Prediction and Delineation of the Hydrocarbon nature (Heavy or Light API) based on the anisotropic data for the limestone province in Potwar area.

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(2021-2023)

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CERTIFICATE

This dissertation submitted by **MUHAMMAD RIZWAN S/O MUHAMMAD NAWAZ** is accepted in its present form by the Department of Earth Sciences, Quaid-i-Azam University Islamabad as satisfying the partial requirement for the award of MPhil degree in Geophysics.

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DEDICATION

Would like to devote my efforts to my cherished family

and my business, PPL who always believe in me

&

My Capabilities and spare time for my work to be completed

with corporate & social responsibility as well

ACKNOWLEDGEMENT

I am writing this to express my deep gratitude and appreciation for your exceptional support and technical expertise in the field of geophysics during my thesis/dissertation journey. Your guidance and knowledge have been essential in assisting me to finish my project successfully.

I'd like to express my heartfelt gratitude to you for your expertise in the field of seismic data analysis and for providing valuable insights and feedback throughout the process. Your willingness to share your experience and knowledge has been invaluable in shaping my understanding of complex seismic data processing concepts and methods.

Additionally, I want to thank you for the technological assistance you have given. Your unwavering support and commitment to helping me overcome any technical difficulties have been a source of great encouragement.

I am grateful for the time and effort you dedicated to reviewing my work and providing constructive criticism. Your dedication and commitment to my academic growth and success are greatly appreciated.

Please accept my sincerest thanks and deepest appreciation for everything you have done to help me achieve my goals.

Sincerely,

MUHAMMAD RIZWAN

(February 2023)

ABSTRACT

The prediction and delineation of the hydrocarbon nature (heavy or light API) is a crucial aspect of hydrocarbon exploration and production. The knowledge of the type of fluid present in a reservoir can have substantial effect on the total success in exploration & production efforts. In this study, we aim to explore the potential of anisotropic data for the prediction and delineation of the hydrocarbon nature in the limestone province in the Potwar area.

Anisotropy is a measure of the directional dependency of physical properties, such as elastic properties and fluid permeability, in rocks. In the case of hydrocarbon reservoirs, anisotropy can provide insight into the type of fluid (heavy or light API) that is present. Seismic data obtained from surveys can be used to calculate anisotropy attributes, such as intrinsic acoustic anisotropy, which can help to identify the presence of different fluids in the reservoir.

In the limestone province in the Potwar area, the presence of anisotropy can be used to predict the presence of heavy or light API hydrocarbons. A high degree of intrinsic acoustic anisotropy in a limestone reservoir may suggest the existence of heavy API oil, while a low degree of anisotropy may suggest the existence of light API oil.

The results of this dissertation show the potential of anisotropic data in the prediction and delineation of the hydrocarbon nature in the limestone province in the Potwar area. This information can provide valuable input for hydrocarbon exploration and production efforts in the region. However, it is important to consider that this is just one of the many factors that must be taken into account when evaluating the potential of a reservoir.

In conclusion, the use of anisotropy data in the prediction and delineation of the hydrocarbon nature can provide valuable information for hydrocarbon exploration and production efforts. This study highlights the potential of anisotropic data in the limestone province in the Potwar area and underscores the importance of considering anisotropy in hydrocarbon evaluation efforts.

The prediction and delineation of the hydrocarbon nature (heavy or light API) based on anisotropic data for the limestone province in the Potwar area can provide important information for exploration and production of hydrocarbon. Anisotropy is the measure in directional dependency of physical properties, such as elastic properties and fluid permeability, in rocks. In the case of hydrocarbon reservoirs, anisotropy can provide insight into the type of fluid (heavy or light API) that is present.

The anisotropy data obtained from seismic surveys can be used to calculate anisotropy attributes, such as intrinsic acoustic anisotropy, which can help to identify the presence of different fluids in the reservoir. These attributes can also be applied to calculate the direction of horizontal max stress, which is a crucial element in deciding the stability of the reservoir and fluid flue direction.

limestone province in the Potwar area, the presence of anisotropy can be used to predict the presence of heavy or light API hydrocarbons. For example, a high degree of intrinsic acoustic anisotropy in a limestone reservoir may suggest the existence of heavy API oil, while a low degree of anisotropy may suggest the existence of light API oil.

It's important to note that the prediction and delineation of hydrocarbon nature based on anisotropic data is just one of the many factors that must be considered in exploration of hydrocarbons. Other factors, such as rock type, porosity, with effective permeability, saturation of fluid, must also be considered to determine the overall quality and potential of a reservoir.

In conclusion, the use of anisotropy data in the prediction and delineation of the hydrocarbon nature in the limestone province in the Potwar area can provide valuable information for hydrocarbon exploration and production.

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Chapter -01

Introduction

Introduction

Seismic data is an important tool for hydrocarbon exploration and production. By analyzing the properties of seismic waves, can gain insights into the subsurface geology and fluid content of a reservoir. One important aspect of seismic data analysis is the measurement of anisotropy, which refers to the directional dependency of physical properties, such as elastic properties and fluid permeability in rocks. Several studies have been conducted to investigate anisotropy in seismic data analysis. For instance, Chakraborty et al. (2020) studied the anisotropy in fractured reservoirs and found that azimuthal anisotropy can be used to determine fracture density and orientation. Schleicher et al. (2017) analyzed seismic data from the Norwegian Sea and found that azimuthal anisotropy can provide important information about the structural properties of the subsurface

These studies demonstrate the importance of anisotropy in seismic data analysis for understanding the subsurface geology and fluid content of a reservoir as role of the azimuthal anisotropic data interpretation by H. B., Campagna (1999).
Anisotropy can provide valuable information for hydrocarbon exploration and production. For example, it can help to identify the type of fluid (heavy or light API) that is present in a reservoir and to determine the direction of fluid flow. Additionally, anisotropy can be used to determine where the most horizontal stress is likely to be, therefore playing a key role in determining the stability of a reservoir.

Focus of this study is on the use of anisotropic attribute analysis for seismic data in the prediction and delineation of the hydrocarbon nature (heavy or light API) in a limestone province of the Potwar area. Anisotropic attribute analysis involves the calculation of attributes such as, intrinsic acoustic anisotropy, from the seismic data. These attributes can provide insight into the presence and distribution of different fluids in the reservoir. This thesis seeks to investigate the potential in anisotropic attribute analysis for the prediction and delineation of the hydrocarbon nature in the limestone province in the Potwar area.

By understanding the relationships between anisotropy and fluid content, we aim to provide valuable input for hydrocarbon exploration and production efforts in the region.

Intrinsic acoustic anisotropy was calculated using a combination of seismic data processing techniques, such as analysis of velocity, NMO, and PSTM. The resulting intrinsic acoustic anisotropy (velocity slowness, fastness, percentile anisotropic dataset) maps were then used to predict and delineate the hydrocarbon nature (heavy or light API) in the limestone province in the Potwar area.

The intrinsic acoustic anisotropy maps showed clear variations in anisotropy that were related to the presence of different fluids in the reservoir. Xu et al. (2021) investigated the effect of fluid saturation on the seismic anisotropy in tight gas reservoirs and found that fluid saturation can significantly affect the anisotropy parameters.

Hydrocarbon exploration in limestone reservoirs demands a comprehensive understanding of the reservoir's inherent properties. This study delves into the significance of acoustic anisotropy as a key parameter for characterizing hydrocarbon deposits in the Potwar area. The investigation aims to provide essential insights that can be utilized to enhance exploration and production efforts in this geological setting.

High inherent acoustic anisotropy values were observed in areas where heavy API hydrocarbons were present, while the low inherent acoustic anisotropy values were observed in areas where light API hydrocarbons were present. The results also showed that the direction of maximum intrinsic acoustic anisotropy was related to the reservoir's fluid flow path.
This will provide input for hydrocarbon exploration and production efforts in the limestone province in the Potwar area.

The information on the presence and distribution of heavy and light API hydrocarbons can be used to optimize well placement, production strategies, and overall exploration and production efforts in the region. This integrated approach will result into let over hydrocarbons extraction in the matured basins like Potwar and Kohat in the upper Indus basin.

1.1 Exploration History & Overview

The Karsal Anticline is a geological structure located in the Potwar Basin, a sedimentary basin in northern Pakistan. There has been much study of the Potwar Basin, late 19th century, and the Karsal Anticline has been a focus of exploration and development efforts due to its potential to find gas and oil deposits.

Exploration in the Karsal Anticline began in the early 20th century, when the first well was drilled in the area. During the next several decades, several more wells were drilled in the area, but it wasn't until the 1960s and 1970s that exploration activities in the Potwar Basin really took off. Late in the 1970s and early in the 1980s, several significant oil & gas discoveries were made in the Karsal Anticline, including the Karsal Field as shown in table 1.

Since then, the Karsal Anticline has been the subject of continued exploration and development efforts. Major oil and gas companies, such as POL, OGDCL, and PPL, have all conducted exploration and production activities in the area. Karsal EL, covering an area of 724.42 Sq. km, is in district Chakwal of Punjab, Pakistan (Figure 1.1). The block lies in the prolific oil and gas Potwar province of Upper Indus Basin where Eocene carbonates and Cambrian clastics are the major hydrocarbon reservoirs with production mainly attributed to fractures.

The Eocene reservoirs consist predominantly of limestone interbedded with shale and marl. Previous operators in the Karsal EL drilled four wells from 1955 – 1960 out of which two wells, Karsal-1 and Karsal-3, produced oil, reportedly of 26 API, but with no production observed from the other two wells, possibly due to poor development of or alignment to fractures. PPL drilled Talagang X-1 well in 2018 after acquisition and interpretation of a high fold ~250 Sq. Km 3D seismic data across the Karsal structure. During a barefoot well test conducted in the Talagang X-1, about 313 bbl/d flow of about 14 API oil marked the discovery in the fractured limestone of Eocene Sakesar Formation.

The Karsal Anticline has proven to be a rich source of oil and gas, and its exploration history reflects the ongoing efforts to unlock its full potential. Advances in seismic imaging and drilling technology have made it possible to better understand the subsurface structure of the

The investigation of the Karsal Anticline aims to pinpoint new potential reserves and assess the subsurface prospect-oriented reservoirs. The geometrical configuration of the Talagang X-1 within the Karsal area is elucidated in the stacked map presented in Figure 1.2.

Delving into the exploration history of the Karsal Anticline in the Potwar Basin reveals a continuous commitment to unraveling the extensive potential harbored within this geologically intricate region. The persistent efforts underscore the significance of ongoing exploration endeavors, reflecting a dedication to comprehensively understand and tap into the rich geological resources concealed within the folds of the Karsal Anticline. The exploration history serves as a testament to the continual pursuit of uncovering and optimizing the substantial reservoirs that lie beneath the surface, contributing to the broader understanding of the geological dynamics in the Potwar Basin.

Well Name	Operator (Date)	Status	TD (Formation)	Target (s)	Comments
Karsal-01	POL (1955)	Oil	3886 (Amb)	Chorgali & Sakesar	Oil discovery from Eocene carbonates
Karsal-02	POL (1957)	P&A	3868 (Hangu)	Chorgali & Sakesar	Testing results of Chorgali & Sakesar Formations were discourging.
Karsal-03	POL (1959)	Oil	3555 (Sakesar)	Chorgali & Sakesar	Oil discovery from Eocene carbonates
Karsal-04	POL (1960)	P&A	3725 (Chhidru)	Chorgali & Sakesar	Testing results of Chorgali & Sakesar Formations were discourging.
Balkassar-1A	POL (1945)	Oil	2559 (Sakesar)	Chorgali & Sakesar	Oil discovery from Eocene carbonates
Kot Sarang-01	OGDCL (1966)	Oil	4153 (Wargal)	Eocene & Plaeocene carbonates	Lockhart flowed 421bopd & 0.717 MMScfd of gas, but flow declined rapidly.
Kot Sarang-02	OGDCL (1985)	P&A	4338 (Sardhai)	Eocene & Plaeocene carbonates	During testing, Sakesar & Lockhart were tight while Amb & Wargal were water wet.
Sarang X-1	PPL (2006)	P&A	4775 (Khewra)	Eocene & Plaeocene carbonates	Chorgali, Sakesar, Nammal, Warcha & Tobra Fmns were tested but well abandoned due to discourging testing results.
Balkassar Oxy-1	OXY (1981)	P&A	3130 (Salt Range)	Permian & Cambrian	Chorgali, sakesar & Lockhart / Patala were tested. Eocene carbonates flowed oil, but productivity was verly low. Paleocene carbonates did not flow
Jhatla-1P	POL (1955)	P&A	1995 (Sakesar)	Chorgali & Sakesar	Chorgali/Sakesar flowed saline water @ 55 bpd with traces of black viscous oil
Dhermund-01	OGDCL (1978)	P&A	4331 (Salt Range)	Eocene, Jurassic, Permian &	Sakesar, Lockhart, Amb & Khewra fms were tested. Only Sakesar Fm flowed hydrocarbons, but flow was inconsistent and productivity was very low
Kalar Kahar-01	POL (1957)	P&A	2173 (Salt Range)	Eocene & Cambrian	Chorgali/Sakesar flowed saline water with traces of tarry oil

Table 1: Different hydrocarbon wells drilled in the study Area.

1.2 Objectives

- Need to determine whether the open fracture network of limestone as Hydrocarbon flow is primarily controlled by presence of open fractures. Not all the fractures help to flow the well
- Study the geology and stratigraphy of the area and understanding the flow of hydrocarbon without the presence of the structure types.
- Building anisotropic data approach and integration to understand the limestone nature and response of seismic amplitude model for true penetration of open fractures. Stress orientation of the surface structure and its integration with drilled sub-surface anomalies. Relationship between amplitude and the hydrocarbons flowed to surface API.

1.3 Study Area

Study area, covering an area of 724.42 Sq. Km, is located in district Chakwal, Punjab, Pakistan. Geologically, the study location is located in the Potwar sub-central basin's region, a proven hydrocarbon province in upper Indus basin (Figure 1.1). Eocene carbonates (Chorgali and Sakesar) are mainly producing reservoirs in different fields in the vicinity of study area. Four wells were drilled on a surface anticline in study area from 1955 – 1960 out of which two (Karsal-1 and Karsal-3) had delivered liquid Hydrocarbons.

But other two (Karsal-2 and Karsal-4) did not produce. Seismic with integrations of available geological tools are commonly used today by an explorationist to address uncertainties and mitigate risks in an area of investigation. Reservoir composite prospect-oriented maps model from top chorgali to last sedimentary reservoir khewra with well trajectory shows the Talagang X-1 way of drilling while encountering multiple reservoirs through single well as depicted in figure 1.2.

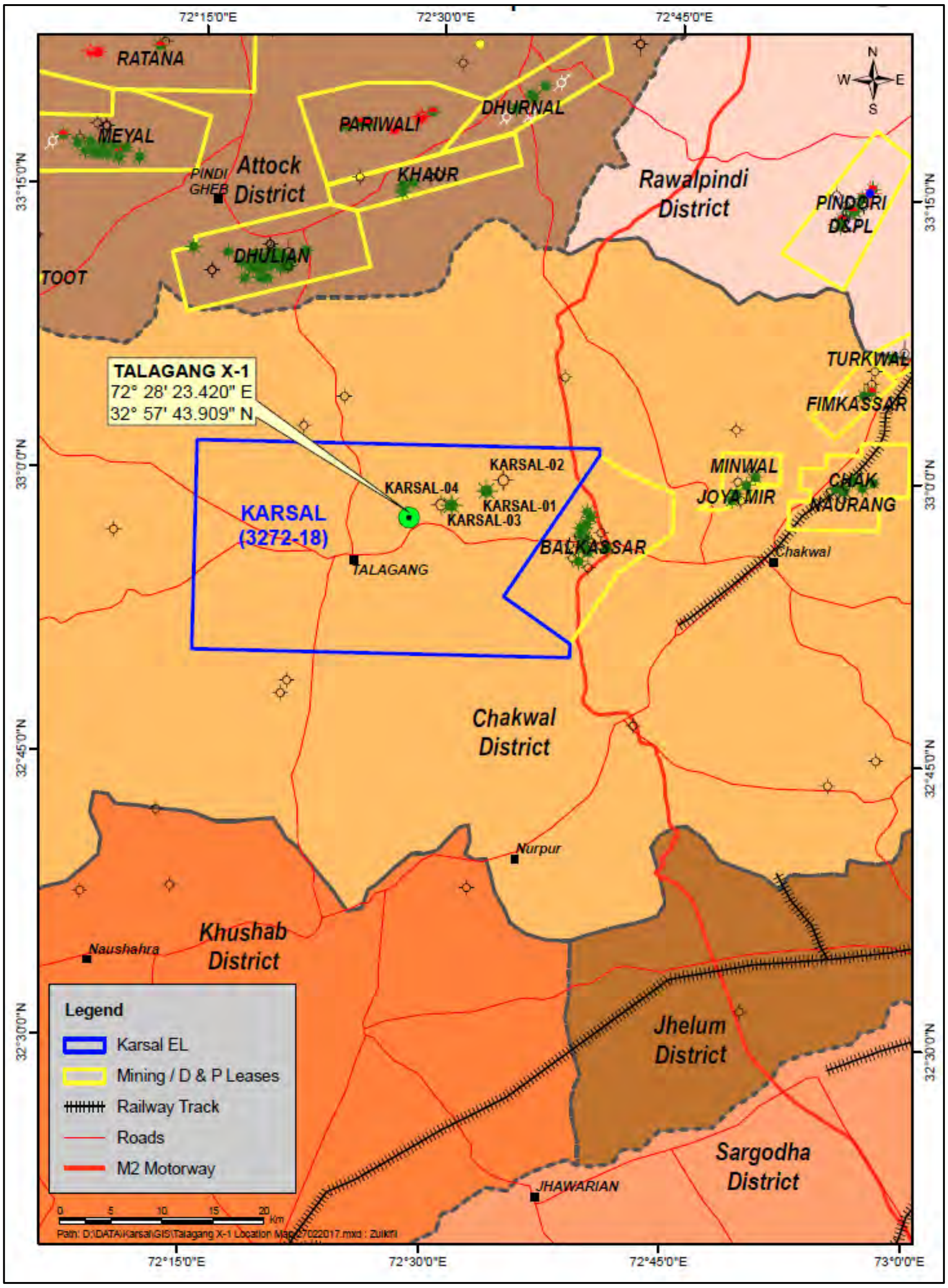

Figure 1.1: Map of the Karsal Study Region, wells and surrounding fields Punjab, Pakistan.

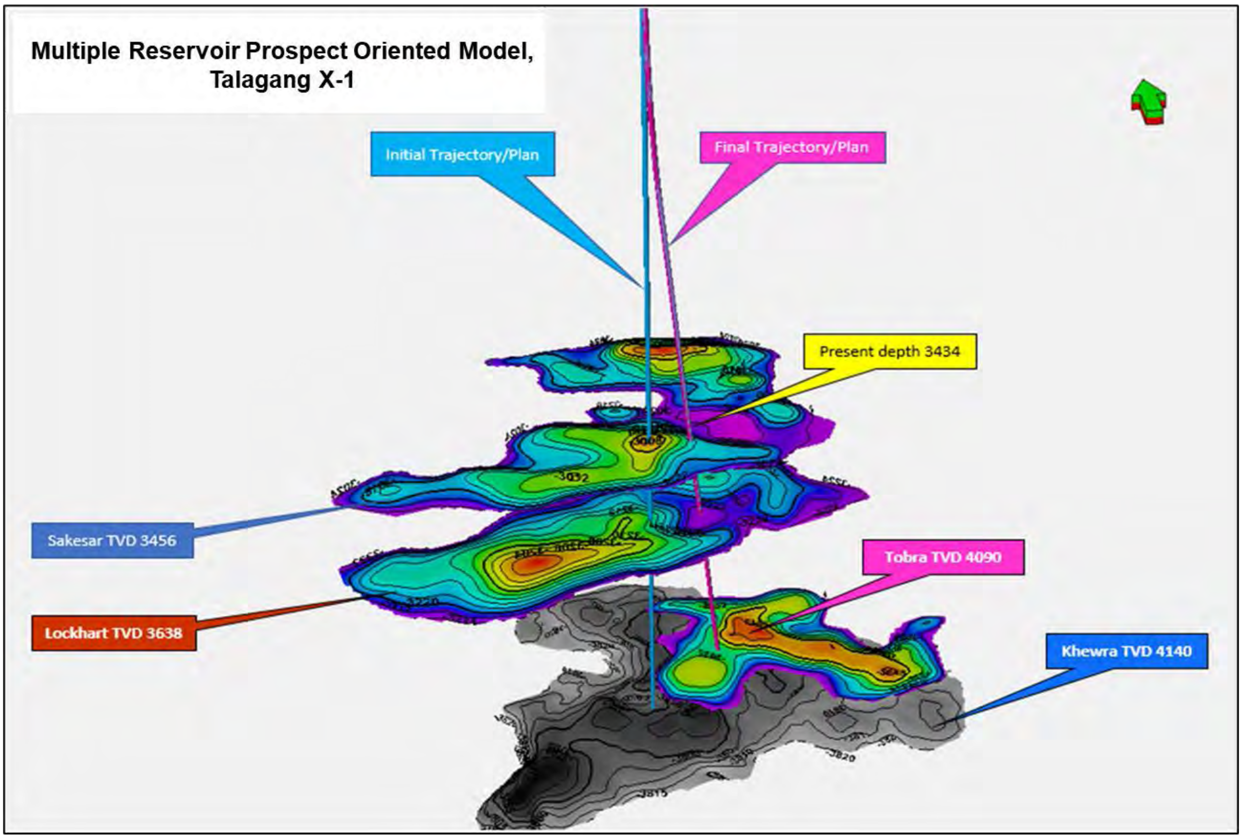

Figure 1.2: Reservoir model of Karsal study area combined reservoir composite prospect-oriented maps model from top chorgali to last sedimentary reservoir Khewra well trajectory shoes the Talagang X-1 way of drilling while encountering multiple reservoir through single well.

1.4 Seismic Data Set

The data used for current research consists of 2D & 3D seismic data set from PSTM, PSDM, RTM versions along with several wells (named in the next section). The base map depicting the seismic lines and wells in the area is given in figure 1.3. Keeping in view the nature of the play, a comprehensive 3D design study was conducted enabling us to experiment with various fracture related attributes with greater confidence. Therefore, high resolution wide azimuth survey design was selected for the data recording. 250 Sq km 272-fold data was acquired with the parameters given in table 2. This design has the required wide azimuth trace distribution for OVT (Offset Vector Tile) gathers and migration. By using the OVT migration we can preserve the azimuthal related velocity information that were utilized for azimuthal velocity analysis. Based on azimuthal velocity analysis it becomes possible to control other fractures related attributes like coherency and ant tracking. The

3D seismic data when loaded into the system its slice view actually shows the contours value in the Z-scale as reflected the amplitude behaviors along the wells drilled already and amplitude snaps as shown in figure 1.4

Vibrator	Channels	RLI (m)	RI (m)	SLI (m)	SI (m)	Bin size (m)	Fold	Aspect ratio	Maximum Offset (m)
4 Sweep, 20 sec, 8-80hz	5440	250	50	250	50	25x25	272	1.06	5801

Table 2: Seismic 3D acquisition parameters selected after comprehensive designing study and used during the data acquisition in Karsal block

1.5 Information of Wells:

List of the wells hat are used in the thesis are listed below which were drilled for the oil and gas The wells are oil and gas and has been drilled up to the pre-Cambrian formation. Talagang X-1 Sarang X-1 data mostly used for the modeling and well failure analysis.

- KARSAL-1
- KARSAL-2
- KARSAL-3
- KARSAL-4
- TALAGNG X-1
- KOT SARANG X-1
- SARANG X-1

1.6 Data Formats

A format is a set structure for material. A computer software receives data in a specific format as input, processes it, and outputs the results in the same format or another. Data about were included in the data set that was widely used to prepare this dissertation.

