifying the lithofacies by employing log crossplotting with the elaboration of depositional environment and mineral contents in the reservoir sands (Khan and Rehman 2019). Facies modeling discriminated between clean potential sand and intercalated shaly-sands with various cements. Overall, the adopted methodology provided trustworthy clues regarding the presence of potential in the shoreface-deposited tidal channel, i.e., reservoir E-sands, which have a 14 m net pay with a gas presence of about 68% within the Kadanwari-18 well location.

Geology of the study area

The LIB is located in the southeastern region of Pakistan and encompasses the most productive oil and gas section in its southern part. The study area is one of Pakistan's largest gas-producing regions and is adjacent to the southern edge of the Sukkar Rift (Fig. 1a) (Khan et al. 2023).

The Kadanwari gas field is made up of right-lateral wrench faults that extend in a NNW-SSE direction and
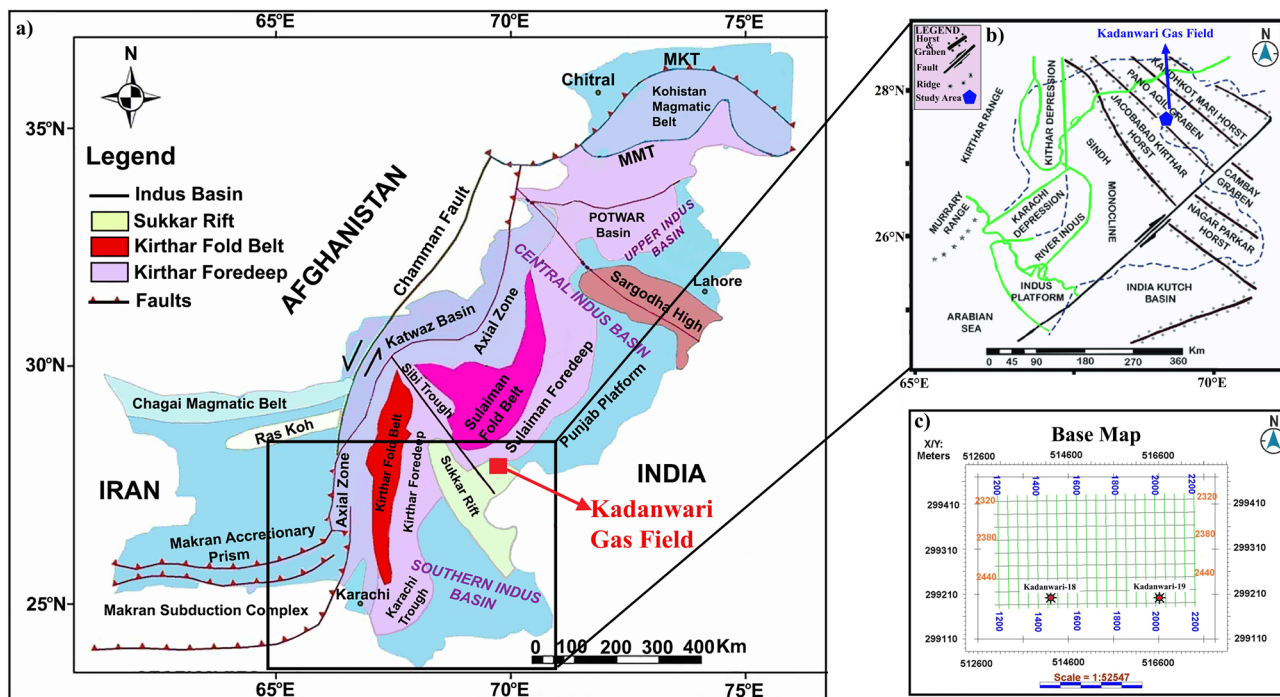
Fig. 1 **a** Location of the study area with major tectonic elements of the region (modified after Khan et al. 2023) and **b** Detail structure surrounding the Kadanwari gas field (modified after Ahmed et al. 2022) and **c** Base map of the study area

have a cross-sectional interpretation similar to a flower structure (Fig. 1b) (Ahmed et al. 2022). The available 3D seismic data along with well location is depicted in Fig. 1c. The success of the Kadanwari field has led to the collaboration of multiple exploration and production (E&P) companies, including ENI, OGDCL, and UEPL, for the exploration of hydrocarbons targeting the Lower Goru sandstones (Raza et al. 2020). The Early Cretaceous prolific gas sands of the LGF are the major reservoir of the Indus platform (Hussain et al. 1991; Zaigham and Mallick 2000). The seal for the entire Sembar-Goru petroleum play is provided by the shales of the Upper Goru Formation.

The simplified stratigraphy inside the LIB is illustrated in Fig. 2a, which includes formations, lithologies, ages, and their related groups (Khan et al. 2023). Figure 2b demonstrates different nomenclatures adopted by E&P companies, including OGDCL, UTP, ENI, and OMV, for the Lower Goru sands classification (Ahmad and Ghazi 2022). In the current study, the ENI nomenclature is followed, as ENI is the operator of the field and has categorized the LGF sand units from B to H intervals. The major gas-bearing clastic units in the study area comprised E and G sands, but D and F sand units also demonstrated gas production in a few wells.

Structural setting and stratigraphy of the study area

The structural settings of the research area were influenced by tectonic events that are categorized into three phases: (a) Uplift and erosion during the period of the Late Cretaceous, (b) Wrench faulting in the epoch of the Late Paleocene, (c) Uplifting in the period of Late Tertiary to Recent along with the inversion of structure comprising Jacobabad-Khairpur high (Ahmad and Ghazi 2022; Ahmed et al. 2022). The wrench faulting detached the research area mostly into the horst and graben while acting as structural traps for the sands of the LGF (Ehsan et al. 2018). The result of wrench faulting caused the reservoirs to be divided into various compartments that are often targeted for the assessment of potential sands (Ali et al. 2019).

The wide platform region of the Kadanwari field was submerged due to the cyclic rifting between the African and Indian plates as well as the effects of eustatic sea level rise during the Callovian-Oxfordian time interval. This resulted in the succession of siliciclastics (Sembar and Lower Goru) above the carbonate systems (Afzal et al. 2009). The shale of the Chiltan Formation, present at a deeper level in the basin, acts as an unconventional reservoir at many locations but mostly as an indigenous source rock with good maturity and TOC having type II–III kerogen (Ahmad et al. 2019). The interbedded shales of the LGF existing at shallower depths
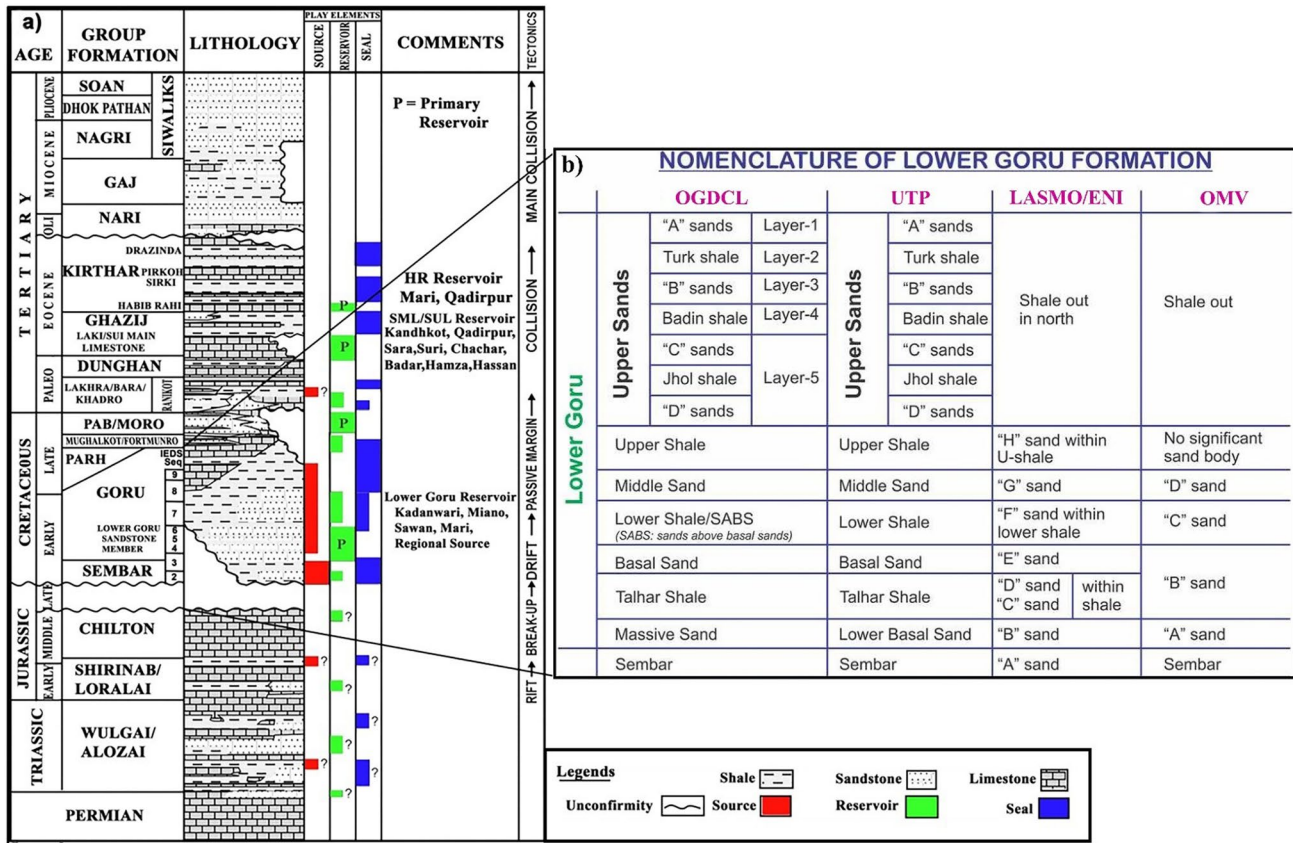
Fig. 2 **a** Stratigraphic sequence of the LIB (Khan et al. 2023) and **b** Nomenclature for Lower Goru reservoir sands by E&P companies (Ahmad and Ghazi 2022)

provide the seal for the sand units (Asim et al. 2014). The Lower Goru reservoir sands are westerly prograding river-dominated deposits drained through the Indian Shield, present in the east and south-east directions of the study area (Ahmad and Ghazi 2022). Locally, prograding or aggrading sands are deposited during an overall rise in sea level. The resultant "backstepping" of successive reservoir units provides the conditions for marine flushing of a regressive sand pod during an overlying transgressive marine episode (Ahmad et al. 2007).

The reservoir E-sands interval is characterized by shoreface sands and tidal channels, which indicate a depositional environment of a flat and shallow seabed (Berger et al. 2009). The conditions allowed a fast progradation of the delta front and the dissipation of flood energy in the mouthbar associated with delta-front lobes. The subsequent reservoir E-sands interval is only 15–25 m thick with relatively uniform facies. The quality of reservoir sands declines from the proximal sand bar locations toward the delta-front lobes that exist at the distal sides. The presence of lobate deltas having excellent quality sands (consistent with producing fields), separated by interlobe zones, is highlighted by assessing the discharge efficiency of the various channels

accompanying the river system (del Monte et al. 2009). The reservoir E-sands interval quality becomes efficient at the depth of 3390 m, where the total porosity averages 18–21% and the permeability ranges in darcies. Petrographic analysis indicated porosity preservation at those levels with less cementation due to the presence of early diagenetic, grain-coating, and chloritic clays that lessen the inhibited cement growth (Ahmad and Chaudhry 2002).

Materials and methods

The present study utilized about 10 km² of 3D PSTM seismic data volume in the Kadanwari field. The quality of the seismic dataset is sufficient for the characterization of the Lower Goru's clastic reservoirs.

A total of 175 inlines and 1028 crosslines exist within the 3D PSTM seismic data, along with the exploratory wells of Kadanwari-18 and Kadanwari-19, while Kadanwari-18 (ST) is the sidetrack well. The well data contain the main logs of Gamma Ray (GR), Spontaneous Potential (SP), Caliper (CALI), Deep resistivity (LLD), Shallow resistivity (LLS), Micro-spherical Focused Log (MSFL),

Sonic (DT), Density (RHOB), and Neutron porosity (NPHI) that were utilized for correlation of seismic data, petrophysical interpretation of reservoir properties, and reservoir facies modeling. The other important information present in the well bore includes the formation tops, mineralogy information, and literature. The workflow followed to demarcate the heterogeneous potential sands in complex structure is elaborated in Fig. 3.

The wells penetrated through the key reservoir E-sand interval in both wells. The key reservoir E-sands were evaluated comprehensively having good net/gross thickness, porous, relatively clean and prone to commercial production (Linn 1998; Ahmad et al. 2007, MonaLisa et al. 2023a). The observed fluid contacts in these intervals were consistent with free-water-levels (FWLs) established by using RFT/MDT data (Ahmad and Chaudhry 2002). Overall, the depths below 3390 m in Kadanwari-18 proved hydrocarbon efficient having capacity for commercial gas production (Ali et al. 2023). The Kadanwari-19 also produces gas but of limited extent in comparison with Kadanwari-18 due to less net thickness of reservoir E-sands. The information about seismic lines and wells is illustrated in Table 1, which shows the geographical coordinates, the depths, and the status of the wells.

The data quality of well logs is appropriate, while all the basic well logs employed in the petrophysical, and rock physical interpretations are available.

The 3D seismic cube was interpreted for the structure delineation of the area by using the Kingdom software of Seismic Micro Technology (SMT). Overall, the integrated workflow was performed in four steps. Initially, the seismic interpretation was achieved by bringing wells into relationship with the seismic data for properly locating the zone of interest, i.e., the E-sands interval. The structural interpretation showed a feasible host-graben structure regarding the trapping of hydrocarbons (Ehsan et al. 2021). Secondly, the seismic attributes were extracted so that the potential capabilities of the reservoir can be found throughout the study area by noticing the trace responses of the seismic. Thirdly, the facies modeling was carried out along with NPHI-RHOB crossplotting at well locations that confirm the presence of sands, shaly sands, and shales along with cements in the LGF, especially at the depths of E-sands. Finally, the E-sand interval is assessed for its reservoir properties, including the porosities and volumetrics of shale and fluids. This integration of techniques successfully reveals the potential efficiency of the E-sands interval throughout the region in connection to the producing wells, especially Kadanwari-18.