- SEG-Y
- LAS
- Navigation
- DFN SET

1.7 Base Map for the Research Area

A base map is a map that can be used to plot source data and interpretations. Shot point maps, which display the orientations of seismic lines and the precise locations at which seismic data were collected, are frequently used by geophysicists to display the interpretation of seismic data. Well locations, seismic survey locations, and other cultural statistics are included, along with geographic coordinates like latitude and longitude. The region's basic map is created by plotting data in the geodetic reference system known as the Universal Transverse Mercator (UTM, Zone 42), Z-Slice view also represent the amplitude behavior over the drilled wells as highlighted in figure 1.3

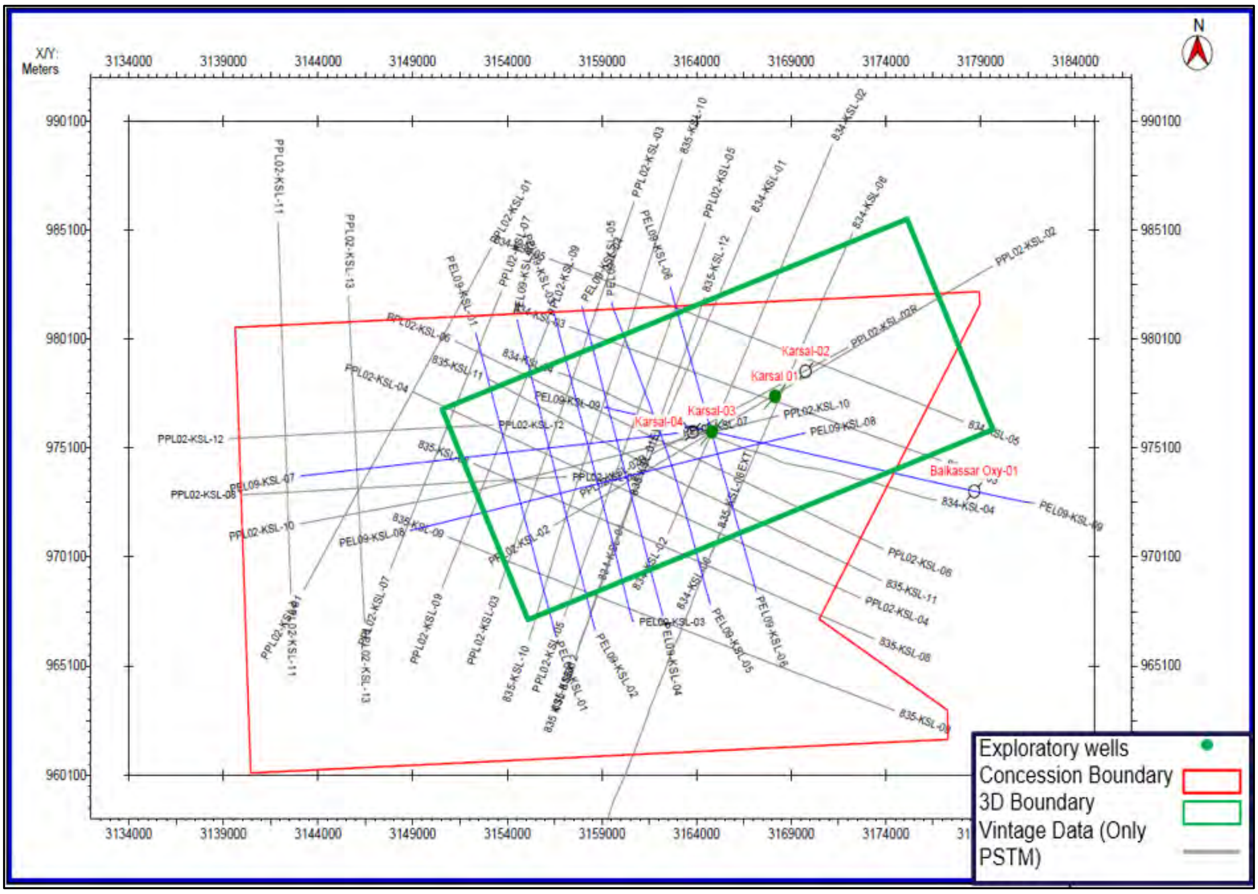

Figure 1.3: Base map area green color polygon is the 3D boundary and red color is the study area Karsal both PSTM and PSDM used along with key highlighted 2D lines.

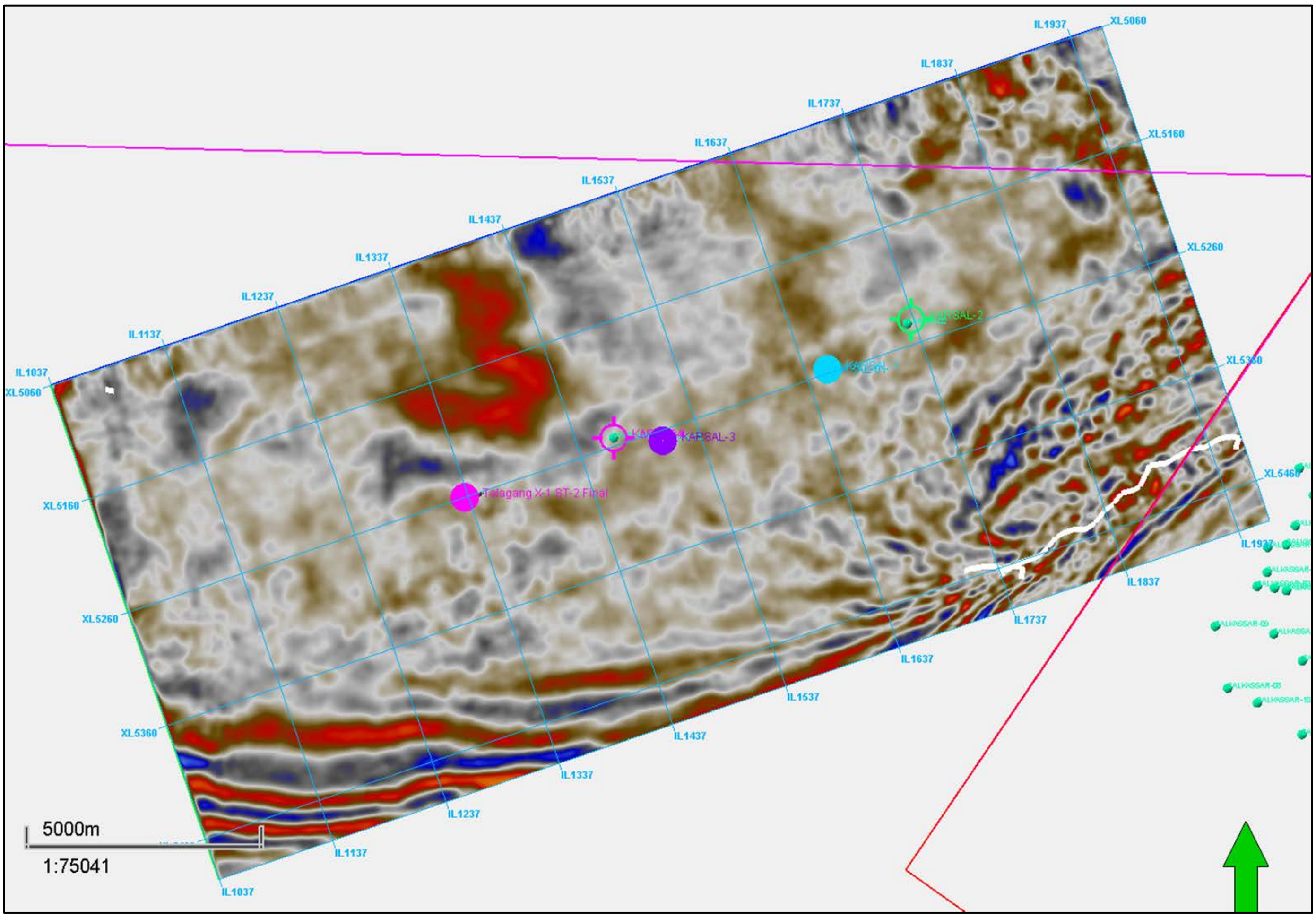

Figure 1.4: 3D data Z-Slice view of Base map for the area of interest Karsal Area.

1.8 Framework Technique

3D seismic data of karsal area which falls in the Potwar used in order to interpret the subsurface structures and other properties. In this practice, software Petrel 2022 has been used for structural interpretation. For this purpose, seismic 3D cube was uploaded in Petrel, creation of the synthetic seismogram was done, using Sarang X-1 data. After those faults and horizon were marked on seismic section, polygons were developed, and time and depth contours were made. Attribute analysis was performed to confirm the interpretation for the identification of the hydrocarbon bearing zones. Seismic and anisotropic data were loaded and interpreted in the Geoteric software. This information has particular relevance in unconventional reservoirs, such as the Bakken Shale Formation, where pre-knowledge of the in-situ stress field and of natural fracture orientations can be used to optimize the effectiveness of hydraulic fracturing and maxi-mize hydrocarbon production (Besler et al., 2007).

Theoretically, seismic based fracture identification has been difficult to image due to limitation of seismic resolution. However, there are some indirect methods to identify the seismic and sub-seismic fractures which contribute to hydrocarbon production from carbonates reservoir rocks. Both pre-& post-stack attributes are available in order to locate the fracture prone zone with relatively high confidence. In pre-stack domain, azimuthal velocity analysis was useful to highlight the fracture zones based on difference of fast and slow velocity in different azimuth (Figure 1.5). In post-stack domain coherency and ant tracking help us to locate any discontinuity of seismic events which is indicative of fractures Sayers, C. M., & Kachanov, M. (1991).

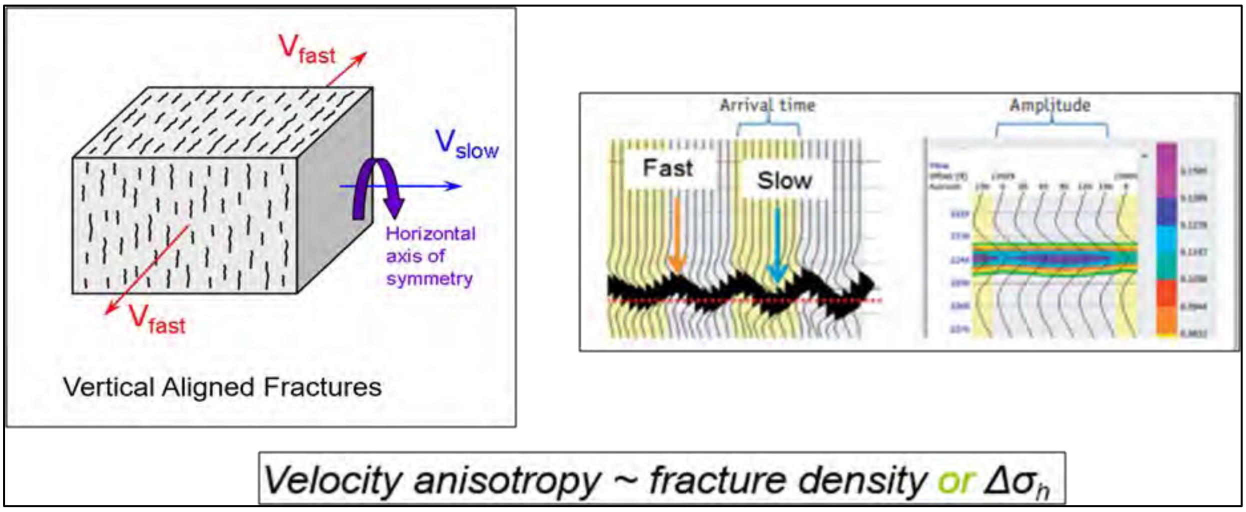

Figure 1.5: Concept of Velocity Anisotropy: Waves velocity is fast along the fractures and slow perpendicular to fracturs.

1.9 Software Tools and Applications

The following software tools have been used for interpretation, analysis and workflows carried out in this thesis.

1.9.1 Petrel 2022

- Synthetic Seismogram , Structural Interpretation , Stratigraphic Interpretation Well Correlation
- **1.9.2 Geoteric Attribute Analysis**
- Anisotropic Data Analysis
- 3D visualization

Chapter -02

Geology and Stratigraphy of Karsal Area of Interest

2.1 Geological overview of Karsal Area

Karsal lies in the Potwar Basin which is northern Pakistan and is characterized by a complex geological history. This region is part of the Himalayan Mountain range & has experienced tectonic activity, including the collision of the Eurasian and Indian plates tectonics, which has uplift and folding in subsurface rocks. Limestones, dolomites, sandstones, shales, and other sedimentary materials make up most of the subsurface geology in the Karsal region. These rocks were settled in a variety of environments, including shallow marine, deltaic, and fluvial environments, and have since been deformed and uplifted due to tectonic activity.

The subsurface rocks in the Karsal area have been grouped into several formations, including the Chorgali Fm, the Sakesar Fm, the Murree Fm, and the Taxila Formation, among others. Formations are composed of interbedded sandstones, shales, limestones, and dolomites, and have been dated to the Eocene to Oligocene, approximately 56 to 23 million years ago. The Karsal area is also characterized by several structural features, including anticlines and synclines as shown in the figure 2.1, which are folds in the subsurface rocks that have been created by tectonic compression. These structural features are important in the exploration and production of hydrocarbons because they can create structural traps that can retain subsurface resources, such as oil and gas.

The study area of Karsal is characterized by a complex geological history and a subsurface geology that is primarily composed of sedimentary rocks that were deposited in a variety of environments and have since been deformed and uplifted due to tectonic activity. The area is also characterized by several structural features, including anticlines and synclines, which are important in the exploration and production of hydrocarbons. The Karsal Block lies in the center of the Potwar basin (Figure-2.1).

The outcrops of Dhok Pathan and Nagri formations of Pliocene age rocks lie the area whereas Tertiary (Eocene and Paleocene), Mesozoic and Permian rocks are exposed southward in the Salt Range. The essential tectonic features of Potwar sub-basin are associated with different events in the geological past mainly due to plate movements during Paleozoic to present. Impact of Himalayan orogeny of middle to late Tertiary time had been significant that contributed to the emergence of NE to SW trending surface anticlines and subsequent compressional stresses give rise the regional faults such as Muree Boundary Thrust (MBT) in the northern side and Salt Rang in the south. Area under investigation lies on the southern flank of the Soan depression in the Potwar Plateau. Near the study area, oil bearing traps are mainly Balkassar and Dhulian oilfields type anticlines or three-way fault bounded. The stratigraphic-structural trap was also found such as entrapped oil in channel sands of Murree Formation, in Khaur field, within the anticline. A stratigraphic pinch out was also observed in Dhulian field in Datta Formation, sandstone of Jurassic age (Khan & Hasany 1998). Reservoir rocks are distributed in carbonates of Paleocene and Eocene whereas clastics and carbonates of Paleozoic and Jurassic sands. Regionally, the source rock is Paleogene shales and carbonates (Figure 2.1, Table 4. The areas to the south and north of Soan syncline is a prolific area for hydrocarbon generation and entrapment. North Potwar Deformed Zone (NPDZ) hosts several larger oilfields. The source rock analysis of Talagang X-1 (PPL) confirms the source potential in Sakesar, Nammal and Patala formations with early oil generation thermal maturity (Table 4).

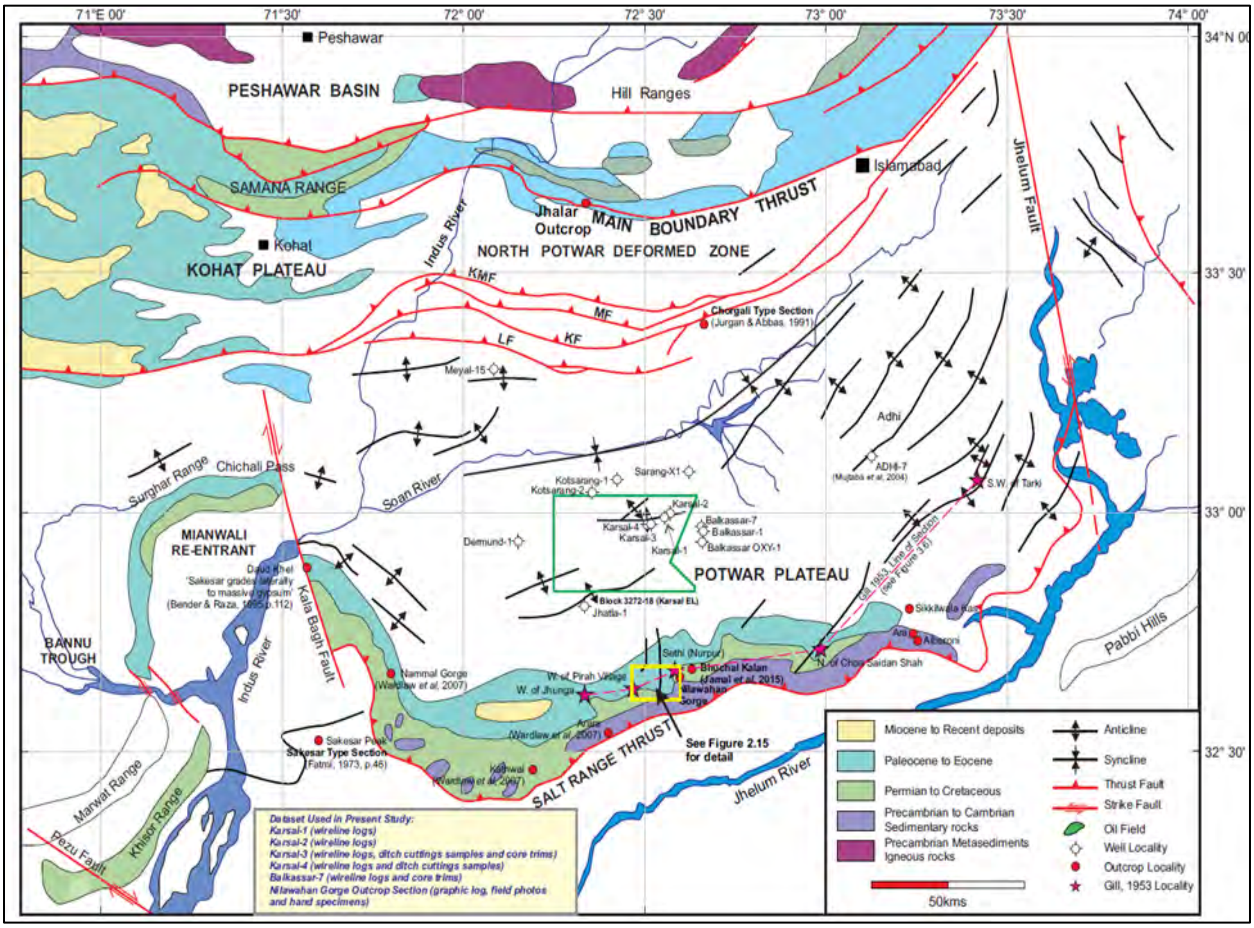

Figure 2.1: Geological & Structural map of Potwar Basin with location of the project area, (Afzal & Jurgan 2015).

2.2 Tectonic & Stress Analysis of study area

In the majority of instances, the trends of fractures exhibit an oblique alignment in relation to the direction of maximum horizontal stress. Nevertheless, there are instances, as illustrated in Figure 2.2, where fractures develop parallel to the maximum stress direction. The spatial relationship of boreholes concerning geological structures and lithological characteristics can significantly impact the development of breakout and induced fractures due to localized variations in stress conditions.

Hence, it becomes imperative to enhance the density of available data, incorporating additional well points equipped with Formation Micro-Imager (FMI) and core data, among other relevant information. Additionally, the integration of seismic data, preferably in three dimensions (3D), becomes crucial for a comprehensive establishment and understanding of the fracture network. This comprehensive approach, combining various data sources, aims to capture the intricacies of fracture development influenced by both regional and local geological factors. Such a data-rich methodology ensures a more accurate and nuanced comprehension of the fracture system, facilitating a robust foundation for further analysis and interpretation.

The predominant orientation of maximum stress in the Central and Eastern Potwar region is identified as being NW-SE, while in the western part, specifically in Dhok Sultan EL, the stress is primarily oriented in the N-S to NNE-SSW direction. Furthermore, in the Mela area, the maximum stress direction is noted to be NE-SW, and this shifts to a NW-SE orientation in the Makori Field within the Kohat basin, as depicted in Figure 2.3. The localized variations in stress orientation observed in Mela are thought to be influenced by the presence of the Kalabagh strike-slip fault, as illustrated in Figure 2.3.

It is noteworthy that the determination of stress orientations, inferred from breakout and induced fractures, finds additional support through alignment with regional structural trends and maps. This coherence between local observations and broader structural patterns enhances the reliability and robustness of the identified stress orientations in the study area. The intricate interplay between localized geological features, such as the Kalabagh strike-slip fault, and broader regional tectonic dynamics contributes to the nuanced variations observed in stress orientations across different locations, offering valuable insights into the complex geological processes shaping the Potwar region.

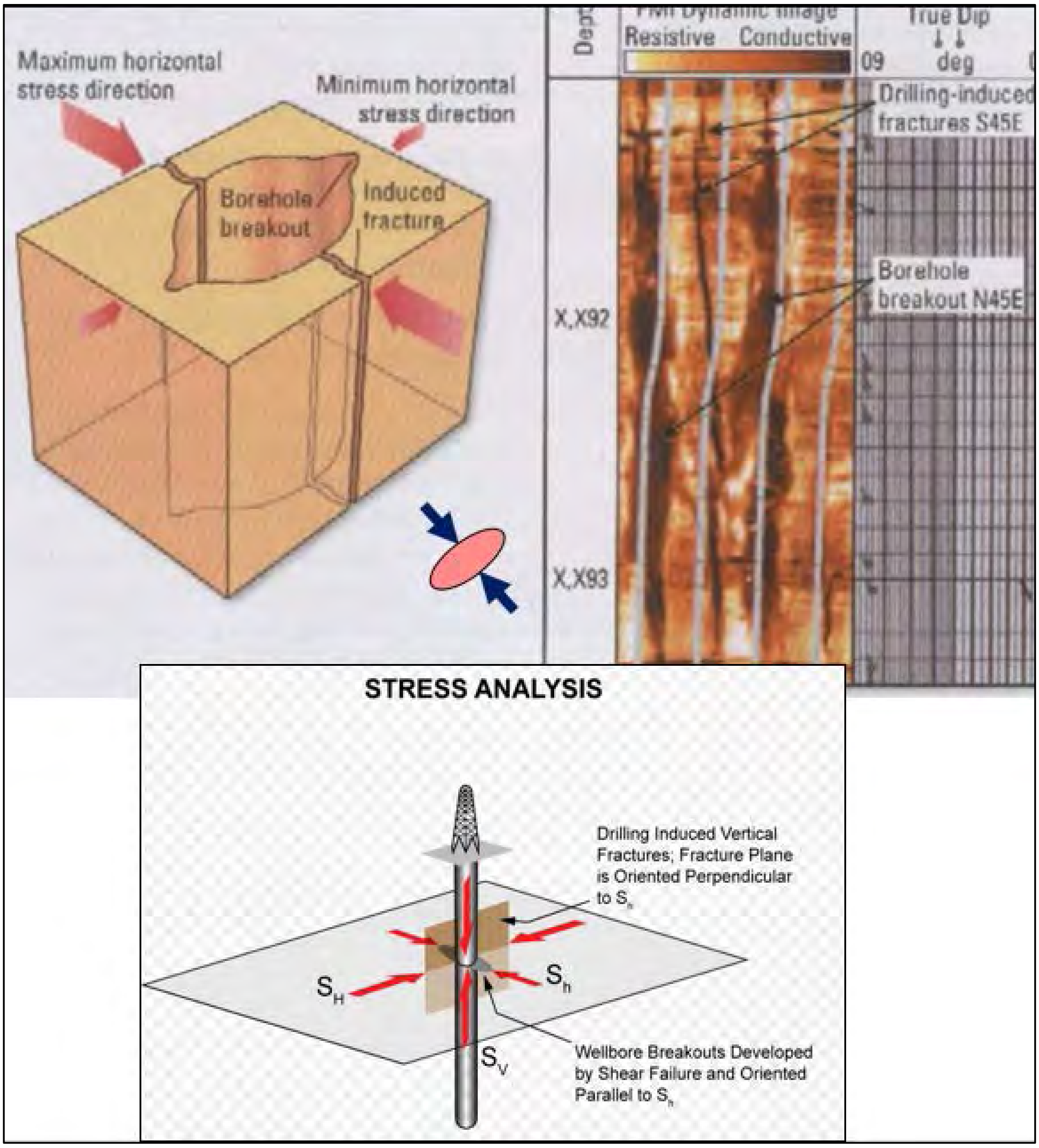

Figure 2.2: The direction of the maximum tension is shown by the minimum diameter, and the direction of the minimum stress is shown by the maximum diameter (Pakistan Basin study, 2009).

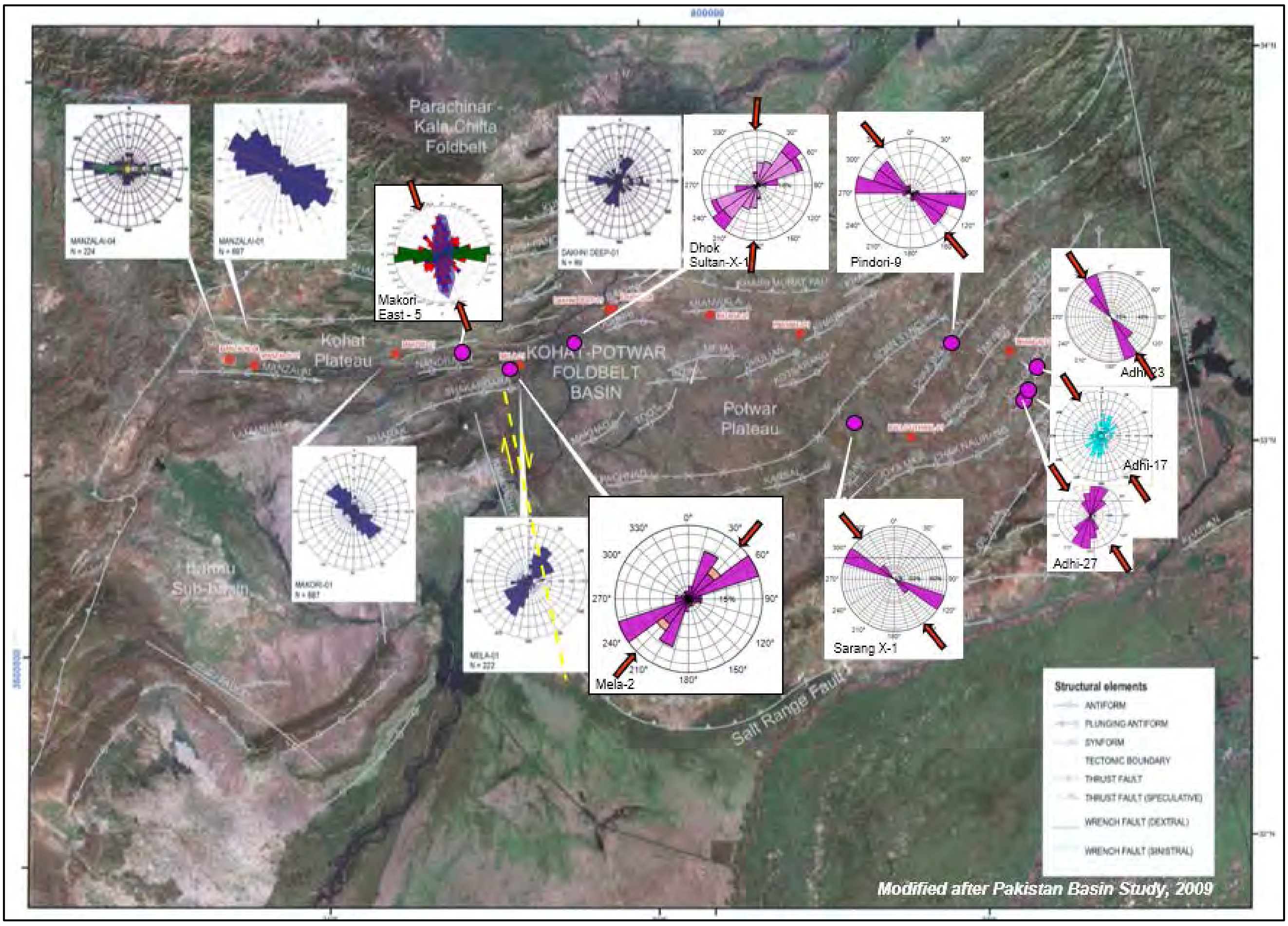

Figure 2.3: Open / Conductive Fracture Strike and Max. Stress Orientation (after Pakistan Basin Study, 2009) surface imagery google earth is overlaid by the tectonic features along with the stress orientation at some specific geological imported locations over the wells drilled in the Potwar basin. Data taken from the Pakistan Basin study geological symbols and the majors thrust represented in the right-side legend.

2.3 Structuration of Karsal Area

In the present-day geological setting, the Karsal Block (33’72') lies within the Upper Indus Basin of northern Pakistan also known as Potwar Plateau. The area carries a special importance due to first oil discovery at Khaur in 1914. The Karsal Field was discovered in 1955. The Potwar Plateau's structural history dates to the Eocene Himalayan impact between the Indian and Asian plates, which produced several foreland basins in Pakistan and India, including the Potwar Plateau (Acharyya 2007). The effects in early Eocene docking with India & Asia has been preserved in the stratigraphic record of the Potwar Plateau. The head-on collision in Miocene/Pleistocene resulted into structural deformation. An area of fold and thrust known as the Northern Potwar Deformation Zone (NPDZ after Jaswal et al. 1997) borders the Sawan Syncline, the major component of the Potwar Plateau, in the north; to the south by the Salt Range the Jehlum Fault to the east, and the Kalabagh Fault and Indus River to the west (Figure 2.3). The Indian Shield, the severely deformed Kirthar Foldbelt, and the Sulaiman Lobe define the eastern and western boundaries of this tectonic province, respectively.

The province is characterized by a wide, gently westerly dipping monocline that is cut by several intrabasinal highs and lows. The Potwar Plateau's location on a chart, along with the Indian Plate. Major structural; trends with respect to contour shape along with sakaesar drilled in the Potwar basin some examples of the wells with depth is mentioned in the tag above in the picture which relate that low relief structuration is mostly linked with heavy oil or low API figure 2.4.

The Eocene era is depicted. The primary tectonic event is thought to have been the rifting of the Indian plate from Gondwanaland in the early Cretaceous, which determined the lower Indus basin's structure and sedimentology. The study region, which is located in the southern Indus Basin, exhibits extensional tectonics and normal faults with horst and graben formations. The Indian plate began to rift from Gondwanaland, which led to the development of NE-SW to N-S rift networks.

At the beginning of the Cretaceous, uplift and an eastward tilting may have been caused by isostatic uplift at the edge of the freshly formed ocean, separation of Madagascar plate from Indian Plate might have caused the creation of sinistral strike slip fault in the region along with the hotspot activity and thermal doming at Cretaceous-Tertiary boundary. Along with the hotspot activity and thermal doming at the Cretaceous-Tertiary boundary, the split of the Indian Plate from the Madagascar Plate may have resulted in the formation of the sinistral strike slip fault in the area.The corresponding occurrence caused Deccan flood basalts to be uplifted, eroded, and extruded with NW-SE striking normal faults (Powell, 1979). On the west-dipping Indus Plain, a typical block faulting caused the construction. The fluids from the underlying Shaly source sequence move along the fault lines. Utilizing all available seismic data and well information, fault trends and outlines are mapped in the field (Powell, 1979).

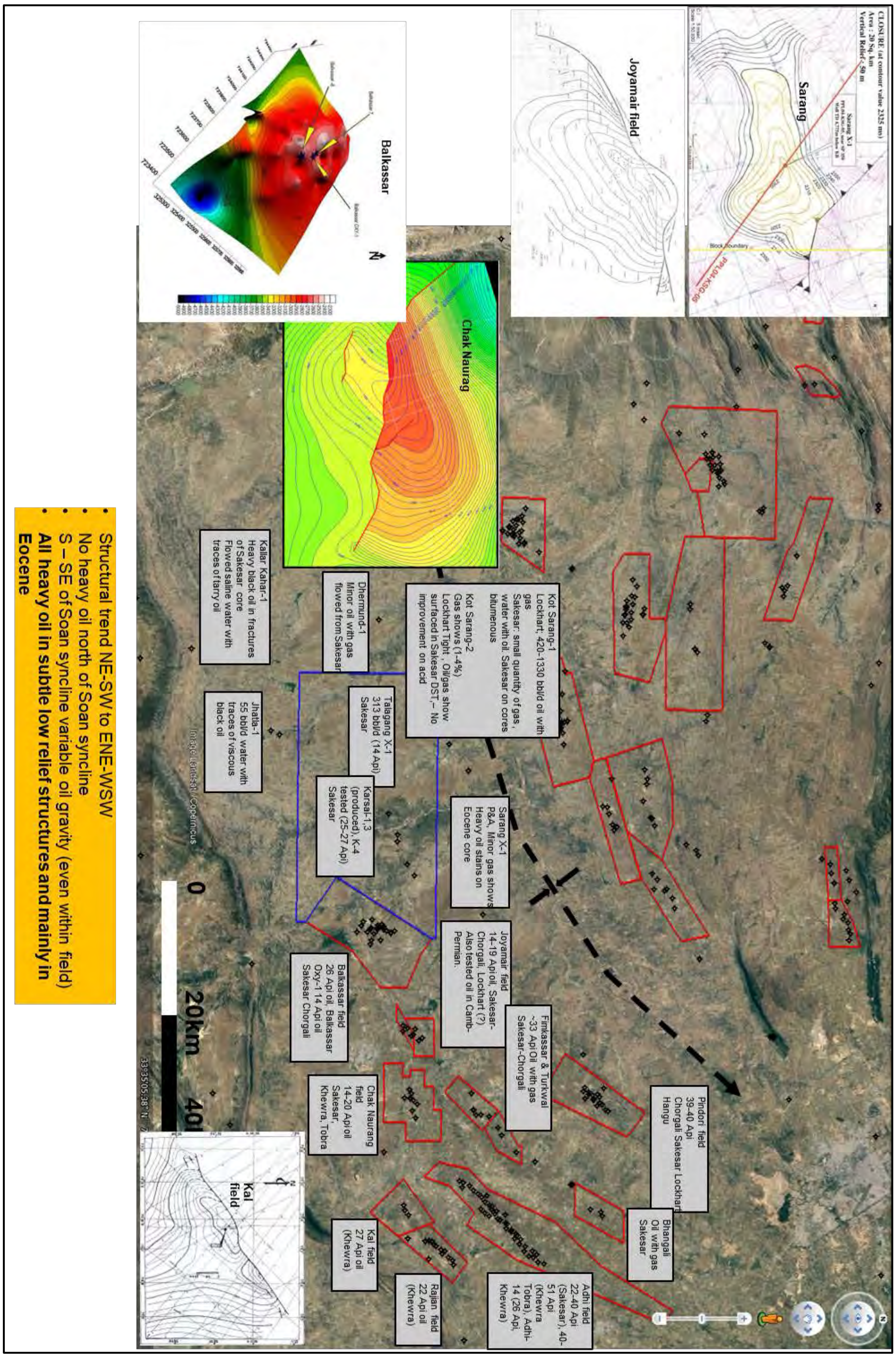

Figure 2.4: Structural setting of Potwar sub-basin source PPL inhouse working for Potwar Basin, 2019.

2.4 Depositional Model

The Sakesar Formation is believed to have been placed in a shallow marine rich environment, such as a shallow shelf or lagoon. The limestone in the Sakesar Formation was likely deposited as bioclastic deposits, including shells and other marine fossils, as well as peloidal and ovoidal grain stones. The presence of these sedimentary structures suggests that the depositional environment was relatively figure-2.5, with limited water energy and a high rate of sedimentation.

The Chorgali and Sakesar formations in the Karsal region were produced, according to their respective depositional models, in fluvial-deltaic and shallow marine environments. Understanding the depositional environment and sedimentology of these formations is important for interpreting the subsurface geology and for exploring the potential of these formations for oil and gas reservoirs.

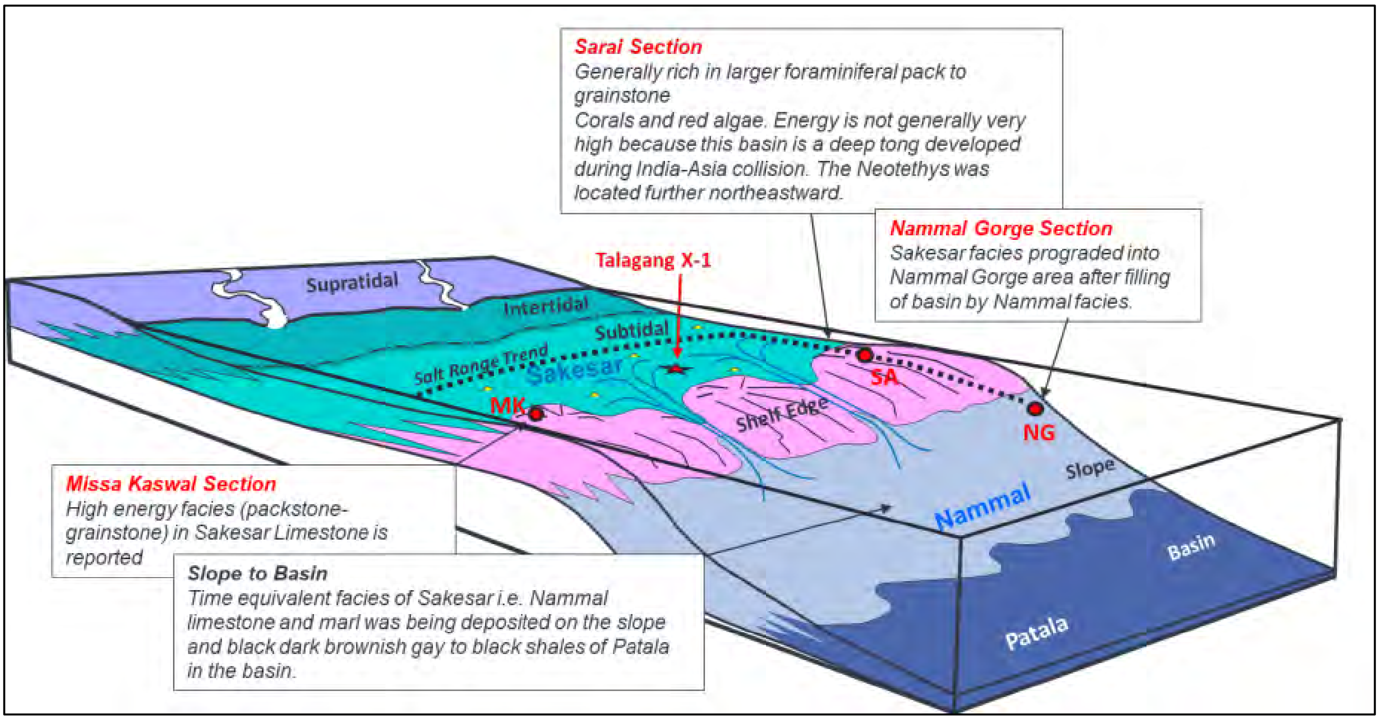

Figure 2.5: Depositional model of the Sakesar formation (a rimmed platform) as depicted based on study of inhouse depositional model by PPL

2.5 Petroleum Play Concept of Karsal

Petroleum system is a geological concept that refers to all the elements and processes involved in the formation, accumulation, with migration, and preservation of hydrocarbons within sedimentary basin. It encompasses a variety of geological, geochemical, and geophysical factors that control the formation and accumulation of hydrocarbons in rock formations, as well as the migration and entrapment of those hydrocarbons into reservoir rocks. The main components of a petroleum play include,

Source rock: group of sediment that contains the organic matter that, over time and with the help of heat and pressure, is transformed into oil and gas.

Reservoir rock: A rock that contains oil or gas in sufficient quantities and of sufficient quality to be economically recoverable.

Seal rock: sediments group that acts as non-communication to the upward movement of oil and gas, preventing it from escaping from the reservoir rock.

Traps: Structural or stratigraphic features that prevent the upward movement of hydrocarbons, causing it to accumulate in the reservoir rock.

Maturation: The process of transforming organic matter in the source rock into oil and gas, which requires the right combination of heat and pressure over time. The study of petroleum systems is important for exploring and producing oil and gas resources, as it helps geologists understand the conditions that led to the formation of oil and gas deposits and predict where additional deposits may be found.

The Petroleum System of karsal is made up of a reservoir (Sakesar, Chorgali, Lockhart), a mature source rock route (Patala, Nammal), a trap, and a seal (Muree, Kamlial). For hydrocarbons to collect and be conserved, the processes of generation, migration, and accumulation must occur at the proper relative timing. Plays and prospects for exploration are usually created in basins or areas where a complete petroleum system has a chance of existing. (Kadri, 1995).

A play is defined as "a collection of geologically connected prospects having comparable source, reservoir, and trap characteristics (Kadri, 1995). The existence of play elements within a basin is crucial to the accumulation of hydrocarbons. The components of the petroleum system are a mature source rock, migration route, reservoir rock, trap, and seal, which were formed at the proper relative times in relation to one another and to the processes of generation. 52% of Pakistan's hydrocarbon production comes from the Upper Indus Basin, which is the country's primary hydrocarbon producing region.

2.5.1 Source Rock

Because of its organic richness in oil-prone kerogen and thermal maturity, the Patala Shales Formation has been demonstrated to be a source for oil and gas found in the Potwar Indus Basin. In Pakistan's Indus Basin, sedimentary rock known as the Patala Formation can be discovered there. The Patala Formation's lithology can differ, but sandstone, siltstone, and shale are usually its main constituents. The Patala Formation's sandstone is typically fine to medium-grained, well-sorted, and frequently exhibits cross-bedding and trough cross-bedding formations. The siltstone is frequently laminated or shows rippled bedding structures and is usually made of fine-grained silty sand. The Patala Formation's shale typically ranges in colour from dark grey to black and is distinguished by its clay-rich composition, poor permeability, and high organic content. H. A. Raza, 1992.

The Patala Formation is an important oil and gas-bearing formation in the Indus Basin, and its unique lithology has been used to help identify and map the presence of hydrocarbons in the subsurface. The presence of sandstone in the Patala Formation provides reservoir rock for oil and gas accumulation, while the shale acts as a source rock and provides seals to prevent hydrocarbons from escaping. The high organic content in the shale, combined with the right temperature and pressure conditions, helps to generate oil and gas over time. Where amorphous organic matter rich oil prone kerogen become dominant and can be regarded as “Potential source rock” (Thompson, 1984).

2.5.2 Reservoir Rock

The main goal in this region is to extract Sakesar and chorgali limestone, lockhart limestone, sandstone from the Tobra and Khewra formation, and limestone from the Potwar basin, especially in the research region. These sands and carbonates are known to be productive in the Potwar subbasin's neighbouring areas of Balkassar, Adhi, Joya Mir, Dhulia, and Khaur Karsal.

The Karsal Anticline, which is situated in the Potwar Basin of northern Pakistan, contains a sedimentary rock succession that includes the carbonate Eocene rocks of the Karsal region. Global temps during the Eocene, a geological epoch that spanned from roughly 56 to 33.9 million years ago, were warm and humid.

During the Eocene, the Karsal area was likely a shallow marine environment, where carbonates were deposited in the form of limestones and dolomites. These rocks were formed from the accumulation of calcium carbonate and magnesium carbonate, respectively, and are typically high in porosity and permeability, which makes them good reservoir rocks for hydrocarbons, Such as formally known as Eocene carbonate of chorgali and sakaesar in the Potwar province and responsible for the 80 % production of the discovered field.

The carbonate Eocene rocks in the Karsal area are part of a larger sequence of sedimentary rocks that have been deformed and uplifted over time due to the tectonic continents of Asia and Europe colliding. The folding and uplift of these rocks has created structural traps that are capable of retaining hydrocarbons and other subsurface resources.

Carbonate Eocene rocks of the Karsal area are an important part of the sedimentary rock sequence in the Karsal Anticline. These rocks were formed in a shallow marine environment and are characterized by high porosity (Chorgali 21 % porosity and permeability as fracture networks, corridors), which make them good reservoir rocks for hydrocarbons. The folding and uplift of these rocks has created structural traps that can retain subsurface resources.

2.5.3 Seal Rock

A thick stratigraphic sequence of shale, sand and marl of Maree Formation serve as cap rock for u The Murree Formation is a sedimentary rock formation that is present in the Karsal area and is considered to be an important seal rock for the subsurface hydrocarbon reservoirs. The Murree Formation is composed of interbedded mudstones, siltstones, and sandstones, and is typically characterized by low permeability and high clay content, which make it an effective seal rock.

The late Eocene to early Oligocene is when the Murree Formation was formed, approximately 33 to 23 million years ago, in a fluvial to deltaic environment. The formation has since been subjected to regional tectonic compression and folding, which has caused it to become an effective seal rock for the subsurface hydrocarbon reservoirs.

The presence of the Murree Formation as a seal rock is critical to the E& P efforts in the Karsal area. The formation acts as a barrier that prevents the migration of hydrocarbons out of their reservoir rocks and into overlying rocks. This helps to ensure that the hydrocarbons remain trapped in the subsurface, making them accessible for exploration and production.

A significant seal boulder in the Karsal region is the Murree Formation. Muree Fm low permeability and high clay content make it an effective barrier for preventing the migration of hydrocarbons out of their reservoir rocks. The presence of the Murree Formation as a seal rock is critical to the Exploration of oil and gas in Karsal region.

2.6 Stratigraphy of Study Area

The stratigraphic sequence in the Karsal Anticline area consists of a variety of sedimentary rocks that were deposited over millions of years and have been subjected to various geological processes, including deformation, erosion, and compaction (Figure 2.6, 2.7).

The region of the stratigraphic cycle in the Karsal Anticline is comprised of Precambrian basement rocks, which are thought to be between 600 and 900 million years old. These rocks are composed primarily of granitic gneiss and other metamorphic rocks and form the foundation upon which the overlying sedimentary rocks have been deposited.

Overlying the Precambrian basement rocks is a sequence of Paleozoic and Mesozoic sedimentary rocks, including sandstones, shales, limestones, and dolomites. These rocks were deposited in a variety of environments, including shallow marine, deltaic, and fluvial settings. The upper part of the stratigraphic sequence in the Karsal Anticline area is comprised of Tertiary and Quaternary sedimentary rocks, including conglomerates, sandstones, and mudstones. These rocks were deposited in a variety of environments, including alluvial, fluvial, and deltaic settings.
The Karsal Anticline is a result due to compaction and sedimentary rocks deformation in the area, triggered by the tectonic plates of India and Europe colliding. Folding & uplift of the rock layers has created structural traps that can retain hydrocarbons and other subsurface resources. The stratigraphic sequence of the Karsal Anticline area provides a complex and diverse geologic history that has contributed to the formation of subsurface traps and other geological features that are of interest to exploration and production companies.

The comprehensive stratigraphic overview of the Potwar Basin encompasses sedimentary sequences ranging from the Precambrian to the Quaternary period, as depicted in Figure 2.6. Within this geological framework, the Chorgali and Sakesar formations emerge as the focal points of exploration, with particular emphasis on their significance in the area.

While the Lockhart formation is recognized as an important reservoir, noteworthy for its potential, it has not exhibited oil production in the Karsal and neighboring Balkassar field. This observation underscores the nuanced nature of reservoir characteristics within this geological setting.