The zone of interest was marked between 2.4 and 3.4 s on a time seismic section that is part of the fluvial-deltaic

Fig. 3 The employed workflow for the delineation of heterogeneous potential sands through integration of wells and seismic datasets
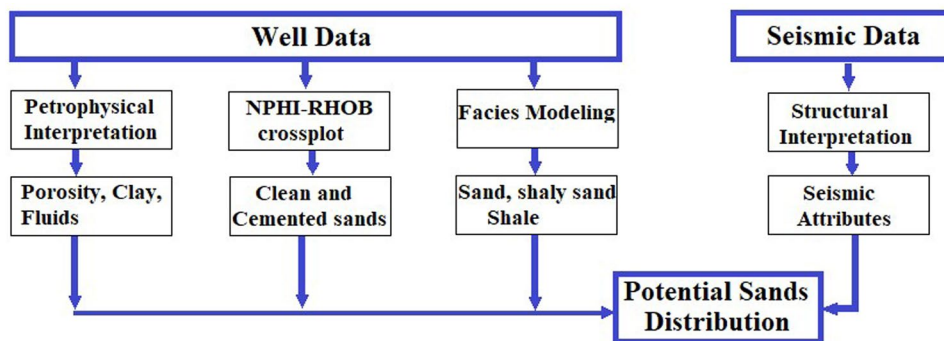

Table 1 Seismic 3D cube information along with well data information

Seismic 3D cube information		
Lines	Start	End
Inlines	2311	2486
Crosslines	1180	2208

Well data information					
Well name	Latitude (degrees)	Longitude (degrees)	Start depth (m) KB	End depth (m)	Status
Kadanwari-18	27.050581	69.141227	59	3545	Gas
Kadanwari-18 (ST)	27.050581	69.141227	59	3673	Gas
Kadanwari-19	27.049794	69.173086	55	3465	Gas

reservoir system of early to middle Cretaceous age. The key horizons, which include the top of Lower Goru, G-sands, E-sands, Sembar, and the Chiltan Formation, were interpreted on seismic sections at fixed intervals and mapped across the study area using gridding and contouring (Fig. 4a). The mapped surfaces were used for analyzing and extracting the seismic attributes at various levels of the reservoir. The fault polygons bisecting the surfaces were illustrated in 3D perspective to visualize the normal faulting effects associated with the extensional regime and delineate the structurally significant zones for hydrocarbon entrapment (Fig. 4b).

A broad variety of seismic attributes are extracted for evaluating abundant geological information in structurally influenced basins. Some of the optimized seismic attributes, i.e., discontinuity, response frequency, instantaneous amplitude, and sweetness, were analyzed in the interpreted zone of E-sands interval to highlight the distribution of reservoirs at the most viable structures (Imam et al. 2022). The extraction of discontinuity attribute aimed to highlight fault patterns and assess the structural style. The structure played a key role in the hydrocarbon entrapment in this field, while the faults provided the migration pathways for the hydrocarbon from source to reservoir. The discontinuity seismic attribute assesses the non-similarity within beds. It depicts low values for similar regions, while high values emphasize the dissimilar zones. In addition to identifying fault zones, which are important for structurally dominant potential zones, it also assists in locating fluvial sand reservoirs in structural pockets (Tayyab and Asim 2017).

The trace-based instantaneous attributes have been reliably applied in various fields of the LIB, i.e., Sawan, Miano, to evaluate Lower Goru sands due to the obvious seismic character for assessing gas anomalous zones (Ashraf et al. 2019; Azeem et al. 2016). These attributes provided detailed information on potential E-sands interval intercalated within shales of the similar LGF in this field as well. The instantaneous amplitude seismic attribute, also known as the amplitude envelope (White 1991), depicts high values for anomalous gas-bearing sand facies having low acoustic impedances (AI) in comparison with shales with high AI values (Adero et al. 2017). Some of its major advantages include the exploitation of gas concentration as bright spots, successive boundary delineation, thin bed tuning effects, main alterations in the depositional environment, 3D porosity correlation, and other lithological variability. Another significant attribute is the instantaneous frequency (response frequency), which is approximated by the derivative of time upon phase. The frequency attribute is widely utilized for hydrocarbon zone delineation by observing low frequencies in the potential anomalies (Barnes 1991, 1993; Marfurt et al. 1998; Naseer and Asim 2017a; Naseer et al. 2014). This attribute can be interpreted for fracture zone delineation as well as huge bed identification, i.e., sand-prone lithologies, where frequencies are trapped to yield low frequencies. Also, the sudden boundary changes, including thinly bedded shales within sand beds, are recognized by the higher frequencies (Naseer et al. 2014; Taner 2001). For a clear understanding of sands and sandstones, the sweetness attribute is adopted as a proven technique (Hart 2008).
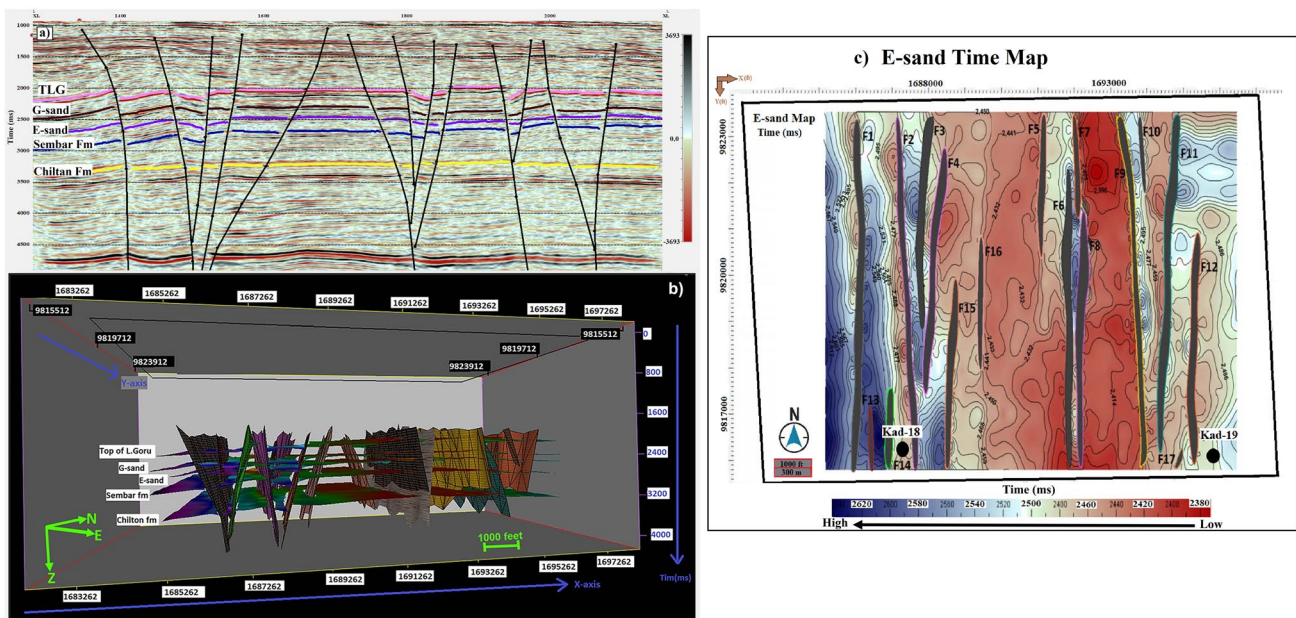

Fig. 4 **a** Interpreted horizons and faults on seismic section delineating the horst and graben structures and **b** 3D structural style of the interpreted faults and horizons and **c** Interpreted E-sand time structural map depicting faults extents and orientation

Basically, it depends on two important attributes, i.e., taking a fraction of the instantaneous amplitude envelope and taking the instantaneous frequency square root (Radovich and Oliveros 1998).