Moreover, the Sakesar, Nammal, and Patala formations, along with those in the Salt Range, are acknowledged for their source potential, contributing to the hydrocarbon richness of the region. The presence of a substantial clay layer from the Murree Formation serves as a robust seal over the Eocene carbonate, ensuring geological integrity and sealing properties crucial for hydrocarbon containment. This stratigraphic insight provides a foundational understanding of the diverse formations present in the Potwar Basin, aiding in the targeted exploration and exploitation of its geological resources.

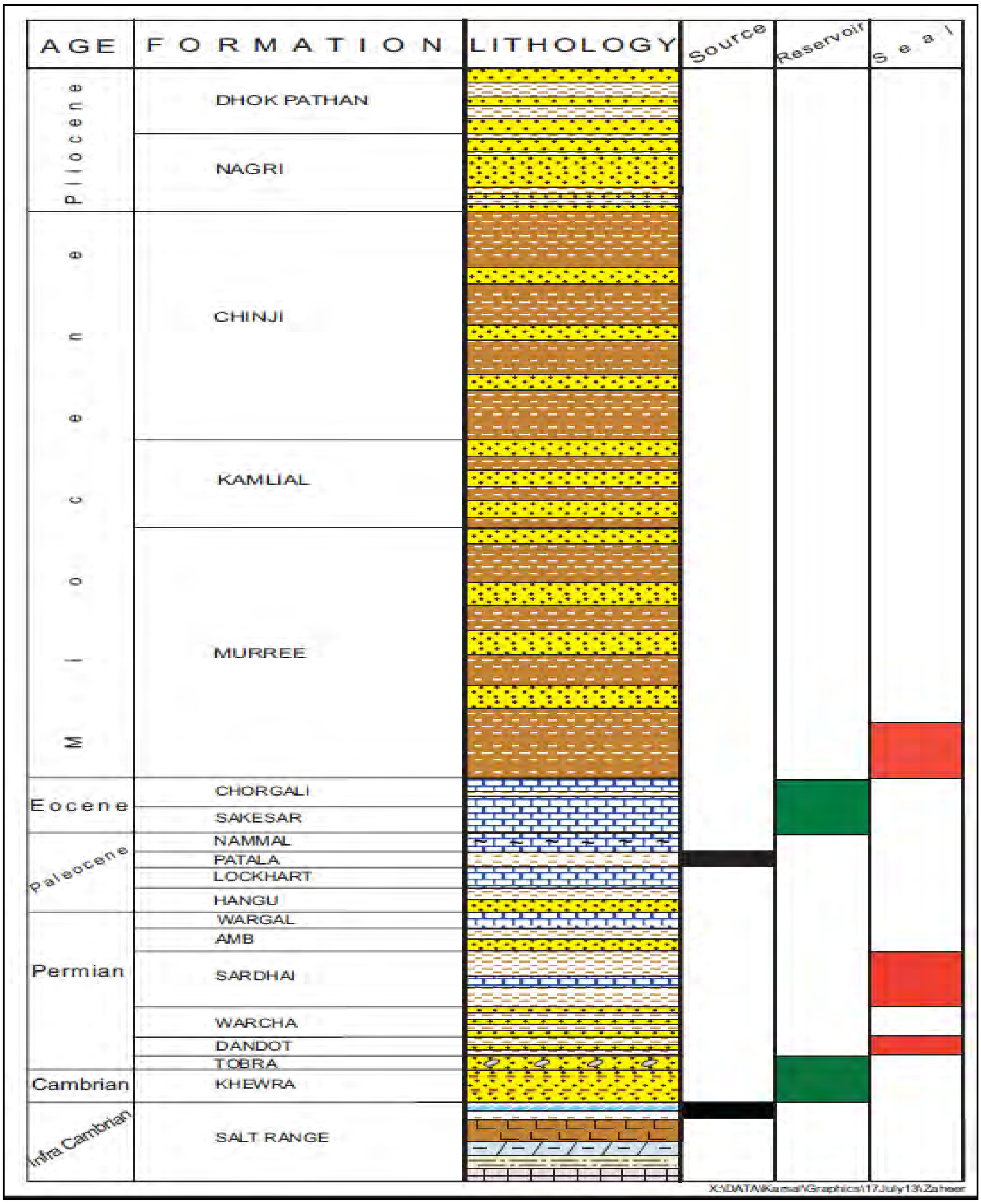

Figure- 2.6: Generalized stratigraphy of the Potwar Basin covering from Precambrian to Quaternary sedimentary sequences. Chorgali and Sakesar formation are the primary targets in the area whereas Lockhart formation also considered as an important reservoir, but it did not produce oil in Karsal and neighboring Balkassar field. Sakesar, Nammal and Patala and Salt Range formations are considered to have source potential. Thick clay of Murree Formation forms a competent seal over Eocene carbonate.

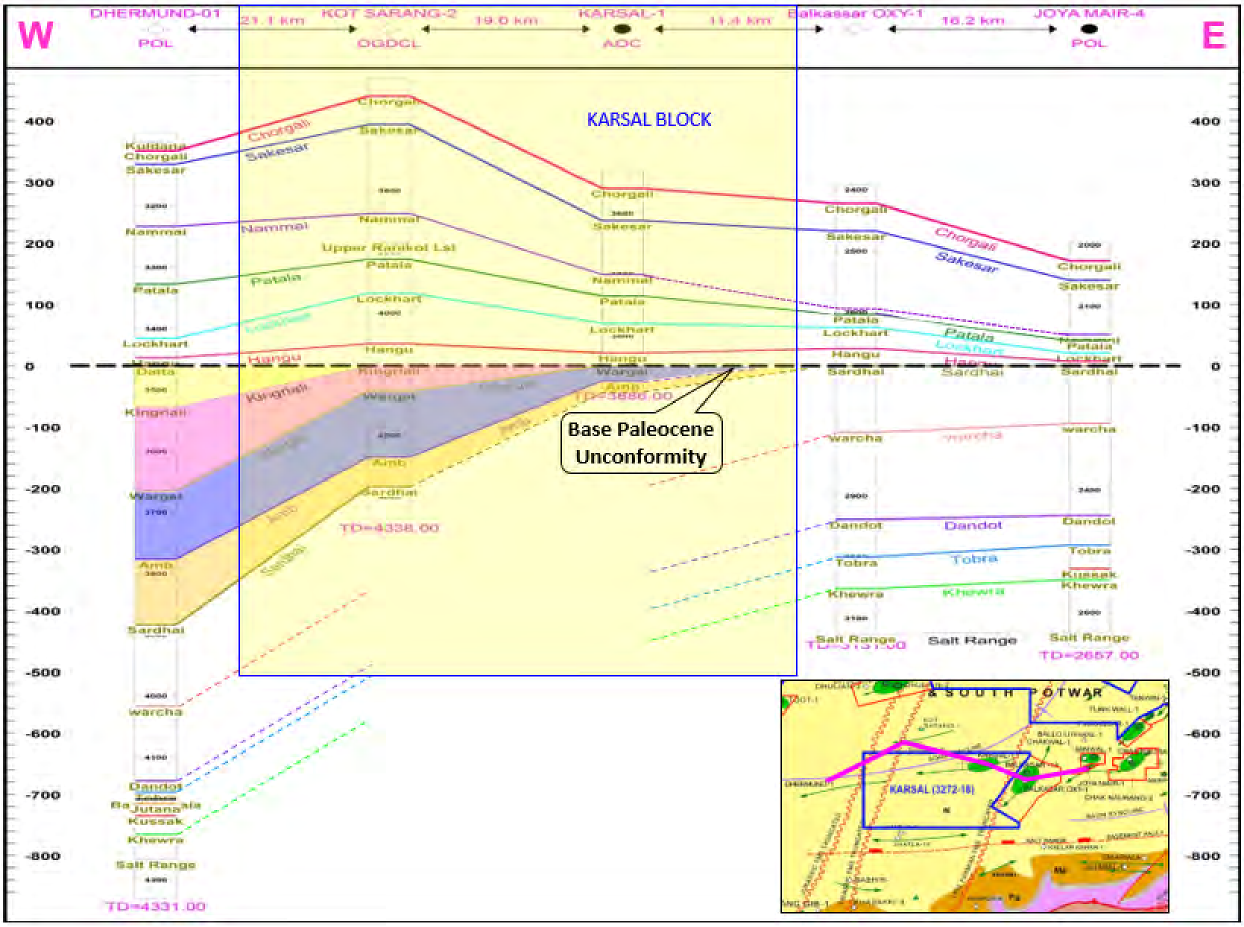

Figure- 2.7: Detailed East west cross section for the wells correlation stratigraphic section of study area.300-420m thick Paleogene sediments comprising Hangu, Lockhart, Patala, Nammal, Sakesar and Chorgali are present in the area. These sediments are underlain by Base Miocene unconformity. Cretaceous and Jurassic sediments are absent/eroded in the block area. Datta Formation of Jurassic age truncated just along the western boundary of the study area. Triassic sediments (Kingriali Fm) are truncated below Paleocene unconformity within the block boundary and restricted only to western part of the study area. Late Permian Zaluch Group; Amb & Wargal Formations are present within study area.

Chapter -03

Interpretation of Seismic Data

3.1 Interpretation Techniques of Seismic

Interpretation using seismic data is the process of analyzing and understanding the information contained in seismic data, which is collected during a seismic survey. The data is used to create images of subsurface geology, and it can be used to locate and identify subsurface geological features such as oil and gas reservoirs, minerals, and geological structures. The interpretation process involves the use of various techniques, including seismic attributes analysis, inversion, and geological modeling, to extract meaningful information from the data and make informed decisions about subsurface exploration and development.

By using interpretation, an effort is made to convert the entirety of the seismic data into a structural or stratigraphic picture of the earth. Since the seismic section is a representation of the earth's geological model, one attempts to identify the zone of ultimate anomaly through interpretation (Sheriff, 1999).

3.2 Types of Seismic Interpretation

The two major categories of seismic data interpretation are:

1- **Structural Interpretation**:

Structural interpretation involves the analysis of subsurface geology, rock and fluid properties, and their arrangement to understand the geometrical and stratigraphic framework of the subsurface.

2- **Reservoir Interpretation**:

Reservoir interpretation It focuses on identifying subsurface hydrocarbon reservoirs, their distribution, and quantifying their fluid content and other reservoir properties.

Both types of interpretation are essential because they provide valuable insights into the subsurface conditions, helping geoscientists and petroleum engineers make informed decisions

3.3 Interpretation Workflow

The interpretation was carried out using different techniques and steps with each step involving different processes which were performed using the various software tools. A simplified workflow used in the process is given in the chart below which provides the complete picture depicting how the dissertation has been carried out by uploading navigation data of seismic cubes and SEG-Y in SLB Petrel Software, base map was generated. Faults and Horizons of interest were then manually picked up. Identification of marked horizons was done with the help of synthetic seismogram, generated with the help of well data and faults were marked by keen observation on seismic section and knowing geologic history of study area.

3.4 Synthetic Seismogram

A vital connection between lithological variations inside a drill-hole and seismic reflectors passing by the location is made possible by synthetic seismograms. They essentially act as a reference point for the analysis of seismic data. Because they can directly connect observed lithologies and seismic reflection patterns, synthetic seismograms are helpful tools for connecting drill-hole geology to seismic sections (Handwerger et al., 2004).

Changes in sediment impedance, which is the result of compression wave velocity and density, can affect reflection patterns. The observed variations in lithologies do not always match changes in these two physical parameters. DT and RHOB logs are contained in Sarang X-1, and they will be used to create a synthetic seismogram in order to designate horizons.

Hence on the basis of the synthetic seismogram, the Eocene Chorgali, Sakesar, Patala, Serdhai, Tobra, and Khewra have been marked. The display of the synthetic seismogram is shown in figure 3.1.

3.5 Well to Seismic Tie

A crucial stage in the interpretation of 3D seismic data is the seismic to well tie because it helps for validation and improve accuracy of the subsurface model. By comparing the seismic data with information obtained from well logs and other sources (Figure 3.1), the interpreter can verify the velocity and impedance values used to generate the seismic data and refine the subsurface model. This information can be used to predict the presence and distribution of hydrocarbons, minerals, and other subsurface resources, as well as to assess the risk of geological hazards such as faulting, subsidence, and erosion. A combined 2D and 3D seismic data is used to get tie from the Sarang X-1 as the well was out of the 3D coverage area (Figure 3.2).Seismic to well tie was carried out at Saranag-X1 well and the following horizons are being picked: Sakesar Patala Lockhart Base-Paleocene Unconformity Sardhai Tobra Khewra Basement

Top of Khewra was picked by extrapolating the velocity trend of the Saranag-X1 well below the well TD. The time and depth structure maps at all the picked horizons were generated. Structural mapping confirmed the presence of two structural-cum-stratigraphic fracture entrapment. The well fence diagram has also been shown in the figure 3.3.

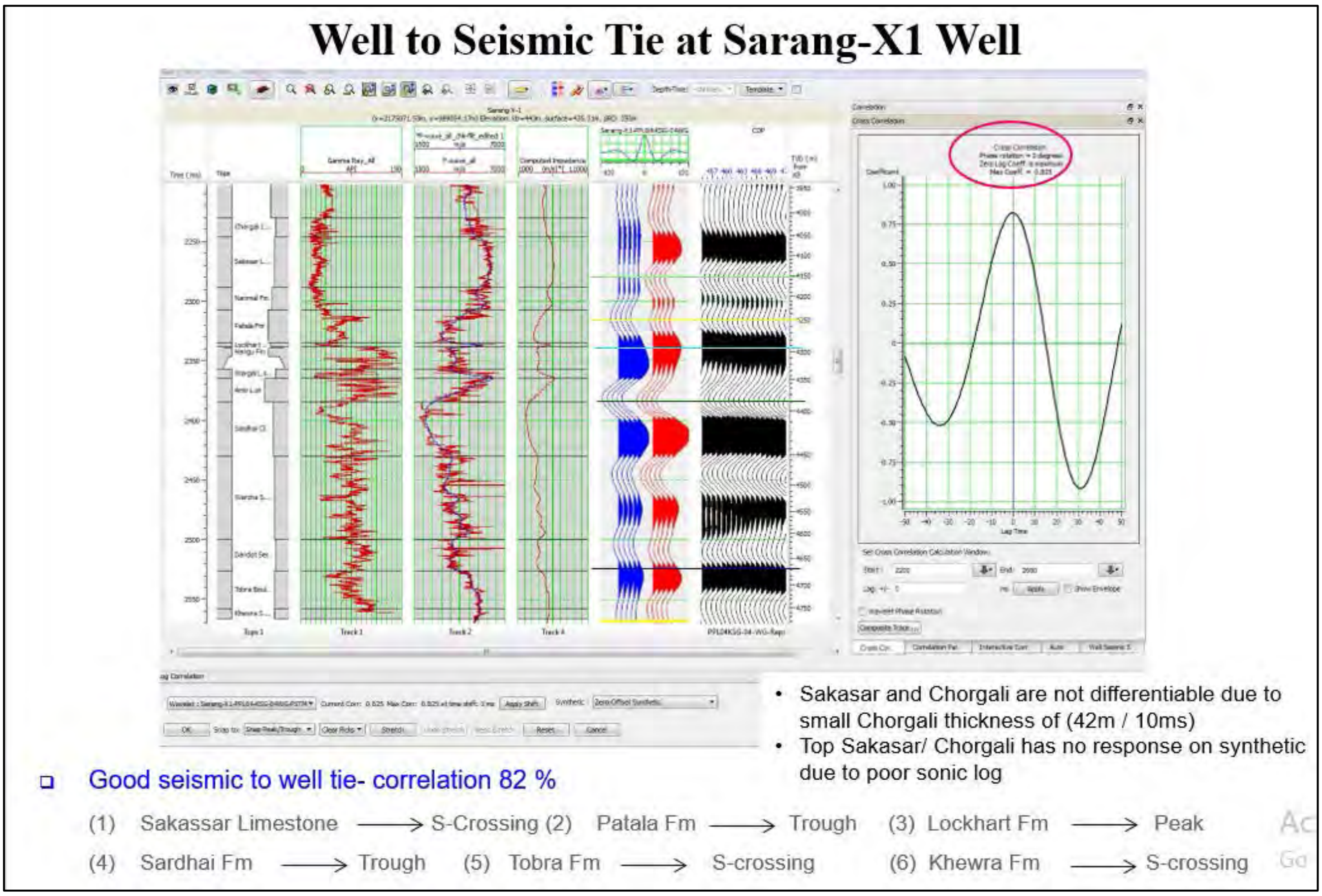

Figure 3.1: Synthetic seismogram generated for the Well Sarang X-1 using well log data.

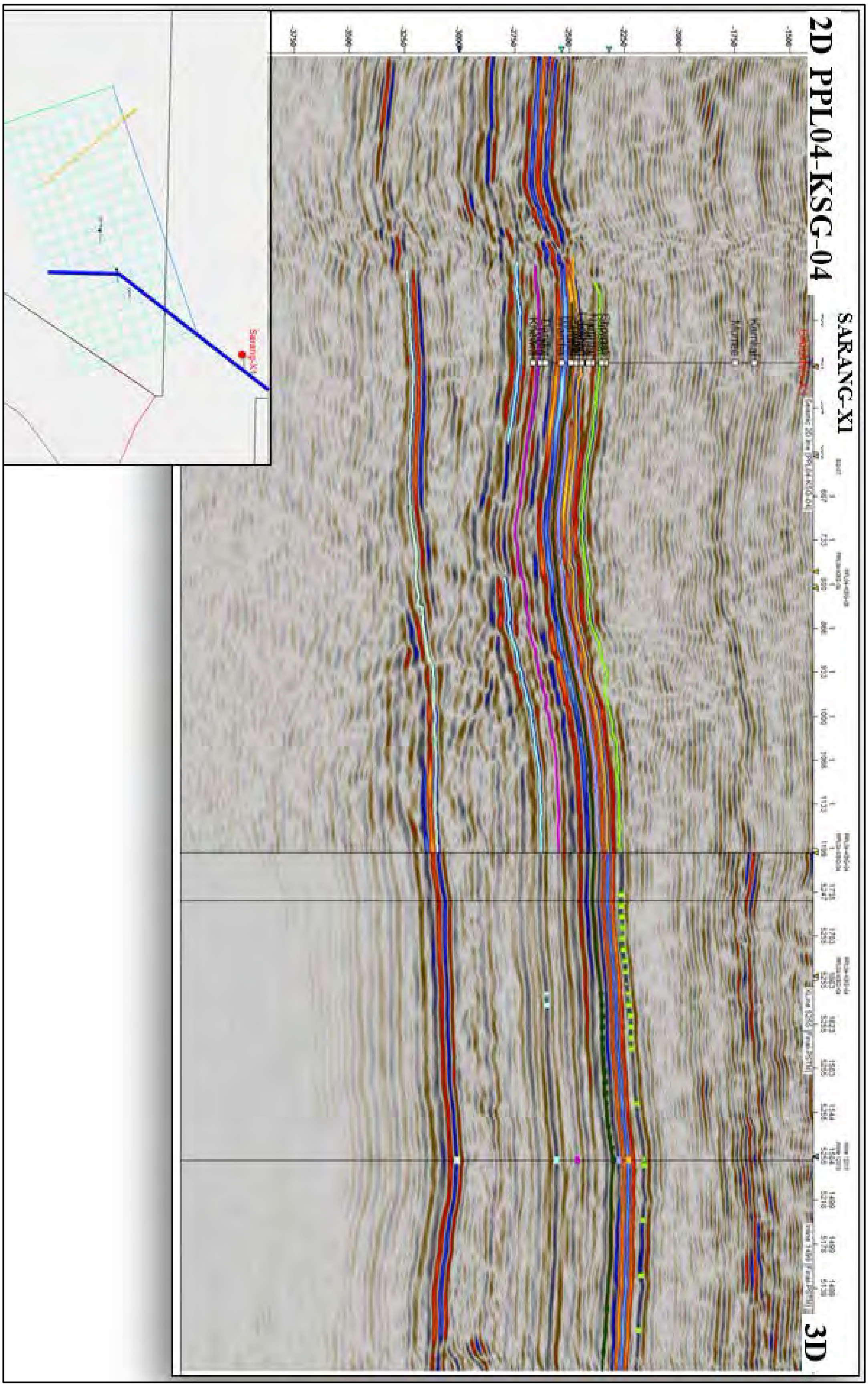

Figure 3.2: 2D and 3D combined section for seismic to well tie as the well was not in 3D data.

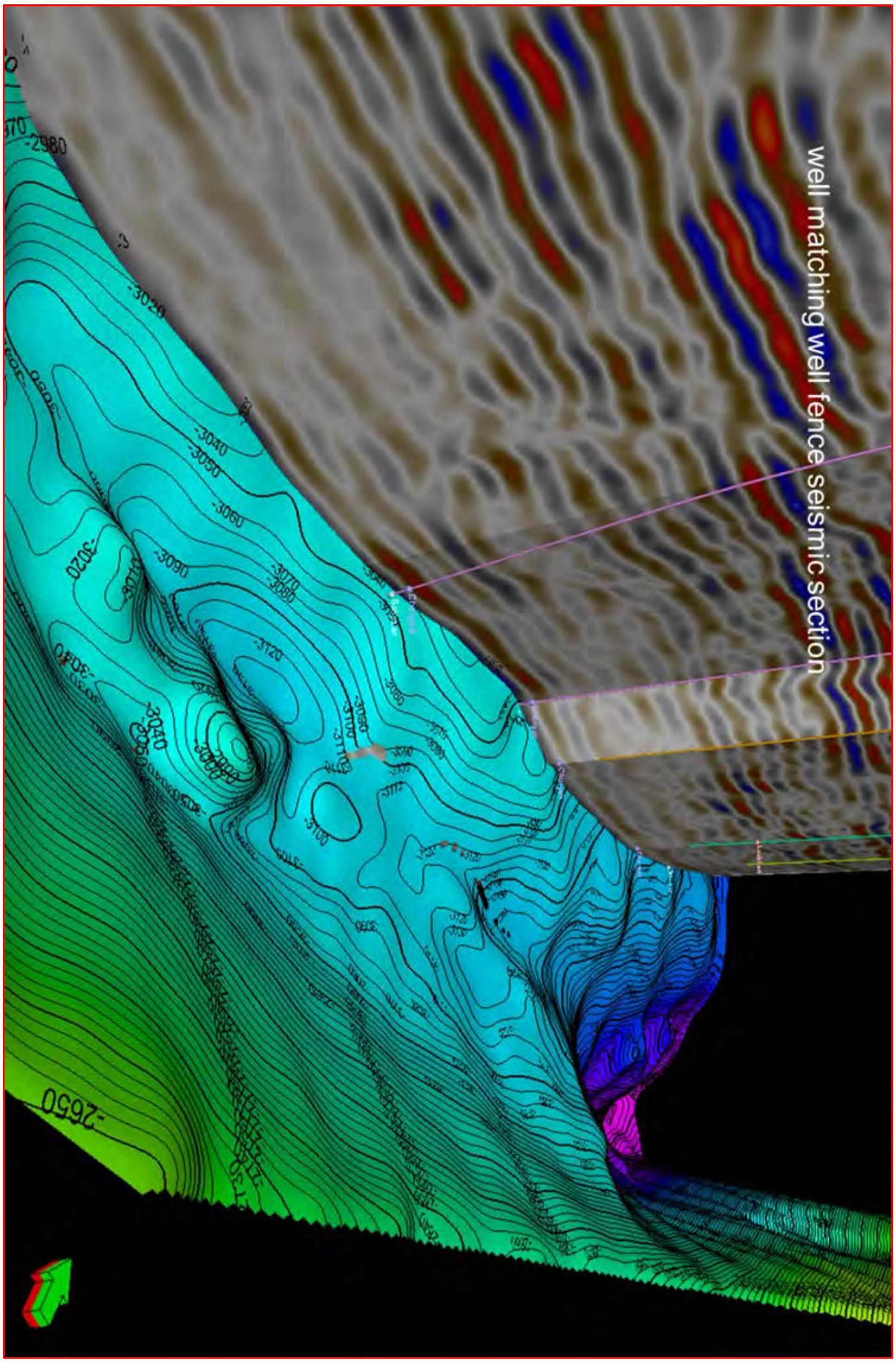

Figure 3.3: well fence diagram for the study area after well correlation with seismic.

3.5.1 Fault Marking

Identifying faults on a seismic section in real time can be a challenging task, especially if the tectonic history of the area is unknown (Sroor, 2010). Typically, faults are identified by observing breaks in the continuity of reflections, which indicate disruptions in the data caused by fault activity.

3.5.2 Horizon Picking

The initial step in seismic data interpretation involves identifying and marking the most significant reflectors, also referred to as horizons, on the seismic sections. A horizon is defined as the boundary or interface between two formations or rock units. The selection of reflectors is based on their authenticity, strong continuity, and their ability to be traced throughout the seismic line, as well as correlated with other seismic lines in the area (Badely, 1985).

This requires a good understanding of the area's structural and stratigraphic features. Horizons are marked on the time section using various sources of information such as synthetic seismograms, well tops, and prominent reflections, basically the horizontal view of the seismic amplitude overlain by the wells drilled already. In this dissertation, four major horizons have been identified and marked on the seismic lines using available information, such as the synthetic seismogram and well tops of Saranag X-1.

3.5.3 Fault Polygons Generation

A fault polygon is a representation of the lateral extent of dip or strike faults with the same trend. It displays subsurface discontinuities by displacing contours. The identification of faults and their lateral extent is necessary to generate fault polygons by analyzing available seismic data. If the same fault is observed on all dip lines, manual joining of all points on the base map can create a polygon. The resulting fault polygons show the high and low areas on a specific horizon, and if dip symbols are not present, the corresponding colour bar gives information on dip directions. All indicated horizons have fault polygons built for them, and they are all NW-SE (Figure 3.4). The shape of the basement is depicted in figure 3.5. Due to time value variation on either side of the polygon, the polygons created at thrust splays at the Eocene level exhibit alternate colour changes, showing normal faulting in the basement and reverse faulting in the Eocene.

3.6 Time slice View

A visualization method called a time slice view of 3D seismic data is used to represent subsurface structures in three dimensions over a particular period. The time slice view is created by slicing the 3D seismic volume along a particular time or depth plane and displaying the resulting 2D image (Figure 3.4). The image shows the seismic amplitudes at a specific time interval, providing an image of the subsurface at given time.

Time slice view is useful for interpreting complex subsurface structures, such as faults, stratigraphic layers, and fluid reservoirs. By visualizing the seismic data at different time intervals, geologists can identify and understand the changes in subsurface structures over time. To create a time, slice view, the 3D seismic data is first loaded into a seismic interpretation software. The user then selects a time or depth plane, and the software slices the 3D data along that plane to create a 2D image.

The image can be viewed from different angles and perspective, and can be overlaid with other geologic data, such as well logs, to provide additional information about the subsurface. The time slice view is an important tool for understanding the subsurface and for making informed decisions about exploration and development. It can be used for a variety of purposes, including reservoir characterization, exploration, and production.

A comprehensive analysis of the image, explored from multiple vantage points and integrated with other geological datasets like well logs, enhances insights into the subsurface. The time slice view stands out as a crucial asset, fostering a nuanced understanding of subsurface dynamics and empowering decision-making in exploration and development endeavors. Its versatile applications span reservoir characterization, exploration strategies, and production planning, making it an indispensable tool in the geoscientific toolkit.

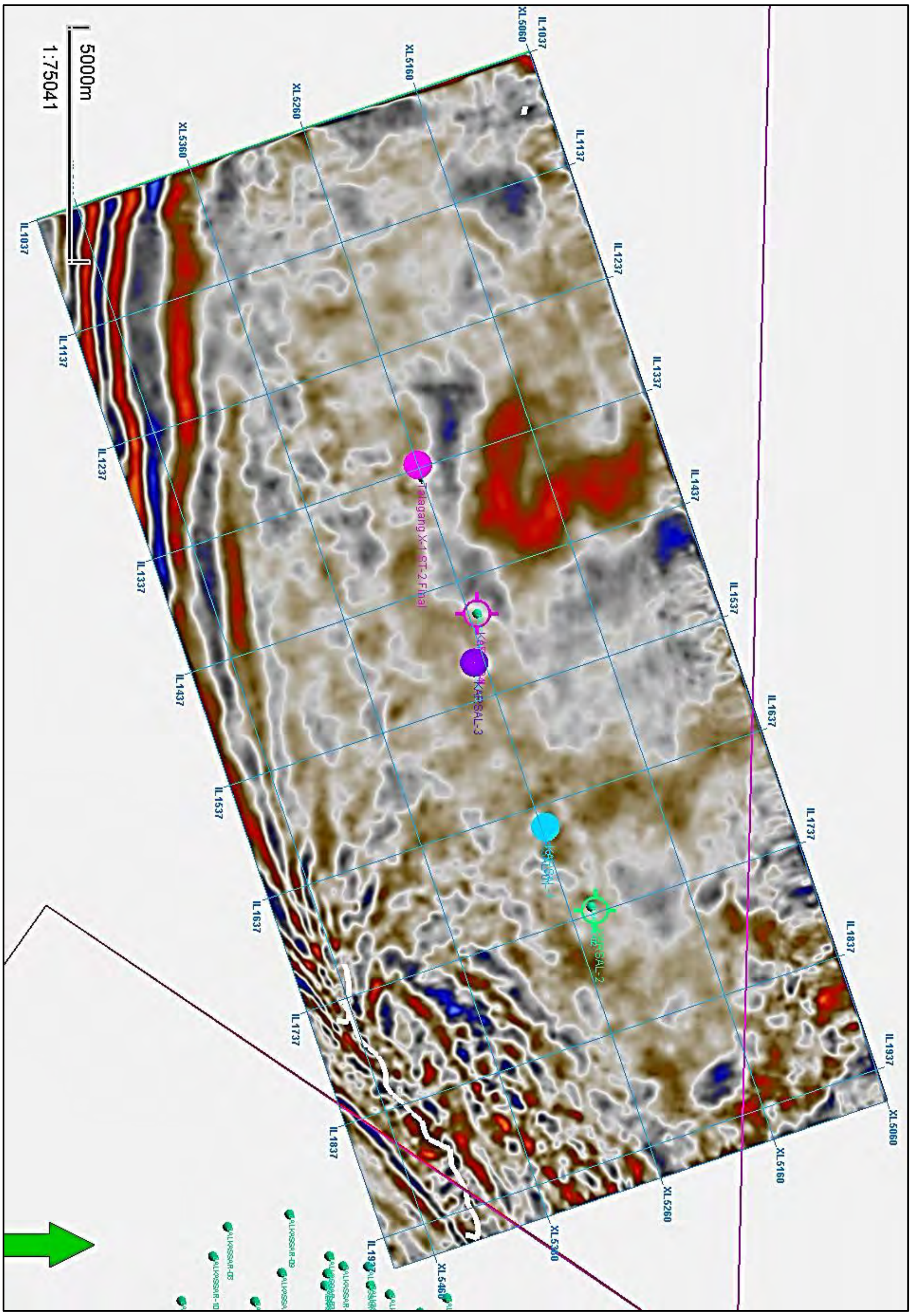

Figure 3.4: Time slice view for the 3D seismic data of Karsal study area.

3.7 Interpreted Seismic Sections

The interpreted seismic sections display the horizons marked on INLINES and XLINES using well data from Sarang X-1. These marked horizons include the Eocene, Palaeocene, Cambrian, and the basement, which serve as the controlling geometry mark for structural evaluation of the Karsal Area of interest 3D geometry reflection based on the interpreted seismic section we can mor easily comments on the subsurface geological investigation, based on the changes in acoustic impedance, as verified by the synthetic seismogram.

3.8 Contour Maps

Contouring is a critical element in the interpretation of seismic data. It involves creating time and depth contour maps that display the most important information extracted during interpretation. Contours are lines of equal elevation, either in time or depth, and are used to depict relief on horizons. These images' contours show the slope, dip, faulting, and folding of formations, making them an essential final product of exploration operations.

A reference datum is first chosen in order to create a subsurface map from seismic data, and it can be either sea level or any other distance above or below sea level. Contouring is a crucial step in seismic data interpretation as it provides a visual representation of subsurface geological structures. Contours can reveal changes in elevation, which can help identify subsurface horizons and structures like faults, folds, and stratigraphic units. Geologists use the contouring process to identify patterns and trends in the subsurface, informing exploration and hydrocarbon production decisions.

It's important to note that contouring is just one aspect of seismic data interpretation and is often combined with other techniques like attribute analysis, well log analysis, and seismic inversion for a complete picture of the subsurface. The accuracy of the interpretation and contouring depending on the standard and high-resolution seismic data with expertise and experience by the interpreter.

3.8.1 Time Contour Maps

A time contour map is a type of subsurface map commonly used in seismic data interpretation. It displays the distribution of seismic reflection events in time and helps geologists understand the subsurface geology of an area. Time contour maps are created by drawing contour lines at equal intervals on a seismic section that represent the TWT of seismic reflections by the surface to subsurface. These contour lines are then used to identify subsurface geological features like faults, folds, and stratigraphic units most of the time structure map as shown in figure 3.6 and also its second variant shown in figure 3.7. They help to visualize the subsurface structure and provide a framework for geologists to better understand the geological history of an area at prospect level as shown in figure 3.8 and prospect time slice view evaluation based on the vertical relief through seismic as shown in figure 3.9 respectively. Geoscientists use time contour maps to identify areas of interest for hydrocarbon exploration and production. By analyzing the subsurface structure and interpreting the geological history of an area, they can identify potential hydrocarbon reservoirs and plan drilling operations.

3.8.2 Depth Contour Maps

Another form of subsurface map used in the interpretation of seismic data is a depth contour map. A depth contour map shows the spread of seismic reflections in depth as opposed to a time contour map, which shows how seismic reflection events are distributed over time.
To create a depth contour map, geologists use information about the velocity of seismic waves in the subsurface to change the TWT of seismic reflections into domain of depth below the surface (Figures 3.10 and 3.11 respectively) as prospect level contour map from 10 meter to 5-meter interval at Sakesar level. For the Lockhart level time structure maps (Figures 3.12 and 3.13 respectively) overlain by the prospect polygon. Amplitude based vertical relief time slice-based Lockhart structure evaluation (Figure 3.14). Respected prospect-based contour maps at the 10 meter and 5-meter intervals (Figures 3.15 and 3.16 respectively). They then draw contour lines at equal intervals on a seismic section that represent the depth of seismic reflections below a reference datum. Depth contour maps provide a more accurate picture of the subsurface structure than time contour maps, as they account for changes in velocity and the geometry of the subsurface layers. They are particularly useful for identifying potential hydrocarbon reservoirs, as they provide a more accurate representation of the thickness and geometry of the reservoirs.

Depth contour maps are also used to identify geological features like faults, folds, and stratigraphic units, and to plan drilling operations. They are often used in combination with other interpretation techniques like attribute analysis, well log analysis, and seismic inversion for a more complete understanding of the subsurface geology. Like time contour maps, the accuracy of the interpretation and contouring depending on the standard and high-resolution seismic data with expertise and experience by the interpreter. The cross-section interpretation of the INLINE an XLINE (Figures 3.17 and 3.18 respectively) with one more INLINE shown in figure 3.19. However cross line shows the overall geometry of the karsal monocline based on the PSTM (Figure 3.20). The bird eye view of the surface Sakesar at the PSDM data set is shown in (Figure-3.21) and the second 3D view is also shown with well oriented angle for the Sakesar depth model (Figure 3.22).

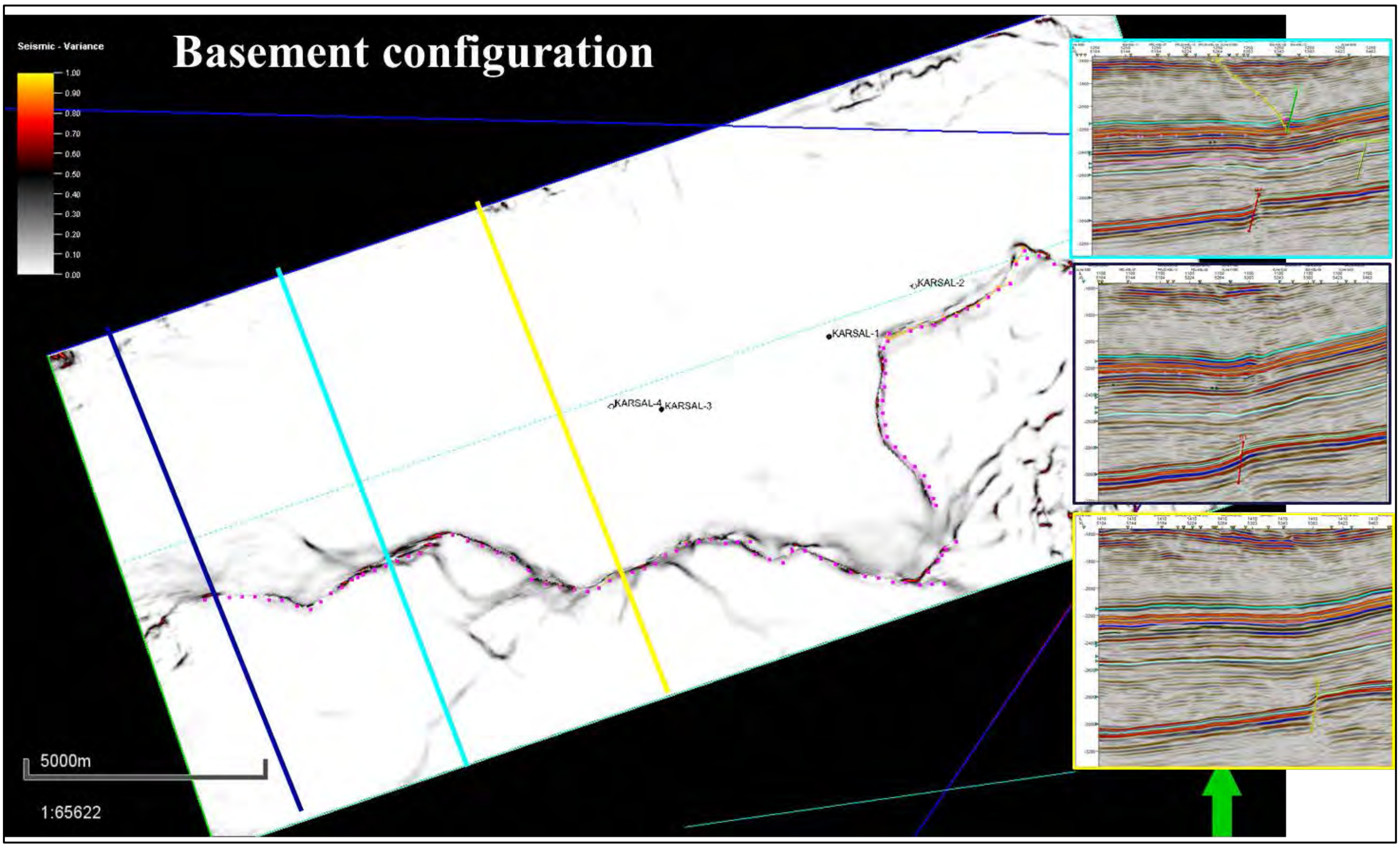

Figure 3.5: Time slice view for the 3D seismic Data of Karsal Study area for basement configuration polygons three different lines represents the right side seismic sections and fault behavior in cross section view basically the basement configuration geometry provide a base for the upward sedimentary structuration which will form the premature pop up and slight hum geometry.

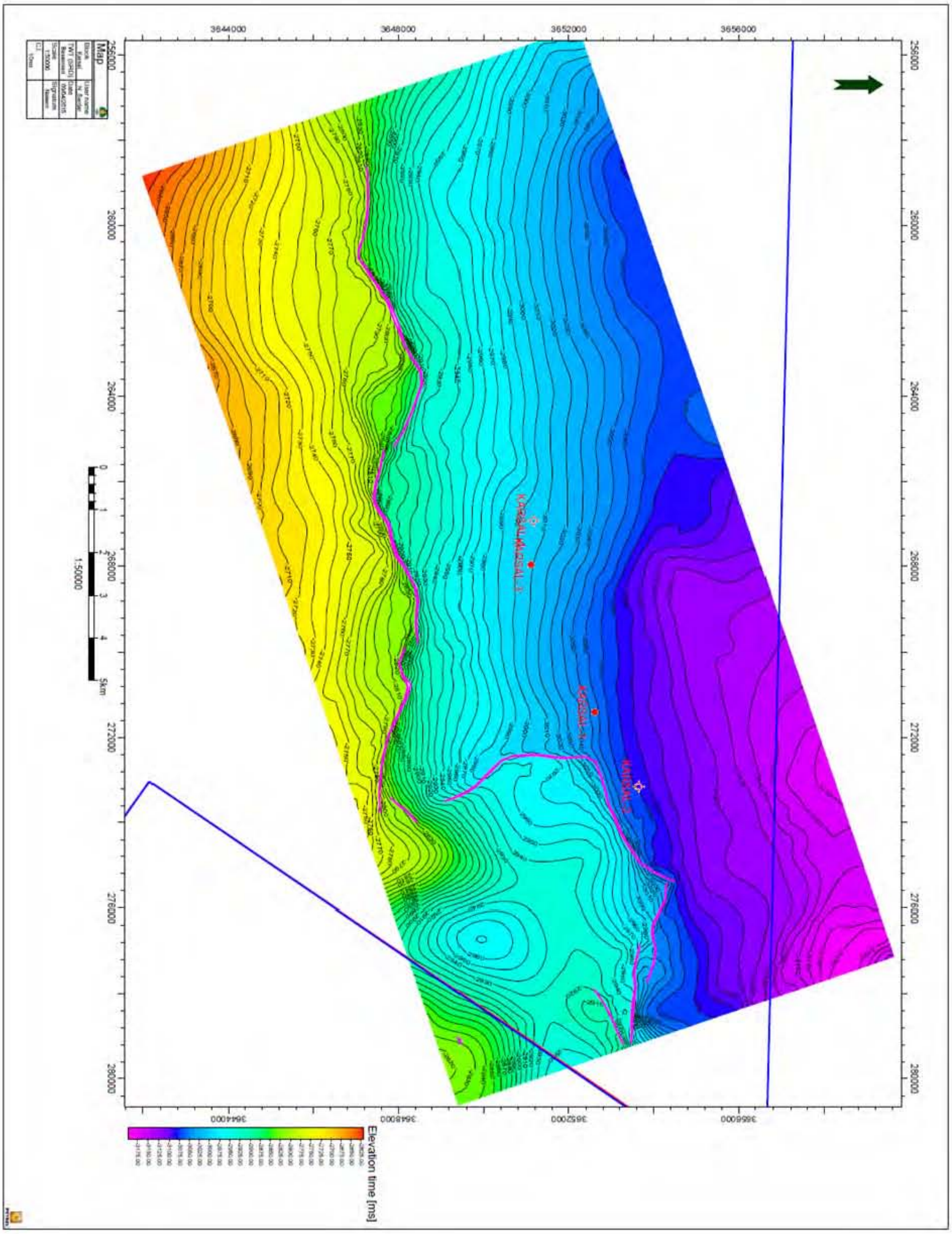

Figure 3.6: Time structure contour map of basement reflector of Karsal 3D area in which yellow color reflect the deeper side and the pink color shows the shallowest part contour interval is 10-meter map scaled is mentioned along with proper legend.

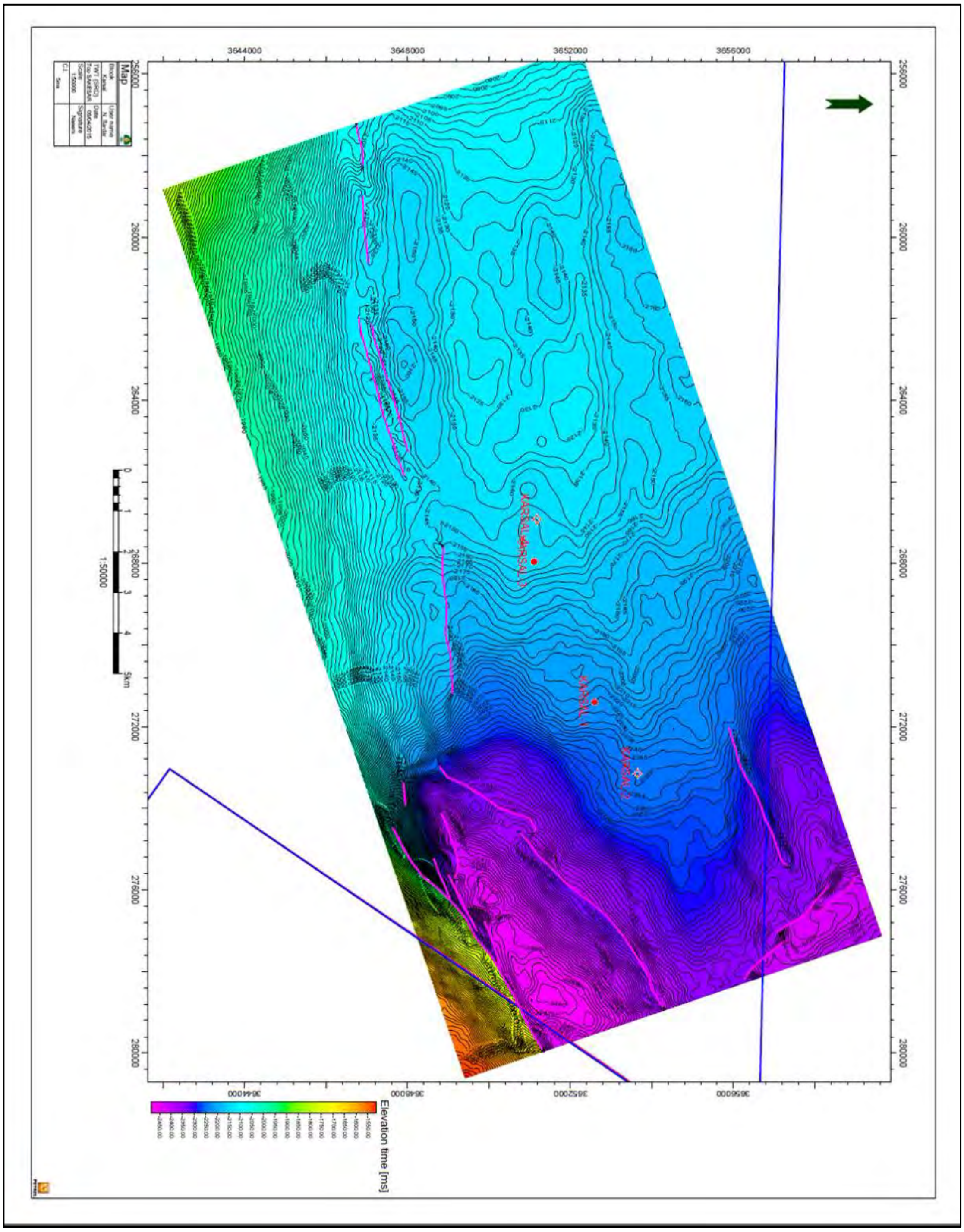

Figure 3.7: Time Structure Sakesar contour Map in which yellow color reflect the deeper side and the pink color shows the shallowest part mostly trending part is karsal monocline structural trend contour interval is 10 meter map scaled is mentioned along with proper legend.