The proper usage of cores, well logs, and drilling outcomes was made in the 1950s through the petrophysics approach, which integrated the properties for the assessment of reservoirs. In the updated second-generation level, the well properties were disseminated throughout the field, which was primarily established on geological analogues. This analogue approach enhanced interwell relationships, but identifying the correct analogue was repeatedly found to be challenging, predominantly in architectural and complex stratigraphic contexts. In the third generation, multidisciplinary techniques attempt to incorporate important information from geophysics, petroleum engineering, and geology, as well as the subsequent outcomes of chance and risk investigation practices, to obtain an optimized reservoir model (Evans 1996).

In the present study, a comprehensive examination of well logs is performed to estimate the reservoir's essential features. Kadanwari-18, a potentially viable well with a full suite of well logs, is focusing on petrophysical interpretation, including porosities, clay volumetrics, and fluid presence. The fluid estimation is done by a widely used Indonesian equation that works well in sand reservoirs with intercalation of sands (Hussain et al. 2017).

The cross plots of rock attributes based on certain well-guided properties, i.e., porosities, fluid saturations, volumetrics, are helpful in the evaluation of wells in collaboration with seismic interpretation. Such integrated analysis is beneficial for the differentiation of facies by highlighting their various lithological behaviors (AlMuhaidib et al. 2012). A similar approach has been carried out by utilizing the wells of the study area for the characterization of potential sands through the cross plotting of important logs such as neutron porosity (NPHI) and density (RHOB). The outcomes comprise lithologic distinction by discriminating different types of sands, such as clean sand, shaly sand, and shale with cement concentration.

Results and discussion

The recently discovered gas deposits in Pakistan are rapidly depleting their resources. The finding of several viable hydrocarbon reservoirs in the early Cretaceous lower Goru sands, such as the Kadanwari-01 well, has provided strong motivation for geoscientists to continue investigating and advancing the Kadanwari gas field. Based on the literature analysis conducted by MIB, it has been observed that there exists a significant amount of untapped potential in virgin plays situated inside mature fields, where traditional hydrocarbon trapping procedures have previously been established.

The interpreted horizons and faults on the time seismic section revealed a structural setting comprising horsts and grabens in the study area, evident from the horizon trend and fault style (Fig. 4a, b). The structure became more evident after the accomplishment of fault correlation, which illustrated the fault orientation and extension throughout the region. A total of seventeen faults were interpreted on the 3D seismic sections with the nature of normal faulting, which basically indicates an extensional regime. The faults are connected in such a structural pattern that the minor faults terminate against the major faults in the form of splays, consequently shaping into negative flower structures (Khan et al. 2022a, b). The interpreted structural pattern is corroborated by the application of a discontinuity attribute. The discontinuity attribute delineates reflector disruption with high values and interprets geological structures such as faults, fractures, and depositional trend variations, while low values indicate continuity in bedding (Tounkara et al. 2023). Similarly, in the research area, the discontinuities of normal faulting are assessed by attribute values greater than 40, as evident in the section and cube views (Fig. 5a, b). The discontinuities demarcated by the extracted attribute showed a good match with the interpreted faults and provided additional discontinuities that were not as prominent on the seismic data.

The main indication of frequency trapping is observed in fractured or cracked sandstones with hydrocarbon bearings, which results in a predominantly low loss of frequency and, therefore, depicts a clear signal of potential zones (Goloshubin and Silin 2005). The extracted response frequencies at the E-sands reservoir level express the gas-bearing sands along with the faulted zones at low-frequency values, which, therefore, provide indications of hydrocarbon motion and accumulation paths (Fig. 6a). The potential sands of the LGF in the Sawan gas field are also distinguished by low-frequency values, indicating attributes' capability of illuminating the gas-bearing sands along with the dry hole demarcation with comparatively high frequencies (Azeem et al. 2016). The mapping of the response frequency attribute at the reservoir level indicates that the Kadanwari-18 well is associated with faulted gas-bearing sands (enclosed by the ellipse). The Kadanwari-19 well is not as significant to the potential anomaly as compared to the Kadanwari-18 well because of the inadequate linkage of faults. The research region demonstrates traits of an extensional regime that has been subject to drifting, including a rotating component. Consequently, the interpretation of the data indicates that the area mostly experiences normal faulting, with some additional wrench components (Khan et al. 2016). The geological features in concern are known as horst and graben. A horst refers to an area of a normal fault that has experienced
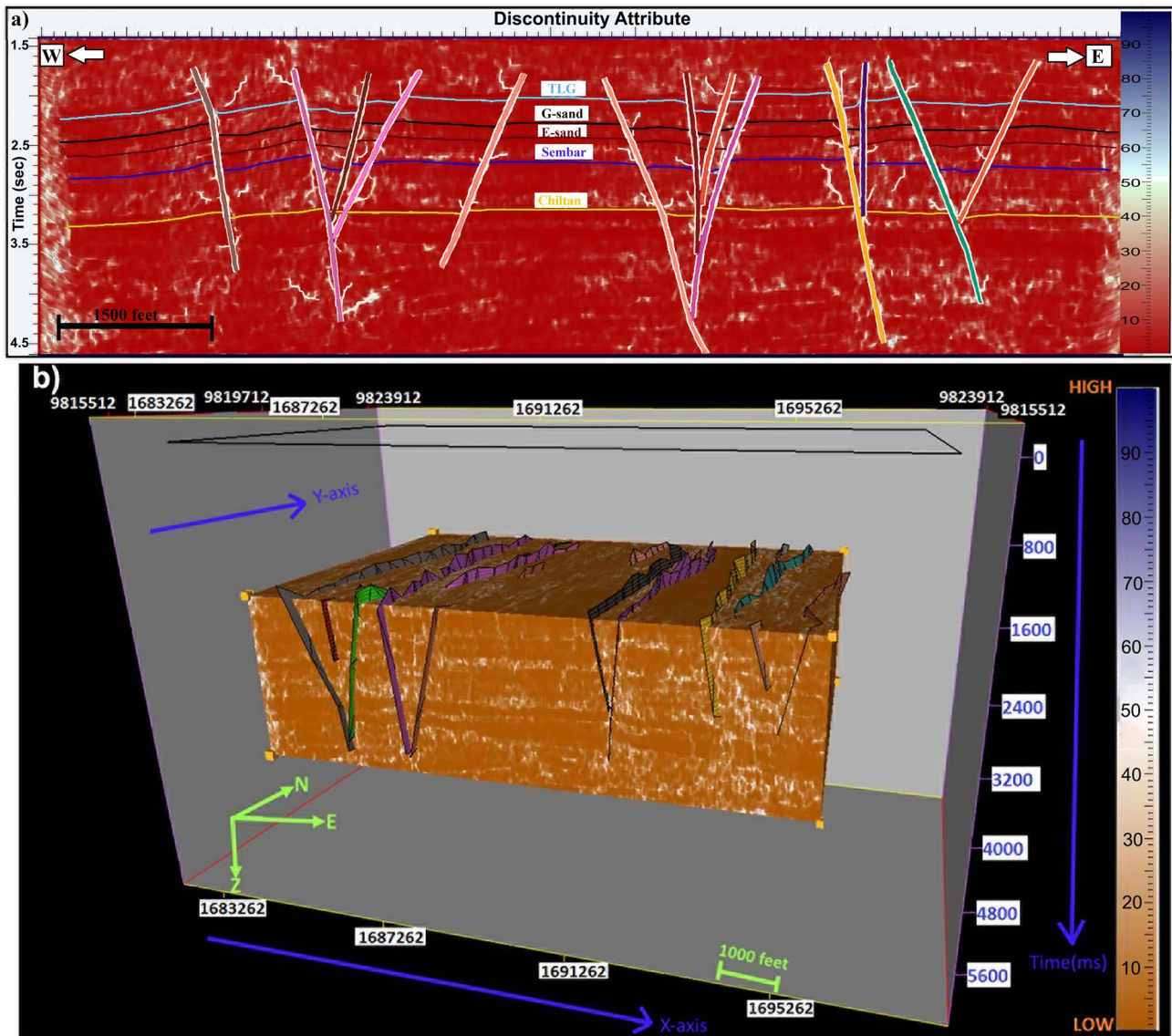
Fig. 5 **a** Fault discontinuities, visible by values above 40 (color bar), match with interpreted faults and **b** Discontinuity cube with the exact locations of the interpreted faults