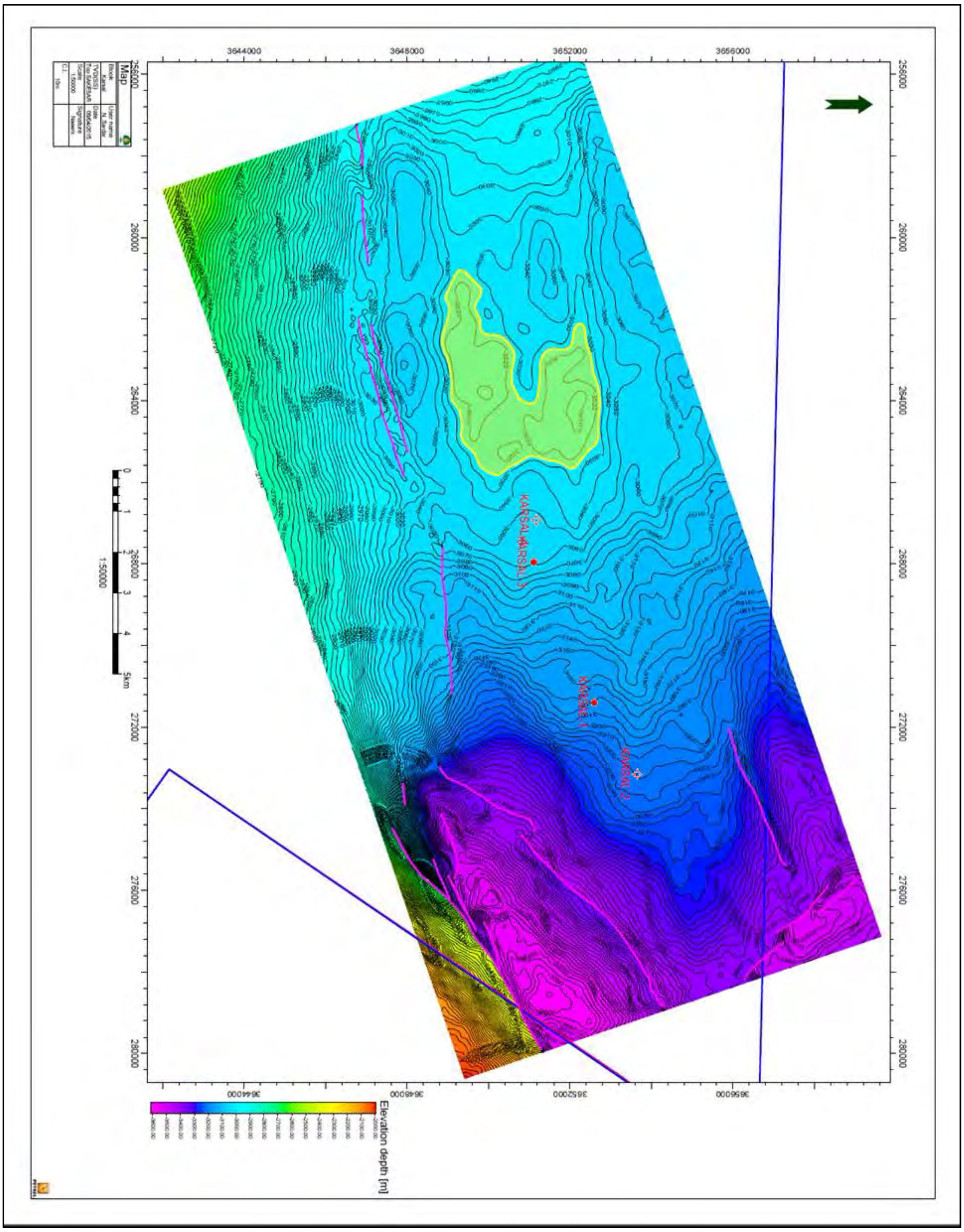

Figure 3.8: Time Structure Sakesar contour Map ,with potential lead polygon yellow color contours area reflect the deeper side and the pink color contour area shows the shallowest part mostly trending part is karsal monocline structural trend contour interval is 10 meter map scaled is mentioned along with proper legend.

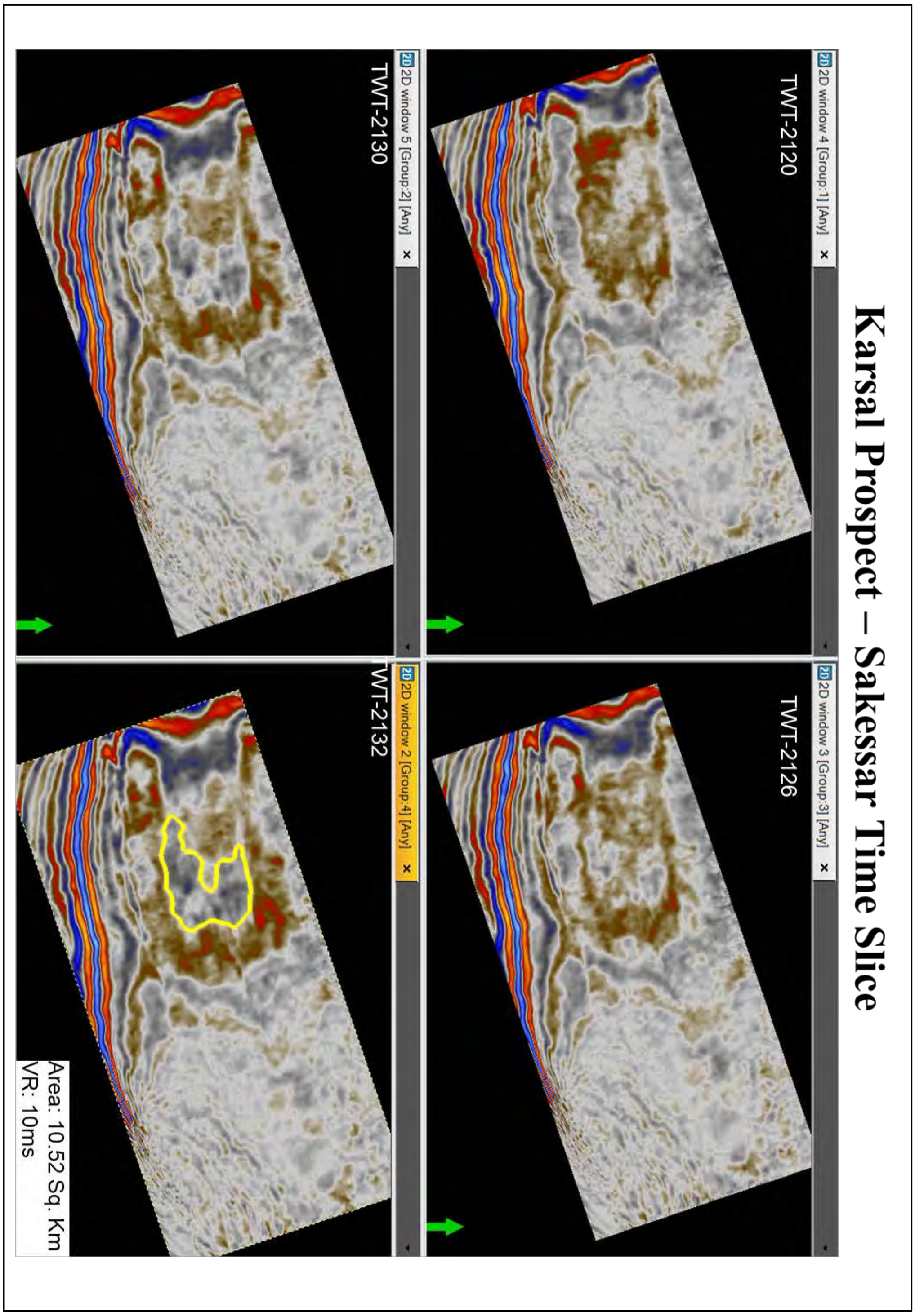

Figure 3.9: Time slice view for the 3D seismic Data of Karsal Study area Karsal Sakesar lead structure evaluation based on the time slice view just 4msec window reflect how in 12 msec total representation of the potential polygon over Talagang X-1 amplitude reflect the real sense of the time slice view. This 12 msec actually reflect the vertical relief of the lead as well.

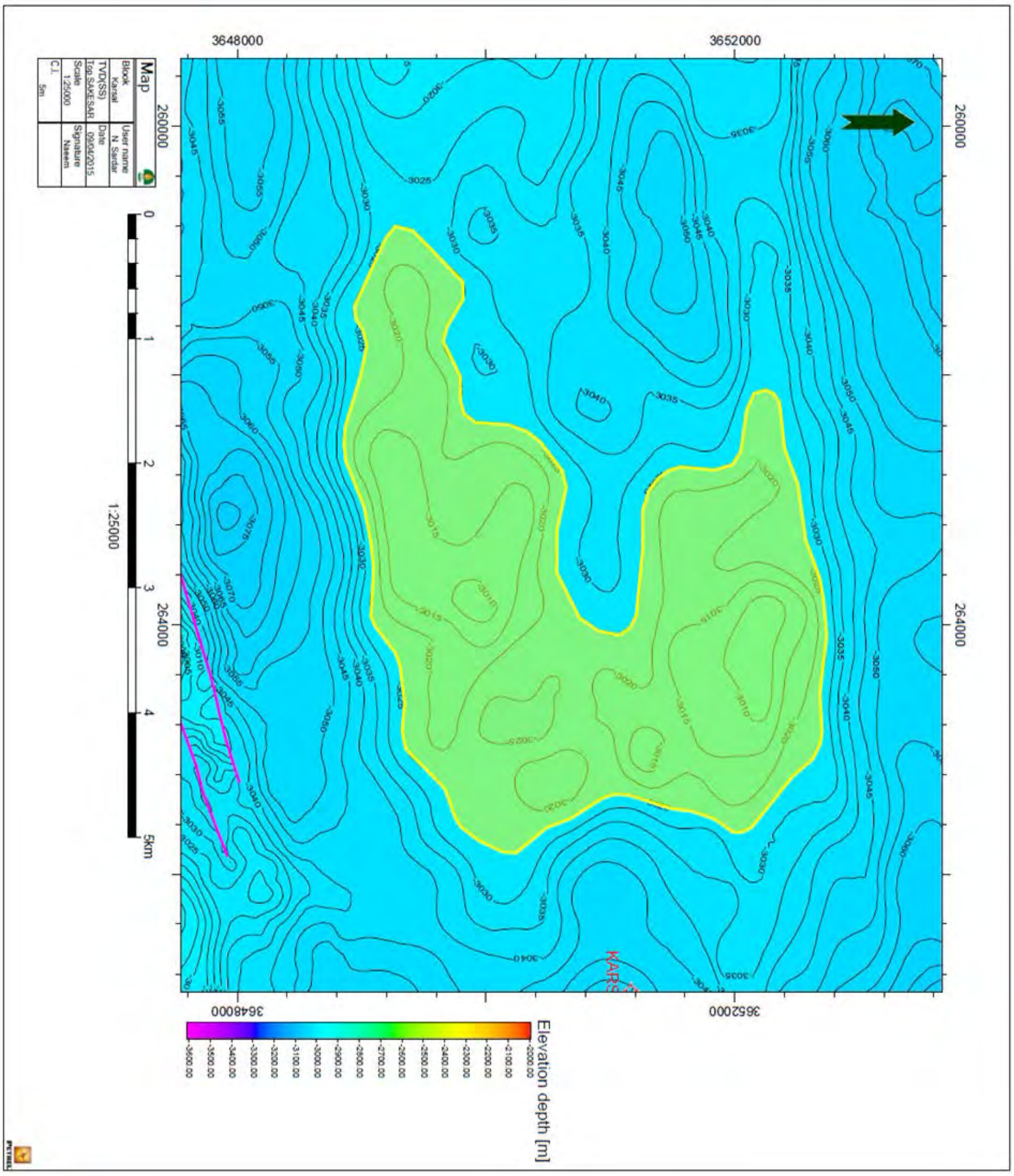

Figure 3.10: Prospect level scaled depth contour map with contour interval 10-meter area 10.2 Sq.km. Time structure map is converted to depth contour map based on the constant velocity multiplication method and scale with legend reflect the formulation of the lead area at Sakaesar level.

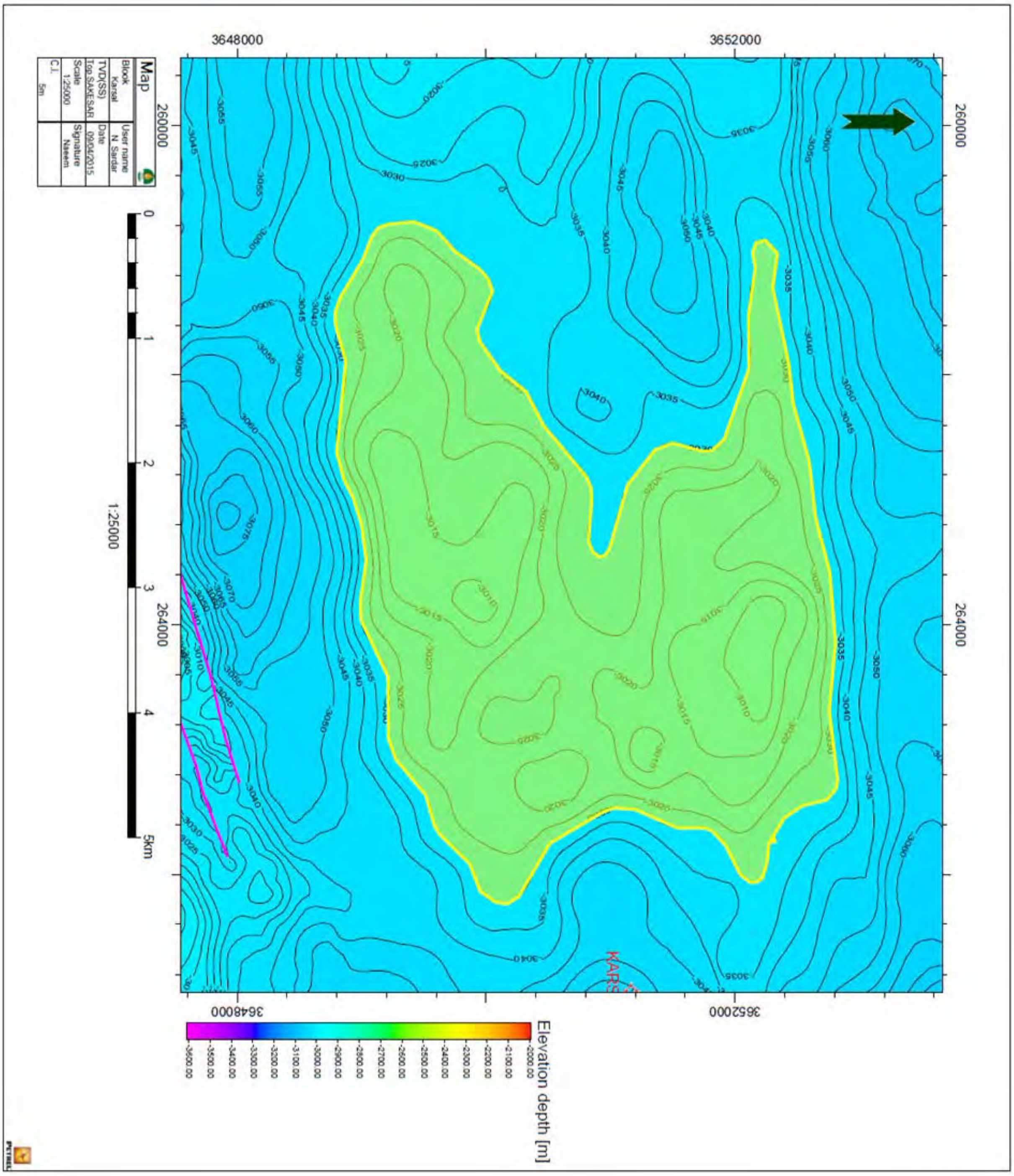

Figure 3.11: Prospect level scaled depth contour map with contour interval 5 meter. Time structure map is converted to depth contour map based on the constant velocity multiplication method and scale with legend reflect the formulation of the lead area at Sakaesar level.

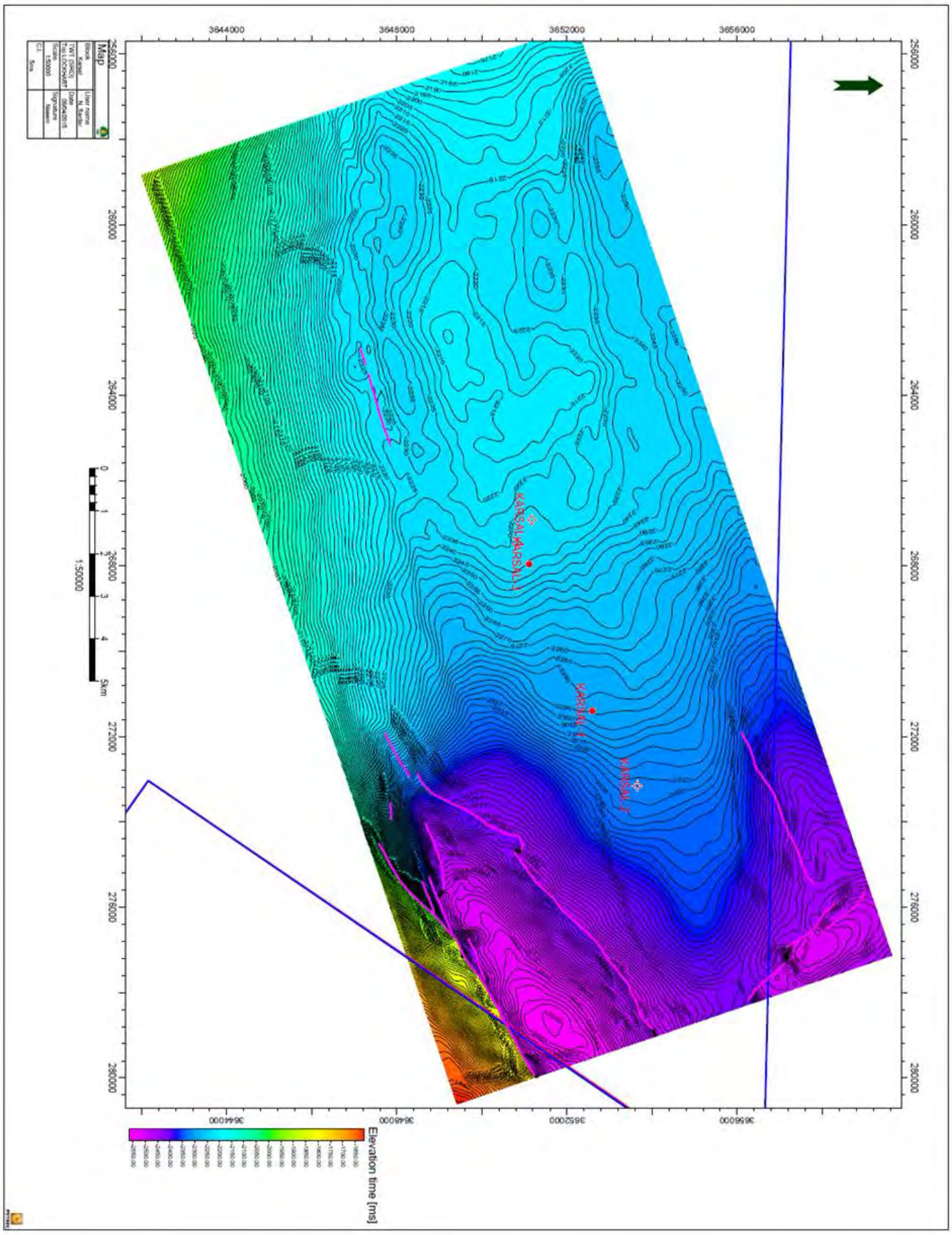

Figure 3.12: Time Structure Lockhart contour Map in which yellow color reflect the deeper side and the pink color shows the shallowest part mostly trending part is karsal monocline structural trend contour interval is 10 meter map scaled is mentioned along with proper legend.

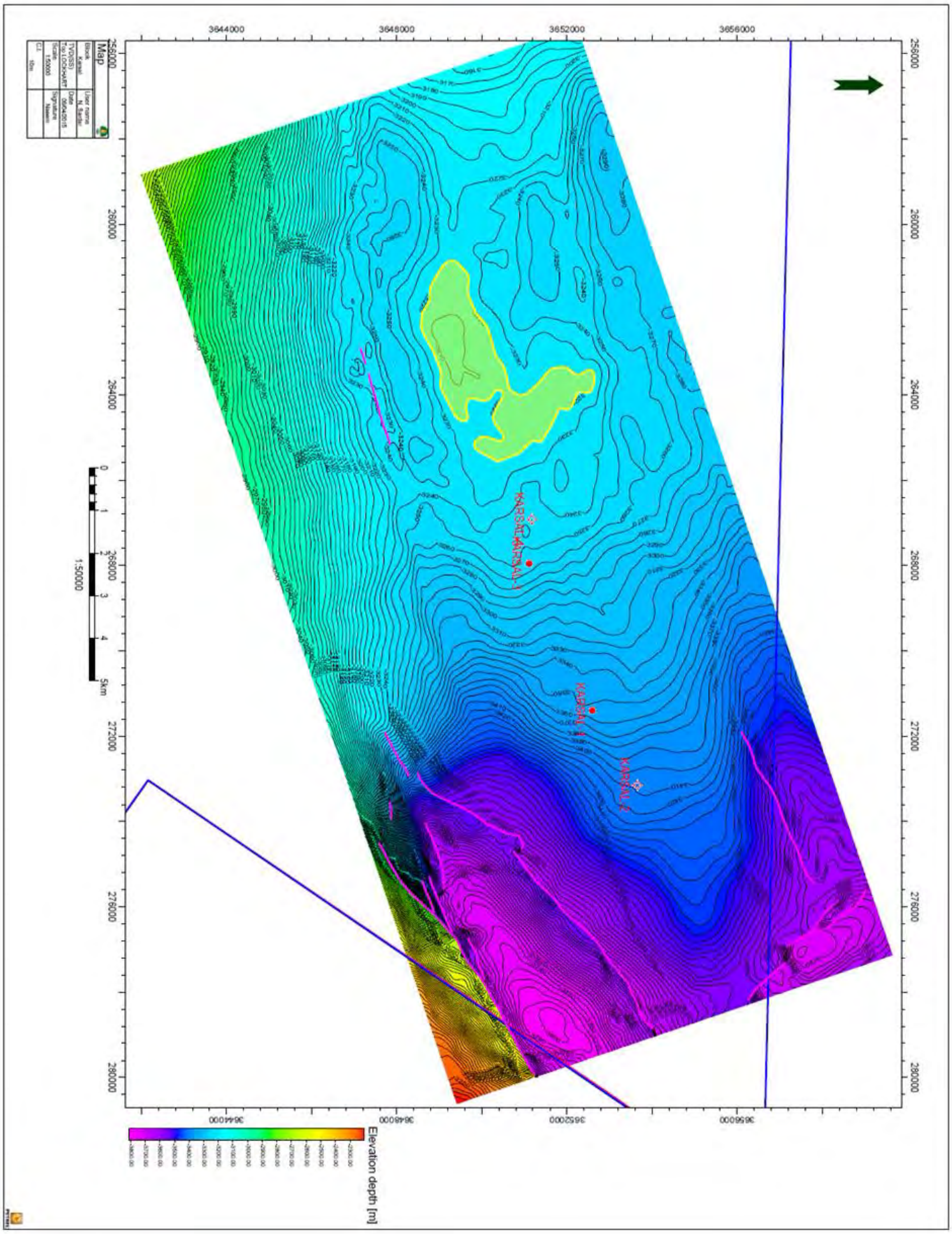

Figure 3.13: Time Structure Lockhart contour Map with protentional lead polygon in which yellow color reflect the deeper side and the pink color shows the shallowest part mostly trending part is karsal monocline structural trend contour interval is 10 meter map scaled is mentioned along with proper legend.

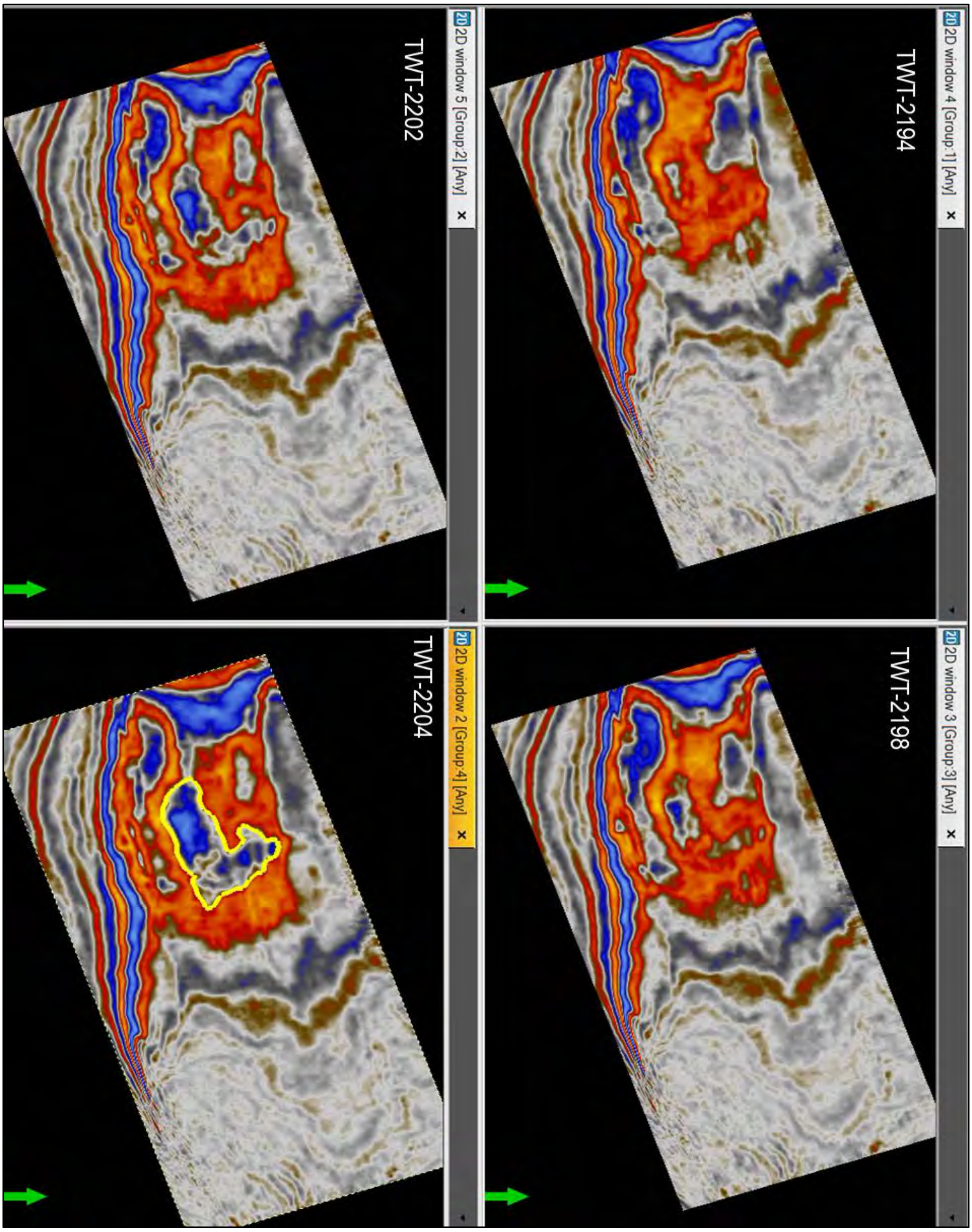

Figure 3.14: Time slice view for the 3D seismic Data of Karsal Study area Karsal Lockhart lead structure evaluation based on the time slice view just 4msec window reflect how in 10 msec total representation of the potential polygon over Talagang X-1 amplitude reflect the real sense of the time slice view. This 10 mese actually reflect the vertical relief of the lead as well.

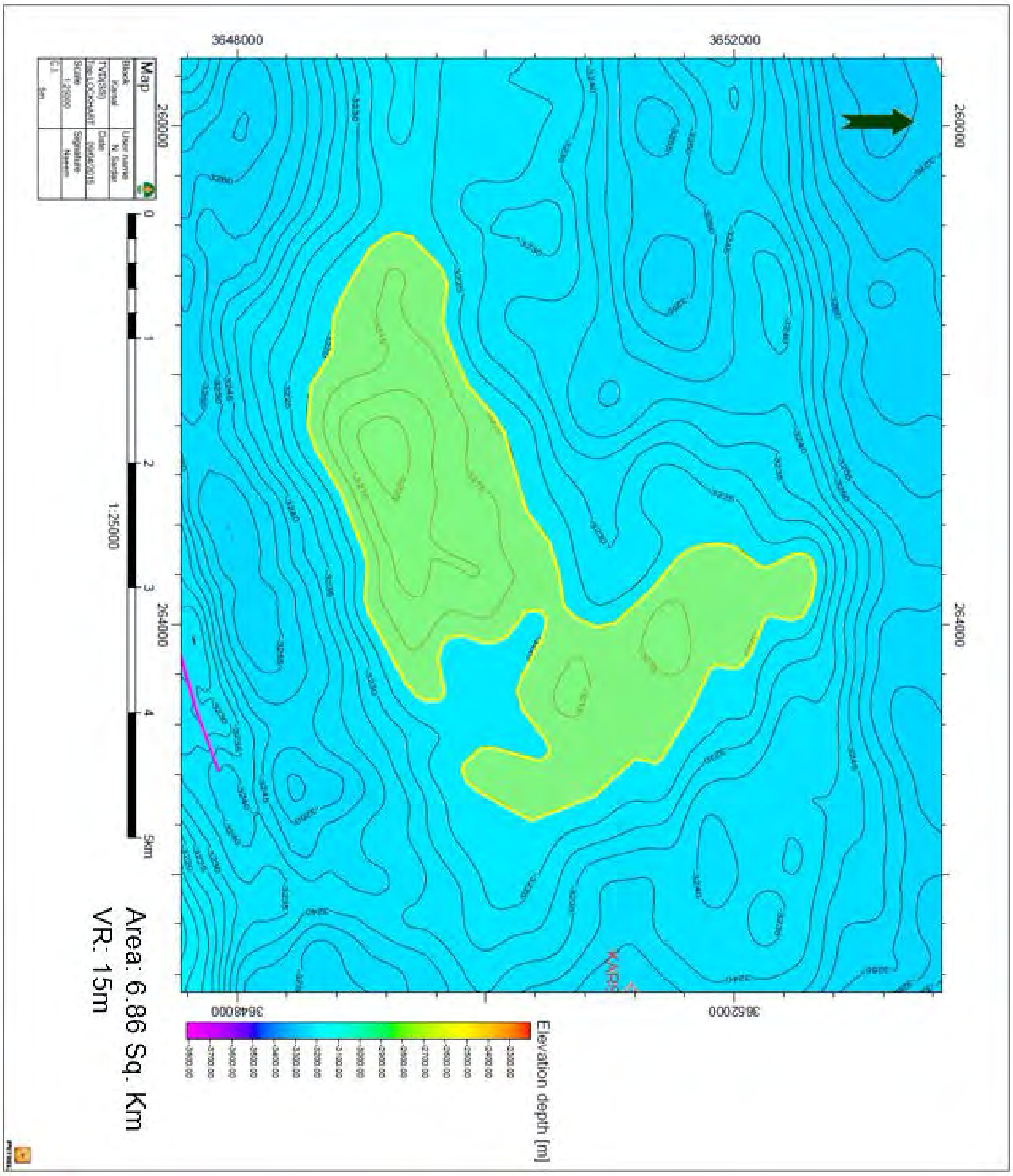

Figure 3.15: Prospect level scaled depth contour map with contour interval 10 meter area 6.86 Sq.km Time structure map is converted to depth contour map based on the constant velocity multiplication method and scale with legend reflect the formulation of the lead area at sakaesar level.

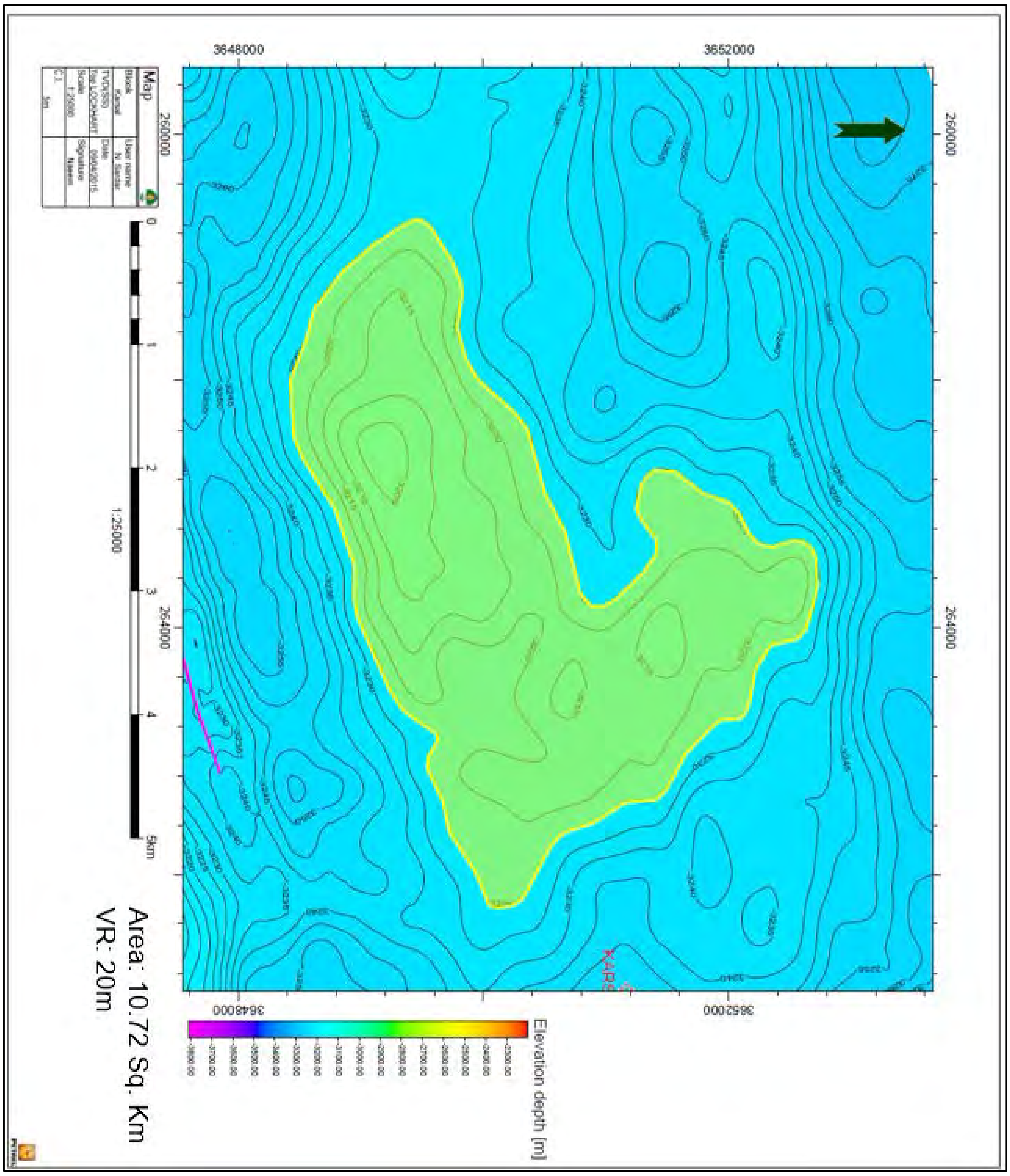

Figure 3.16: Prospect level scaled depth contour map with contour interval 5 meter area 10.72 Sq.km Time structure map is converted to depth contour map based on the constant velocity multiplication method and scale with legend reflect the formulation of the lead area at sakaesar level.

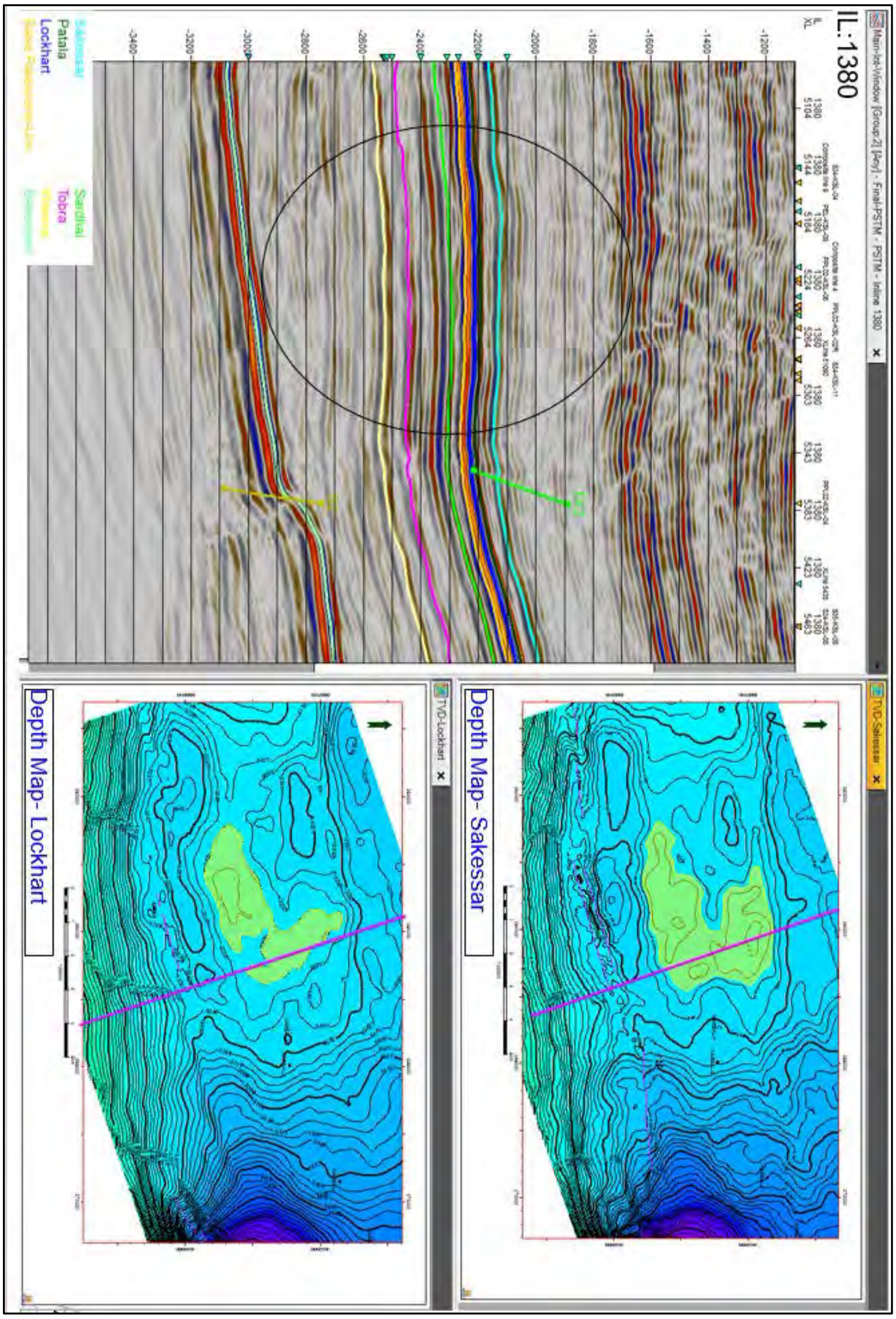

Figure 3.17: Structural interpretation cross section view over sakaesar and Lockhart using inline no 1380 detailed interpretation is carried out all key horizons were picked along with basement as well their respective map view is also attached do the right hand side pink color passing line location is shows in the left hand seismic cross section. Circled area in black color represent the anomalous behavior of the seismic response on the Talagang X-1 location related anomaly at sakaesar to khewra level.

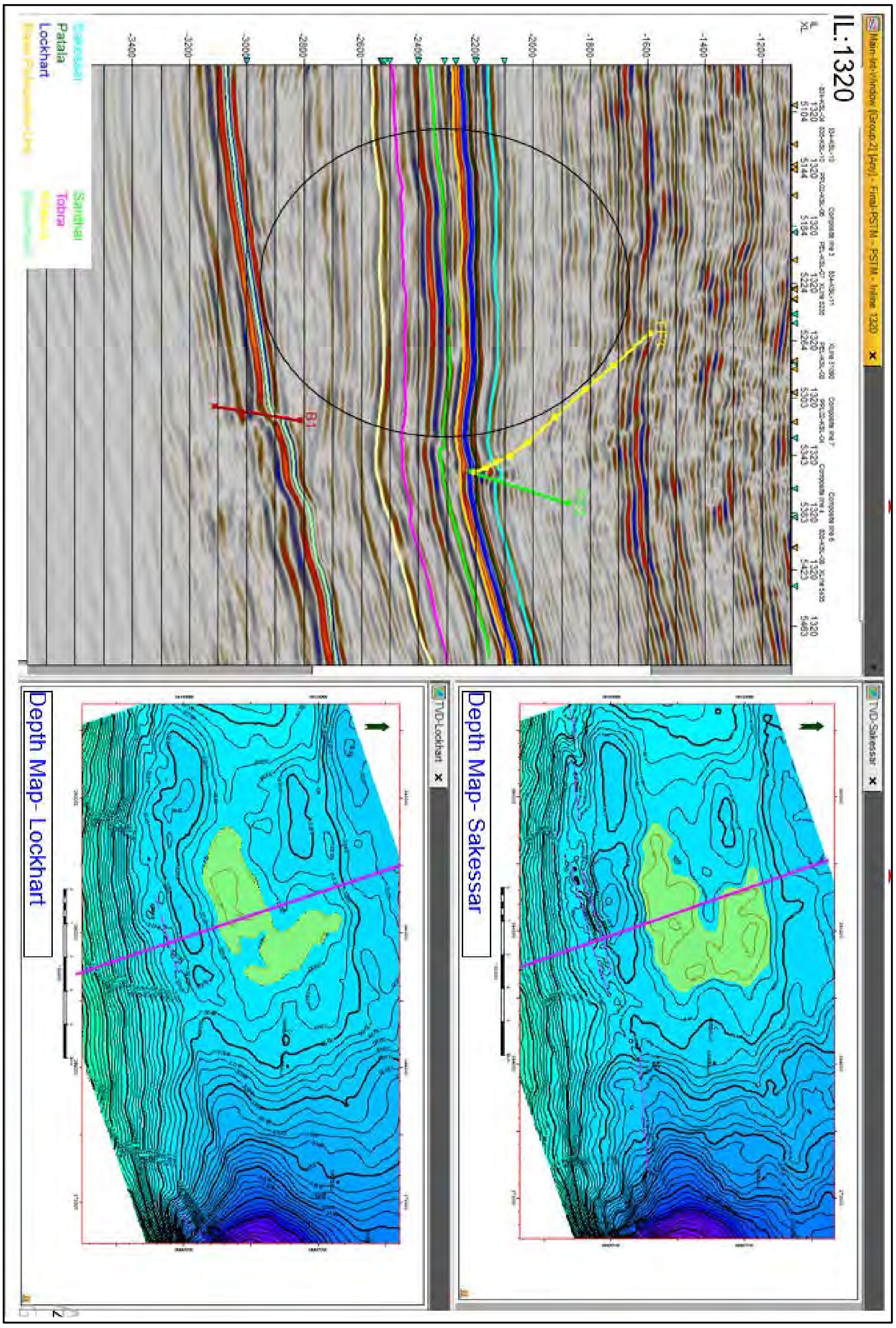

Figure 3.18: Structural interpretation cross section view over sakaesar and Lockhart using inline no 1320 detailed interpretation is carried out all key horizons were picked along with basement as well their respective map view is also attached do the right hand side pink color passing line location is shows in the left hand seismic cross section. Circled area in black color represent the anomalous behavior of the seismic response on the Talagang X-1 location related anomaly at sakaesar to khewra level.

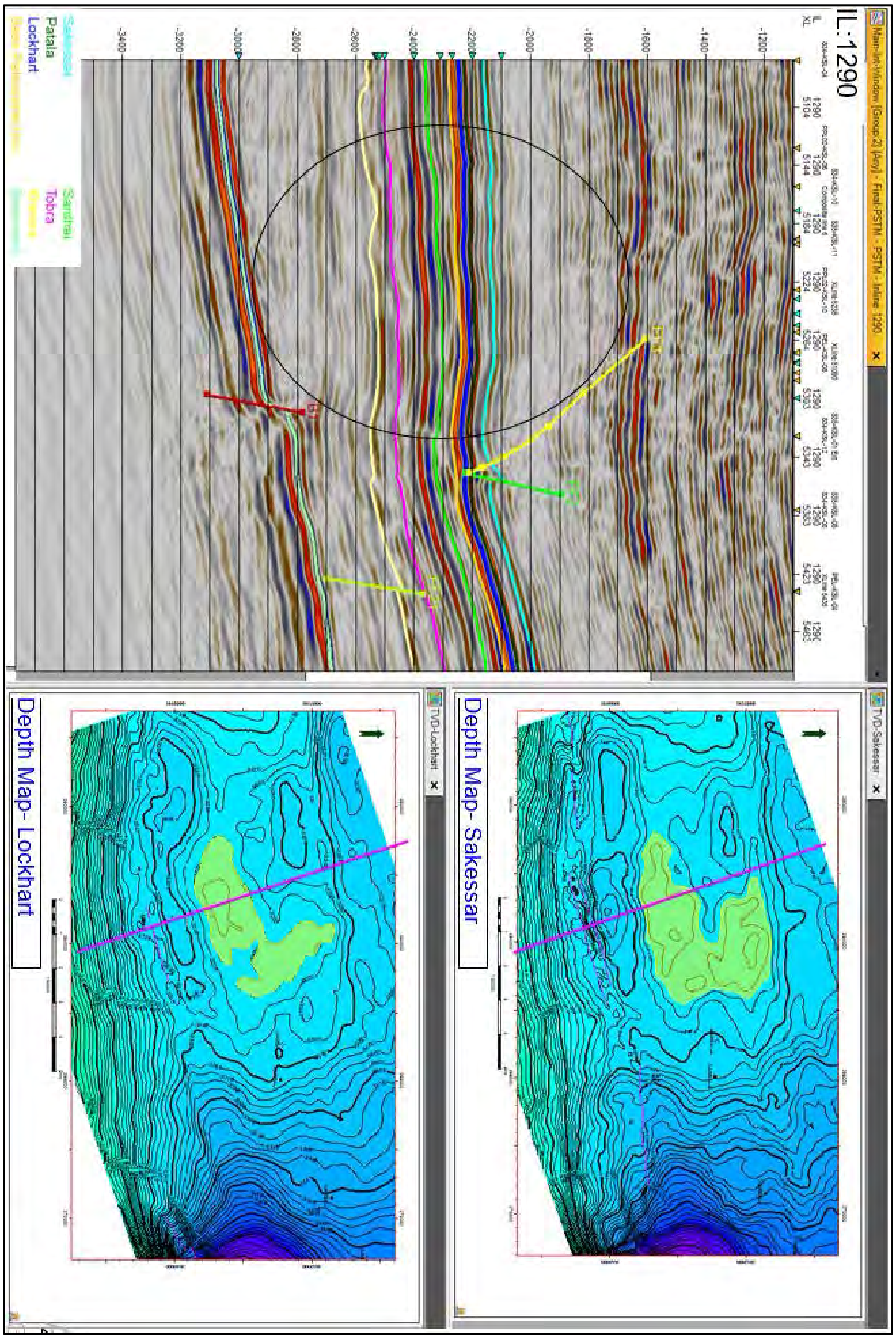

Figure 3.19: Structural interpretation cross section view over sakaesar and Lockhart using inline no 1290 detailed interpretation is carried out all key horizons were picked along with basement as well their respective map view is also attached do the right hand side pink color passing line location is shows in the left hand seismic cross section. Circled area in black color represent the anomalous behavior of the seismic response on the Talagang X-1 location related anomaly at sakaesar to khewra level.