uplift, while a graben refers to the downward section of the fault that is surrounded by normal faults. The graben is a geological feature characterized by its relatively significant depth, which in turn reduces the likelihood of hydrocarbon accumulations. Each horizon or formation exhibits horst and graben geometries since hydrocarbons consistently migrate from regions of high potential.

Sand facies are observed through the high values of the amplitude attribute in collaboration with other attributes (Naseer et al. 2016). Therefore, the detection of gas-bearing zones in the E-sands level is evaluated by the extraction of this attribute. A stratigraphic map, retrieved at the E-sand horizon, is inspected for potential sand distribution in the 3D perspective (Fig. 6b). The map illustrated gas anomalies

with high amplitudes while additionally illustrating another enhanced package of high amplitudes, enclosed by an ellipse highlighting a gas-prone sand package. This additional high-amplitude anomalous zone may be regarded as a new potential location for further drilling of a well. The absence of plausible high-amplitude sections on the response frequency attribute might be the source of tuning effects that have hidden the low-frequency content at the reservoir level owing to interbedded thin shales. The potential sands associated with delta distributaries up to proximal delta-fronts settings are feasibly assessed by the amplitude attributes in the fields of Miano, Sawan (Ashraf et al. 2019; Azeem et al. 2016). The attribute clarified the presence of reservoir porous sands
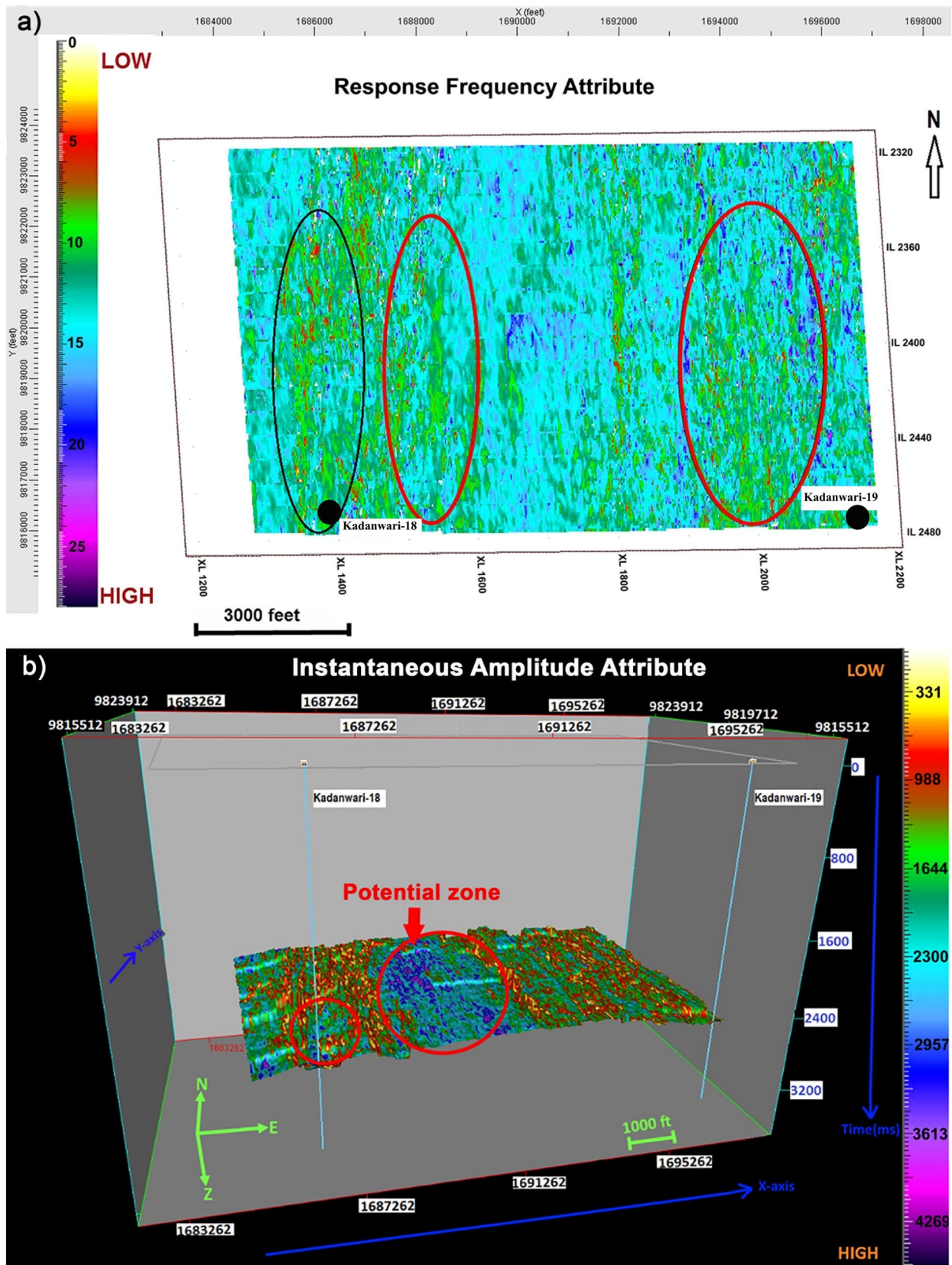
Fig. 6 a Response frequency at the E-sand horizon encircling the low-frequency anomalous zones and **b** Potential zones highlighted by the high instantaneous amplitude of E-sands interval with additional zone enclosed at center (3D view)

facies with high amplitudes while low to moderate indicated the presence of sandy-shale facies.

Sweetness is one of the important empirical attributes that can locate sweet spots in plausible gas reservoirs. The sweet spots are observed using a seismic dataset for imaging the prospective locations by noting the high-amplitude values with low frequencies. Its interpretation closely resembles that of the reflection strength, as the amplitude's effects are more robust than the frequency's (Koson et al. 2013). The attribute is effectively implemented for fluvial-deltaic sands assessment locally, i.e., Sawan gas field, and regionally, such as Save Depression (Ashraf et al. 2019; Novak Zelenika et al. 2018). It can identify isolated sandstone bodies in fluvial systems as it generates stronger reflections than shales present in the surroundings. The E-sands reservoir's map is generated by extracting the sweetness attribute that demarcated the potential channel sands of the fluvio-deltaic deposits (Ahmad et al. 2004; MonaLisa et al. 2023b) (bounded by polygons) (Fig. 7). The encircled zones validate the potential competencies by illustrating high values of sweetness attributes, while the central region of the E-sands map validates the presence of gas in well-sorted sands, expected to have valued porosities. This joint attribute of amplitude and frequency results in a more comprehensive and reliable way

of detecting the potential reservoir sands, especially in the central part. The sand's quality confirmation is assessed by facies modeling along with petrophysical interpretation that demarcates the potential viability, excellent porosities, and depositional influences concerning shoreface.

The important petrophysical logs, i.e., RHOB and NPHI, are often run together during wellbore data acquisition and employed in the detailed petrophysical evaluation to discriminate lithologies and cements via cross plots (Krygowski 2003; Dar et al. 2023). The cross plot of these properties is constructed for the sands and interbedded shale packages within the LGF (3340–3412) of the Kadanwari-18 well (Fig. 8a). For the interpretation of lithologies, the cross plot is characterized by three lines: the upper line delineates the clean sands; the central line distinguishes the shaly sandstones with the mixture of calcite cement; and the base line depicts the dolomitic cementation in the intermixed sand–clay lithologies. The presence of dolomite in potential reservoir sands of Kadanwari gas field were evaluated by the NPHI vs. DT crossplot while the carbonates is confirmed by the M–N crossplot (Ali et al. 2022). Above all the aforementioned lines, gas-bearing sands exist, having dispersed points representing low density values with NPHI values of about 12%. All the identified facies correspond
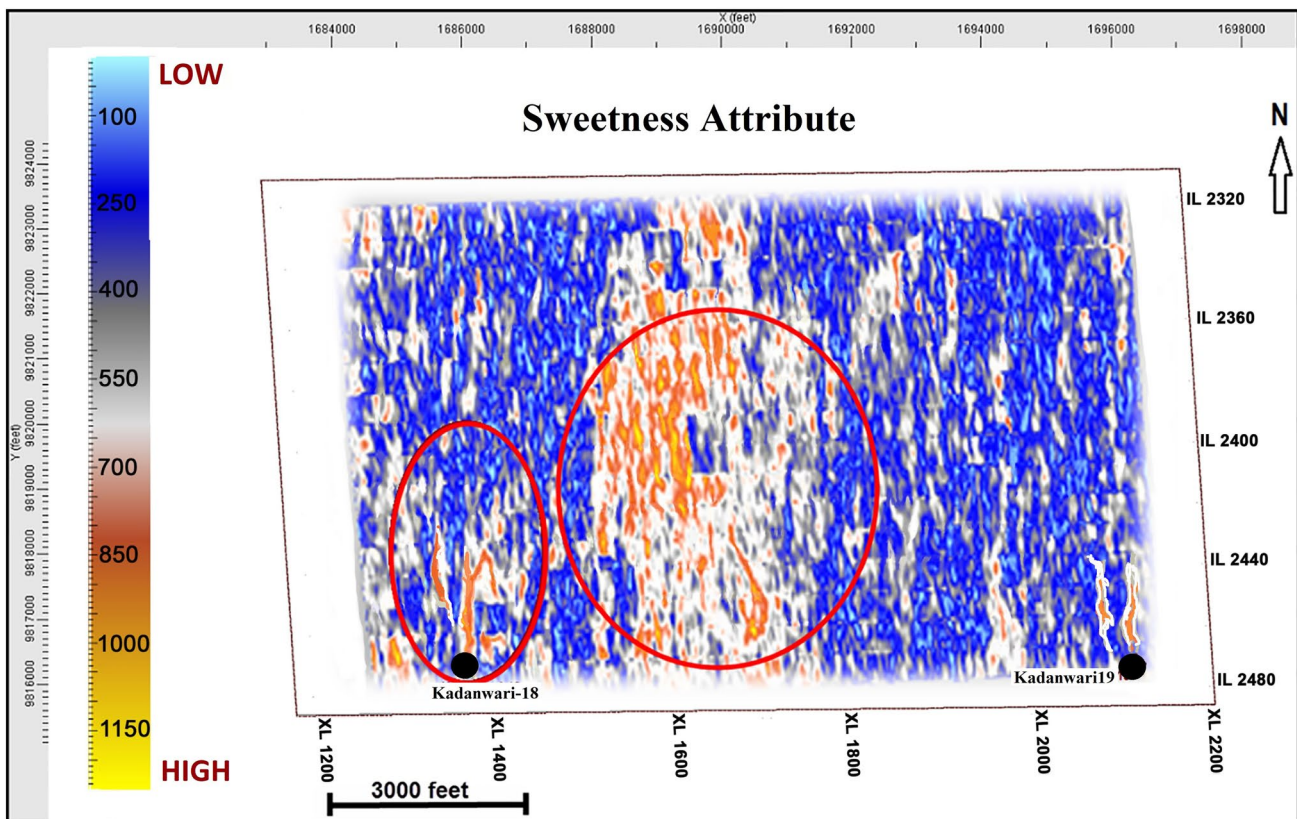

Fig. 7 High values of sweetness attribute encircle gas-bearing zones with major potential present at the center
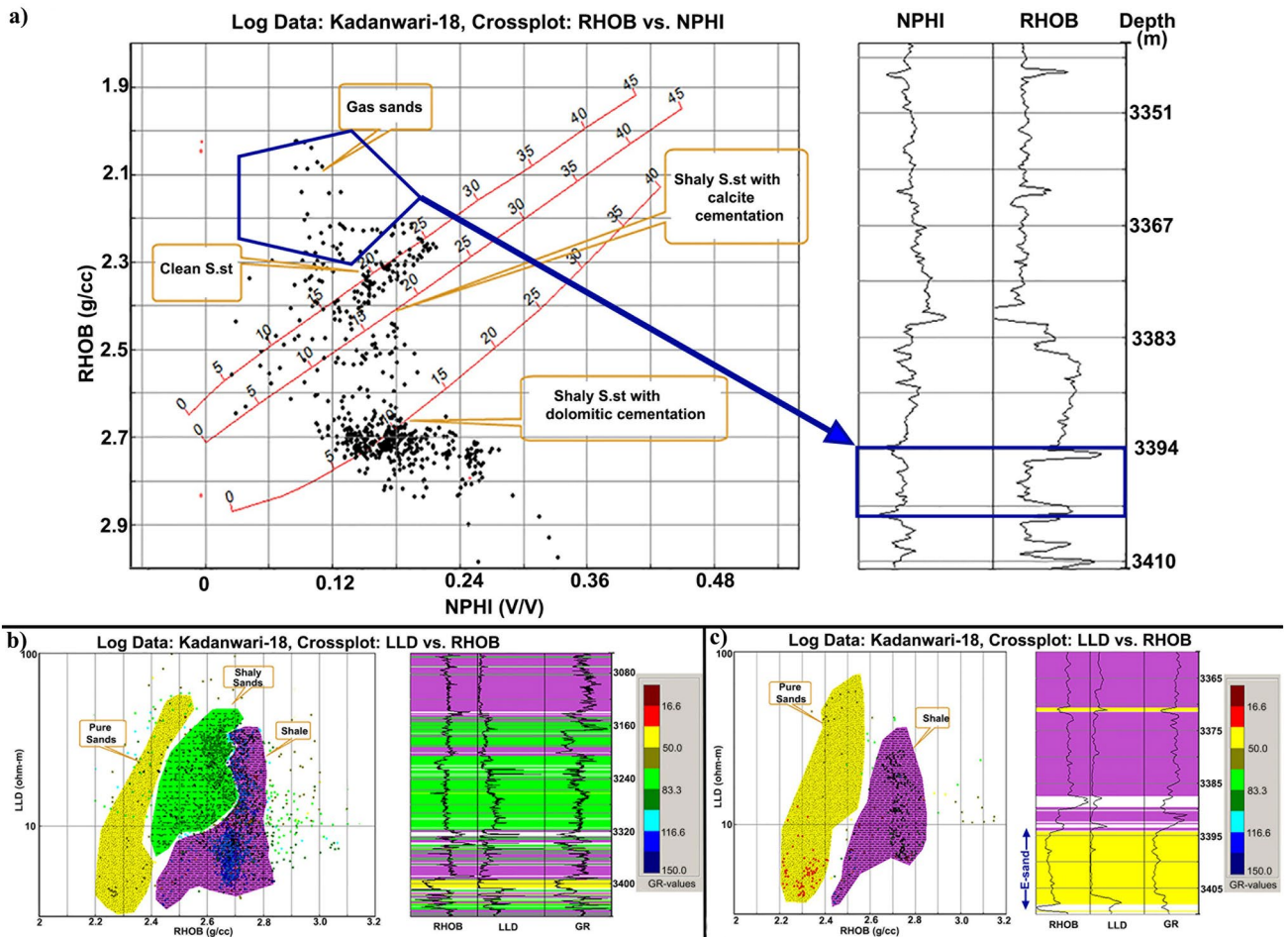
Fig. 8 **a** Cross plot of NPHI and RHOB logs separating sand facies in the Kadanwari-18 well and **b** Facies modeling of complete LGF in the Kadanwari-18 well highlight three facies and **c** Facies modeling at E-sands interval clarify the gas-bearing sands from shales

to specific features related to the sedimentation process, the depositional environment, and the source of previously deposited sedimentary rocks. The GR trend interprets the deposition of sediments as fluvial flood plains, tidal flats, and canyon infills (Ahmad and Ghazi 2022; Dar et al. 2023). Also, detailed petrographic characterization was carried out previously for the assessment of depositional settings and sands characterization (Dar et al. 2023). Overall, the broadly deposited sands were found to be heterogeneous throughout the basin, while the potential sands, such as the E-sands interval, are well sorted with good porosity. The diagenesis of the reservoir occurred with the cementation of calcite, chlorite, dolomite, etc., that either increased or decreased the porosity at various locations throughout the basin (Dar et al. 2023).

For the detailed analysis of observed facies within the LGF, the technique of facies modeling is used. This technique enhances reliability regarding composition, stratigraphic variations, and sedimentary texture (Ali et al. 2021; Lai et al. 2018; Salim et al. 2017). Overall, three well logs

are incorporated, i.e., RHOB (*x*-axis) having a range between 2.0 and 3.2 g/cc, deep resistivity (LLD) on the *y*-axis with values of 1–100 Ω-m, and gamma-ray (GR) as a color code on the *z*-axis having 1–150 API values. Primarily, the facies are deliberately modeled for the whole LGF (3050–3450 m) so that facies variation is widely categorized in the thick bed (Fig. 8b). Three zones are distinctly categorized in the massive LGF, keeping the GR as a reference lithological tool, such as pure sands, shaly sands, and shales. Interpreting the cross plot, i.e., low GR (1–50 API) illustrates "pure sands," demonstrated by high LLD values among low densities, present within the E-sands interval (3390–3410 m) and encompassed by a polygon. An analogous scrutiny was accomplished for GR ranging from 55 to 100 API, which suggested "shaly sands" on the cross plot, while GR values between 100 and 150 GR reflected shale. The wellbore section shows the response of well logs to individual lithofacies identification. For accurate facies delineation in the concerned E-sands interval by adopting a similar technique, the modeling zone is concise within a 3360–3410 m depth

interval (Fig. 8c). The distinguished lithologies, including the pure sands of the E-sands stratigraphic interval and the shaly portion, are evident by the RHOB and GR values.

The implementation of petrophysical methods in the Kadanwari-18 well quantitatively evaluated the reservoir E-sands interval for volumetrics calculation (shale), porosity determination, and fluids, i.e., hydrocarbons (Sh) and water (Sw) quantities (Fig. 9).

The potential significance of this reservoir is determined early in the estimation of its various elastic properties through supervised machine learning (Ahmed et al. 2022). Petrophysical investigation establishes an association between the geologically preserved rock's physical aspects and the liquids confined in the pores, therefore, assisting in reservoir characterization by providing a bridge. The significant logs for petrophysical assessment are illustrated in their respective tracks, i.e., the "lithology track," depicting sand zones by the low GR values. The "resistivity track" depicts the rise in LLD values compared to the mud-cake resistivity (MSFL), distinguishing the reservoir's more resistive in situ fluids from saline drilling muds. The "porosity track" demonstrated the crossover of RHOB and porosity NPHI logs, validating the less dense and porous gas-bearing zone. The appraised sand volumetrics, along with porosity predictions like density-porosity (PHID), total porosity (PHIT), effective porosity (PHIE), and estimated Sw, designate the prospect competence of the reservoir E-sands facies. The key factor PHIE is approximated by considering PHIT and the shale volume in a relationship [(PHIT*(1-Vsh)], delineating that high values of shales are influenced by clay minerals that reduce the effective porosity (Khan et al. 2022a, b). The relationship is helpful in the absence of core data; however,

many petrographic studies have been carried out to analyze the porosity and permeability of reservoir sand intervals in the LGF (Ahmad et al. 2004; Mohsin et al. 2010; Dar et al. 2023). The average values of the estimated petrophysical properties are summarized in Table 2.

Overall, the adopted methodology, based on the integration of seismic extracted properties and well logs petrophysical assessment delineated efficiently the potential capabilities of E-sand interval in the field. Figure 10a depicts the Lower Goru play fairway in the region with the delineation of the depositional environments and contours of LGF thickness (Ahmad et al. 2012; Siddiqui et al. 2014; Ahmad and Ghazi 2022; Dar et al. 2023). Various compartmentalized sand units, i.e., B, C, D and E, produced from the major fields including Sawan, Miano, and Kadanwari gas field that are the fluvial-deltaic shallow marine sands deposited in the eastern side (proximal) (Afzal et al. 2009). The shelf/slope transition line separated these potential sands from the outer-shelf to deep-basin deposited shales with possible sands.

Table 2 Summary of the estimated petrophysical properties of E-sands interval

S. no	Calculated parameter	Percentage (%)
1	Average volume of Shale = Vsh_{avg}	35
2	Average density porosity (PHID) = $\varnothing_{D-avg}$	18
3	Average porosity (PHIT) = $\varnothing_{T-avg}$	17
4	Average effective porosity (PHIE) = $\varnothing_{E-avg}$	12
5	Average water saturation = Sw_{avg}	32
6	Average hydrocarbon saturation = Sh_{avg}	68

Fig. 9 Petrophysical analysis of E-sands in the Kadanwari-18 well delineating estimated sands, porosities, and saturations
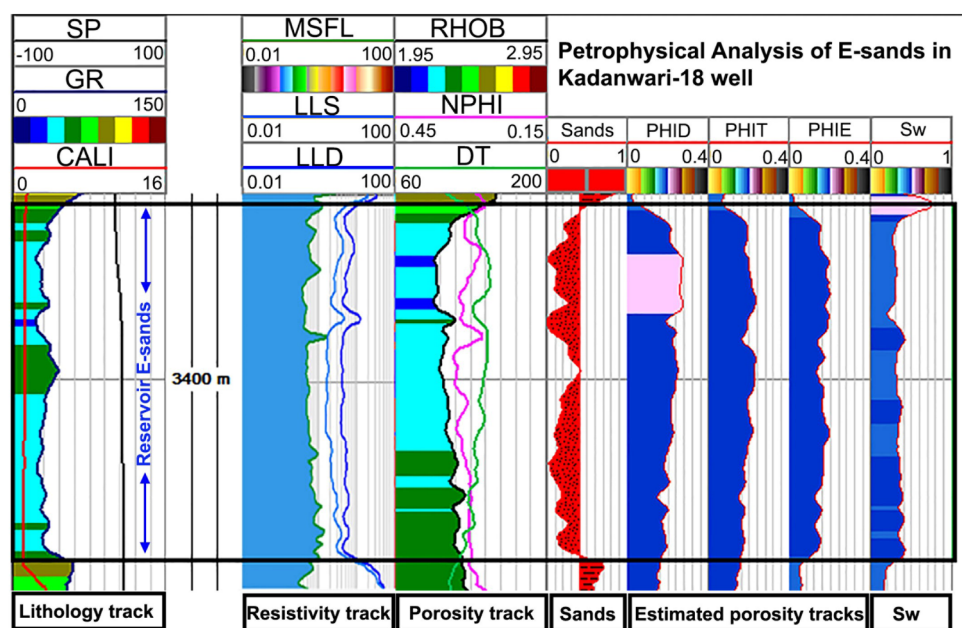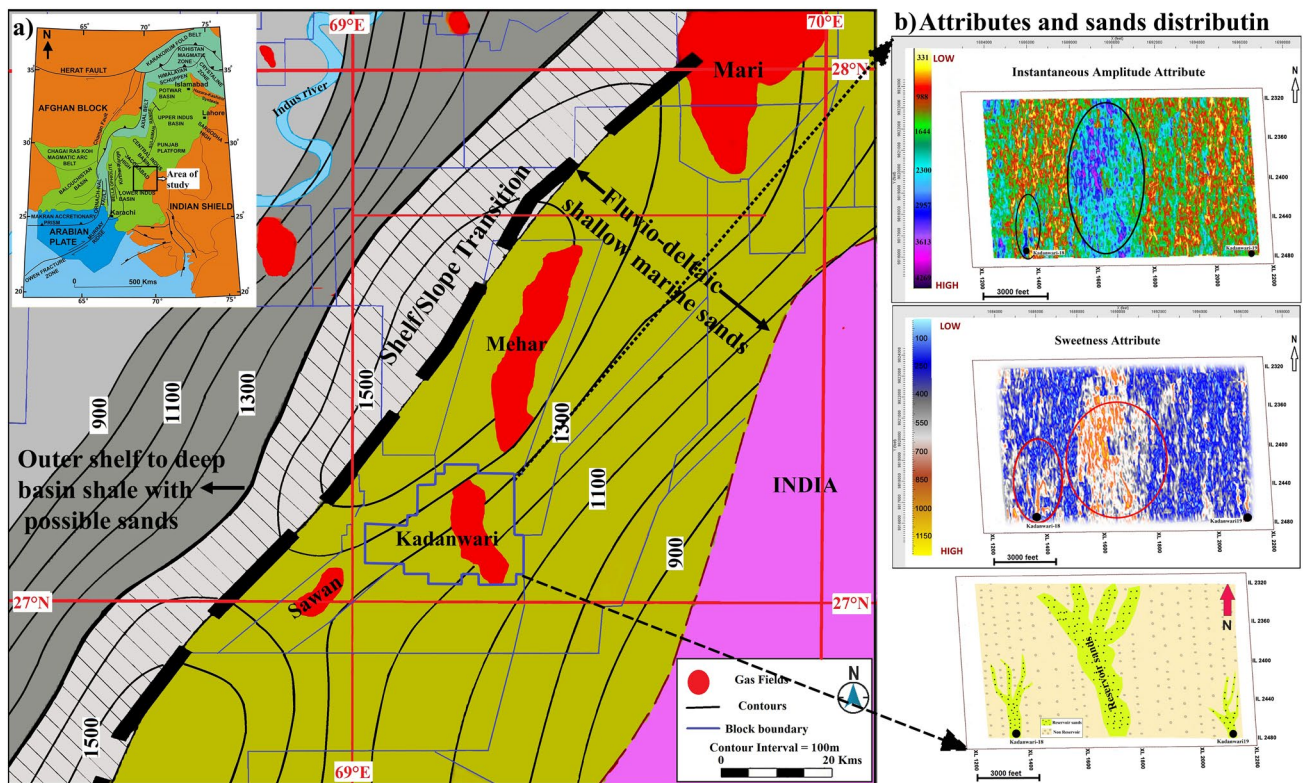
Fig. 10 a Lower Goru play fairway depicting the fluvial-deltaic shallow marine sands at the eastern side (proximal) where study area lies, then shelf/slope transition and finally outer-shelf to deep-basin shale with possible sands (Ahmad et al. 2012; Siddiqui et al. 2014; Ahmad and Ghazi 2022; Dar et al. 2023) and **b** Integrated assessment of key attributes and deposition of potential sands

Similarly, the key attributes (amplitude and sweetness) clearly demarcated the reservoir sands distribution with the major potential present in the center that can be drilled for optimized productivity of the field (Fig. 10b).

The present study provided comprehensive information; however, the hydrocarbon reserves can be more realistically estimated throughout the Kadanwari field by incorporating the increased number of wells along with the extended coverage of 3D seismic data.

On the other hand, assessment of petrophysical analysis and seismic attributes indicates that the LGF prospect zones may not possess substantial potential for the accumulation of hydrocarbons. This study has the potential to enhance future activities related to the exploration and exploitation of hydrocarbon resources in certain regions of the LIB in Pakistan. However, the acquisition of findings is solely reliant on petrophysical analysis and seismic features. To enhance the reliability of the projected outcomes, it is advisable to include geochemical data pertaining to the fundamental characteristics of the source rock, as well as core data for the determination of absolute reservoir attributes, throughout the process of prospect creation.

Conclusions

The integration of wells and seismic characteristics successfully examines the research area's potential capabilities.

- The seismic interpretation identified the critical horst-graben geometries with an overall style of negative flower structure, verified by the discontinuity attribute, and is regarded as favorable for hydrocarbon migration and accumulation.
- Valuable seismic attributes, including sweetness and instantaneous amplitude, illuminated the potential E-sand interval with high value ranges and depicted channels passing through well locations, with an additional potential zone in the central part of the study area.
- The response frequency characteristic captures the low-frequency potential anomalies at faulted zones near well locations; however, the central portions of the anomalies are impeded, possibly due to tuning effects arising from thin shales in the compartmentalized sands.
- The crossplot analysis, facies modeling, and petrophysical evaluation identified the cementations in the reservoir, distinguished between the cleaner and shaly

sand facies, and comprehensively designated the potential zone of the E-sands interval.

- Overall, the integrated techniques delineated 68% hydrocarbons with 35% clay content and a good effective porosity of about 12% in Kadanwari-18, while plausible shoreface-deposited channelized E-sands have prospective competences that can be drilled for enhanced production.

Data Availability Statement The data used in this work are available on request to the corresponding author.

Declarations

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