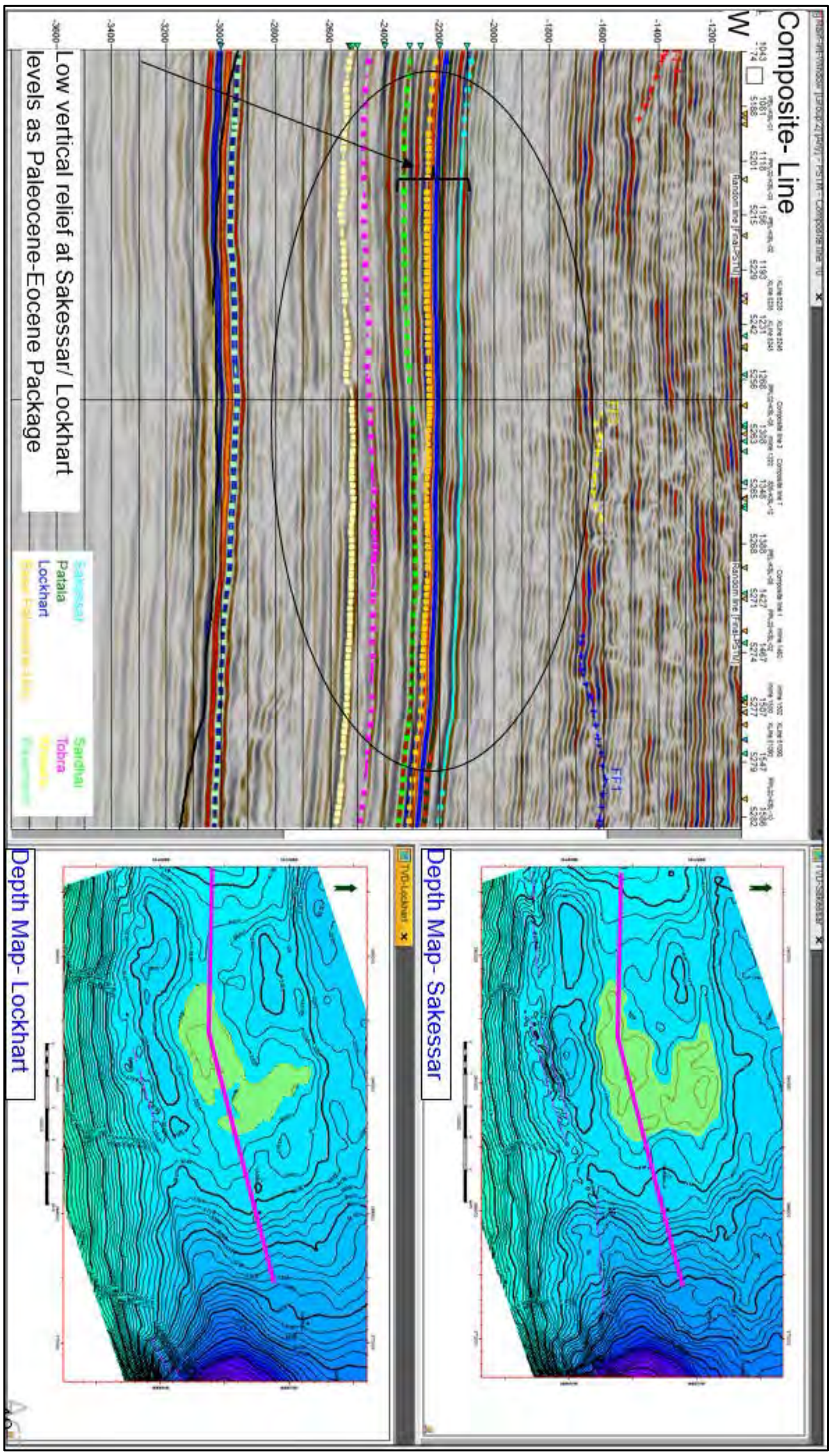

Figure 3.20: Structural interpretation cross section view over sakaesar and Lockhart using composite line detailed interpretation is carried out all key horizons were picked along with basement as well their respective map view is also attached do the right hand side pink color passing line location is shows in the left hand seismic cross section. Circled area in black color represent the anomalous behavior of the seismic response on the Talagang X-1 location related anomaly at sakaesar to khewra level.

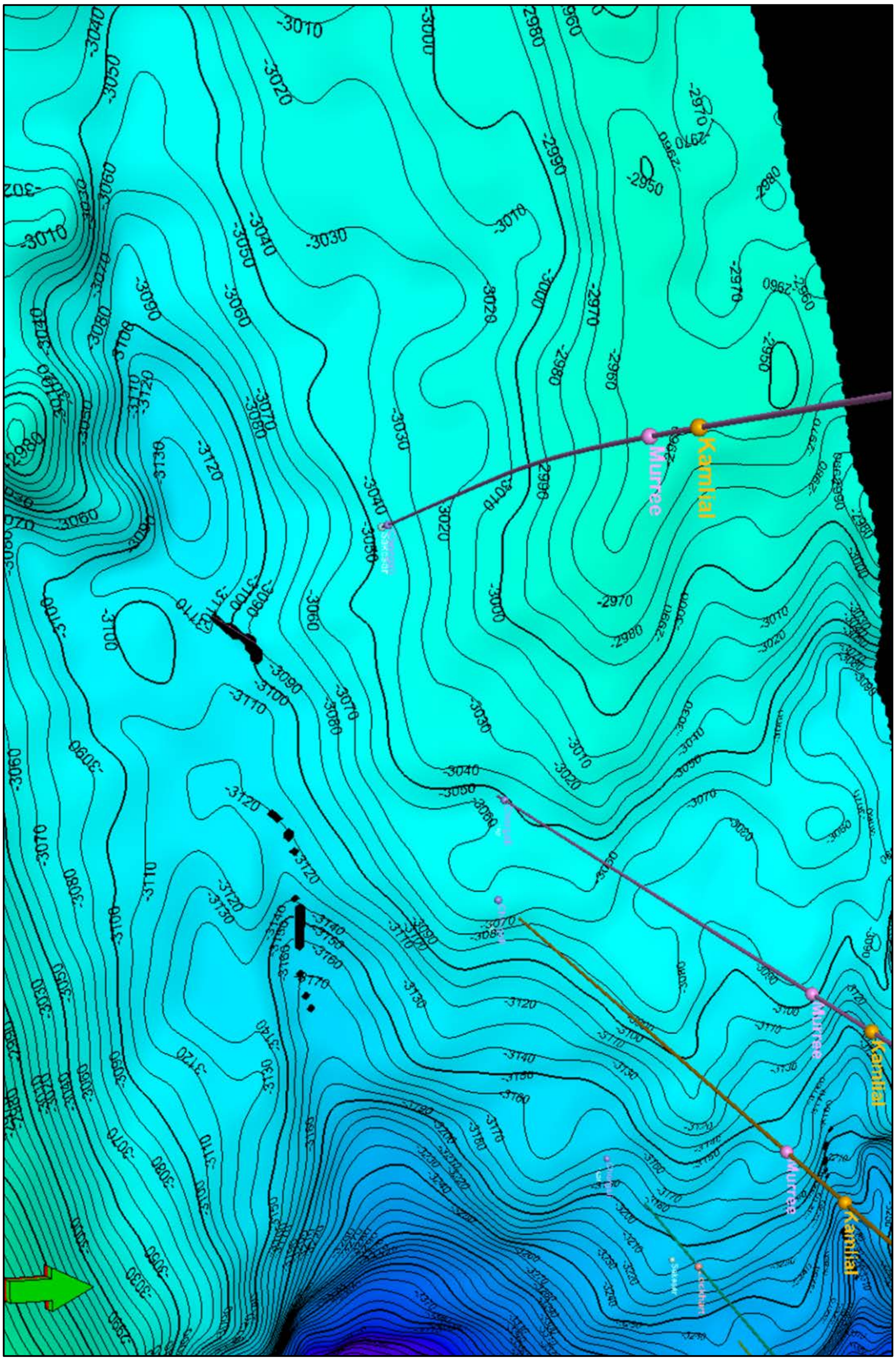

Figure 3.21: 3D seismic contour map 3D view using PSDM dataset with well trajectory 3D view reflecting the monocline behavior of the karsal structure at sakaesar level along with all wells drilled along with well tops are also highlighted o the contour map in 3D visualization which shows the clear anomalous trend around the Talagang X-1 over sakaesar.

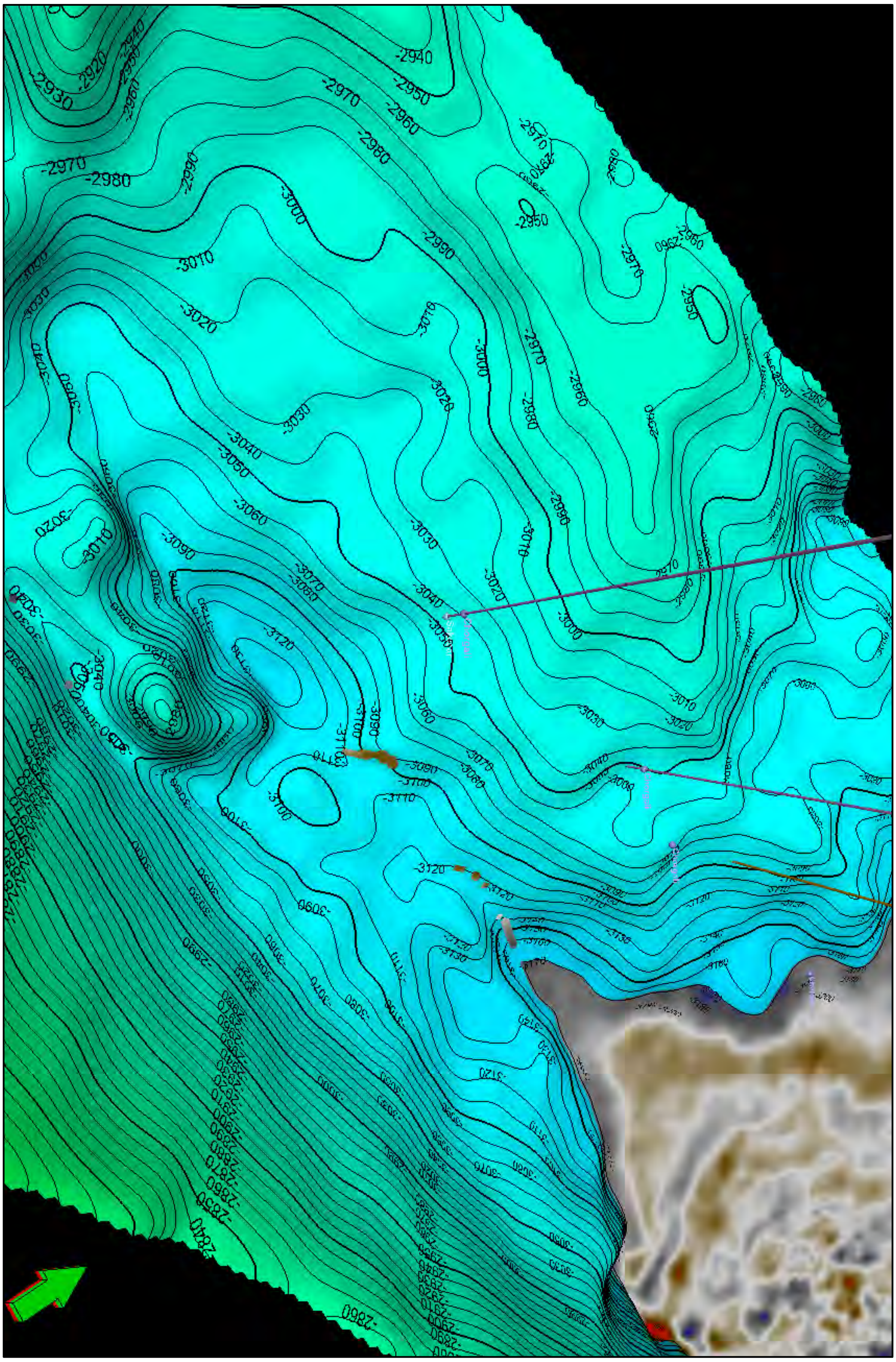

Figure 3.22: 3D seismic contour map 3D view using RTM dataset with well trajectory 3D view reflecting the monocline behavior of the karsal structure at sakaesar level with all wells drilled along with well tops are also highlighted o the contour map in 3D visualization which shows the clear anomalous trend around the Talagang X-1 over sakaesar.

3.9 Amplitude data interpretation

Frequency-specific anomalies in amplitude data interpretation refer to unusual or unexpected variations in the amplitude values of seismic data at certain frequencies. These anomalies can be caused by various factors, including noise, multiples, coherent noise, etc. Understanding and interpreting these anomalies is important to obtain precise and trustworthy outcomes from seismic data interpretation.

Noise, is a common source of frequency-specific anomalies in seismic data. This can arise from various sources, such as instrumentation, environmental factors, or the subsurface itself. To address this issue, geophysicists typically use frequency filters or noise reduction techniques to remove or reduce the noise from the data, so that it does not affect the interpretation.

Multiples, or reflections from subsurface interfaces, can also result in frequency-specific anomalies in seismic data. Multiples can cause significant changes in the amplitudes of seismic signals, making it difficult to accurately interpret the subsurface structure. To address this issue, geophysicists use various techniques, such as demultiplex techniques, to separate the primary and multiple reflections, so that they can be analyzed separately.

In the case of coherent noise, the noise is not random and has a distinct frequency content that can affect the interpretation of the seismic data. To address this issue, geophysicists use various noise suppression techniques, such as PCA principal component analysis or ICA independent component analysis, to overcome the coherent noise from the seismic data.

In summary, frequency-specific anomalies in amplitude data can arise from various sources, including noise, multiples, and coherent noise. To obtain accurate and reliable results from seismic data interpretation, it is important to understand and interpret these anomalies and to use appropriate techniques to address them. 3D seismic data amplitude interpretation using spectral decomposition involves the separation of seismic data into its component frequencies, with the goal of improving comprehension subsurface geology. The first step in spectral decomposition is to convert seismic data from the time domain to the frequency domain, allowing for the visualization of the various frequencies contained in the data.

One common technique for spectral decomposition is the Fourier transform, which transforms time-domain data into its frequency-domain representation. In the frequency-domain, each frequency component is assigned a unique amplitude that represents its strength or contribution to the overall signal figure 3.23.

Once the seismic data has been transformed into the frequency-domain, it can be analyzed in terms of its frequency content, including the dominant frequencies and their amplitudes figure 3.24. This information can then be used to make inferences about the subsurface geology, such as the presence of thin beds, channels, or other geological features.

The noise is one example of a frequency-specific anomaly that can be found using spectral decomposition and removed or decreased to enhance the quality of the seismic data figure 3.25. Geophysicists can also choose the best methods for processing and analysis by examining the frequency content of the seismic data, including, for instance, the use of frequency filters, wavelet decomposition, or inversion methods.

The utilization of spectrum decomposition in the exploration of subsurface geology offers significant advantages, particularly in the interpretation of the amplitude of 3D seismic data. Geophysicists can leverage this technique to enhance their understanding of the subsurface, enabling more informed processing and evaluation of seismic data through insights into its frequency content.

The outcomes of spectrum decomposition provide valuable information, as illustrated in Figure 3.26, where ant tracking results depict the delineation of fracture corridors. This analysis sheds light on the intricate network of fractures within the subsurface, contributing to a more comprehensive understanding of the geological dynamics. Furthermore, Figure 3.27 captures the depiction of faults, ranging from the most shallow to deeply rooted ones. This detailed representation aids in recognizing and assessing the fault structures at various depths, providing crucial insights into the subsurface geology.

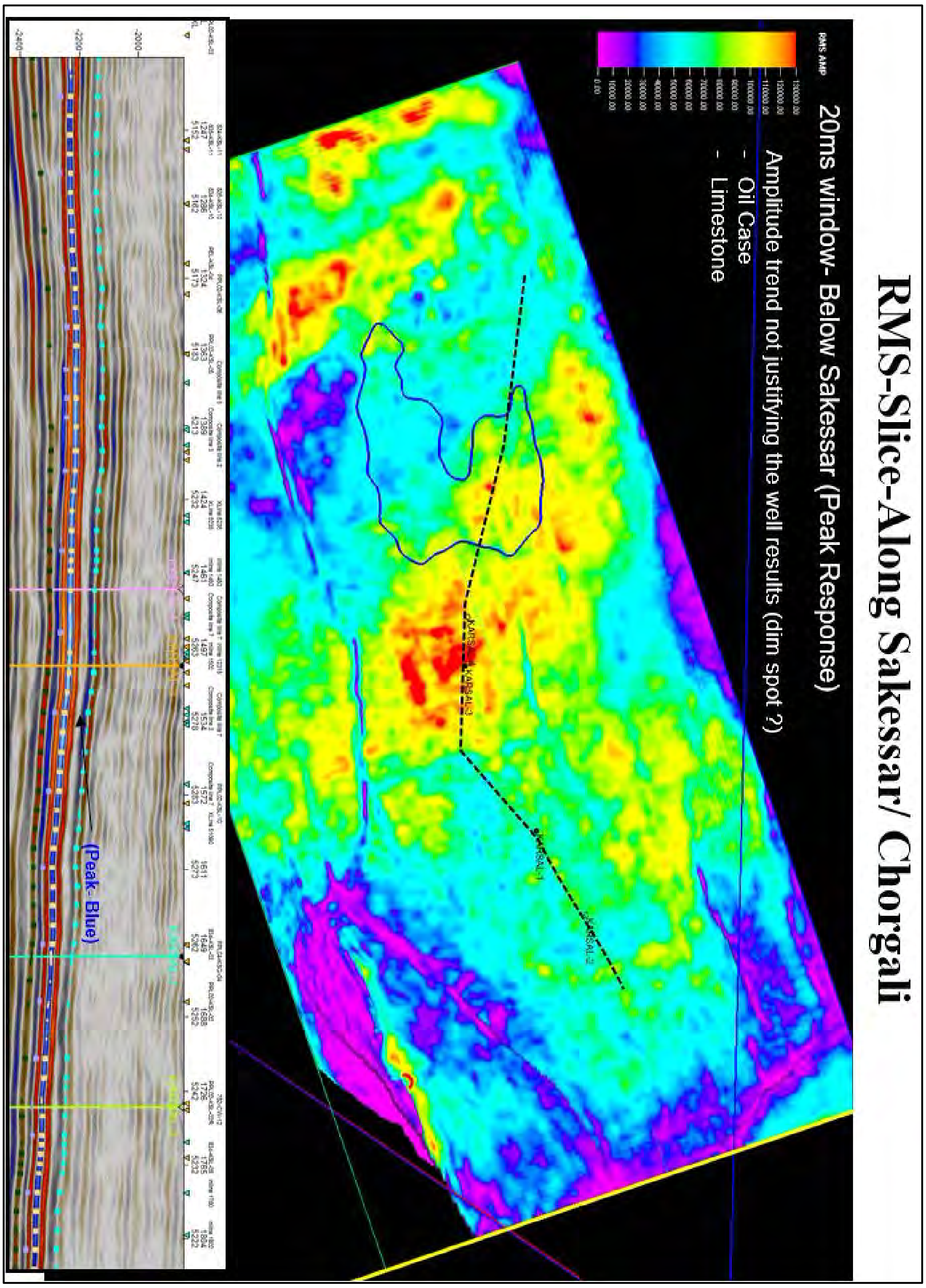

Figure 3.23: Time cross section view along with RMS slice over sakaesar with well composite lines passing through well Talagang X-1with amplitude peak response window length of 20 ms. Arbitrary section was taken into account to see the effect of the frequency content and amplitude together cumulative effect in the RMS slice view at sakaesar and chorgali where yellow color shows the presence of the high frequency content I this case spectral decomposition did not follow the lead trend over Talagang x-1.

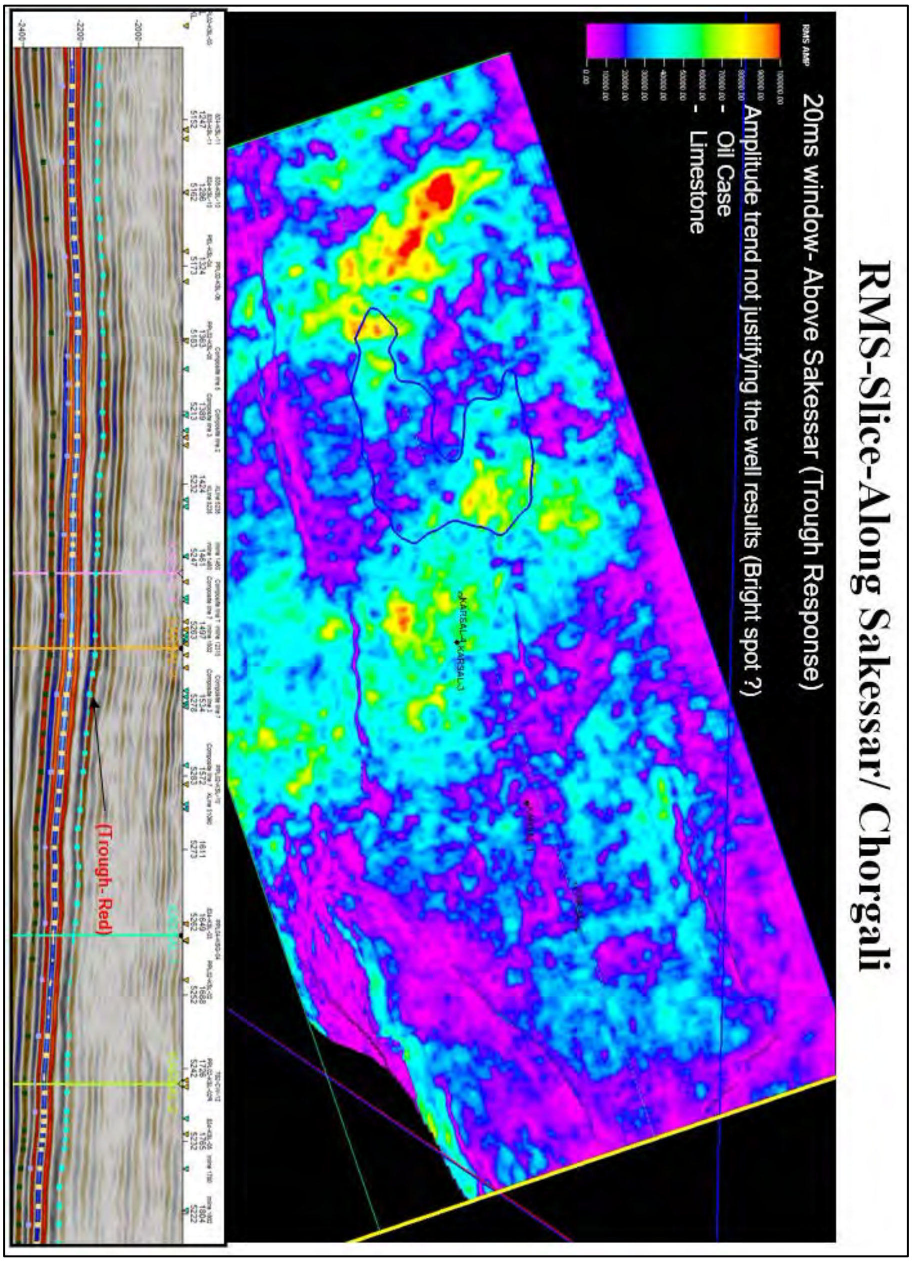

Figure 3.24: Time cross section view along with RMS slice over sakaesar using spectral decomposition with well composite lines passing through well Talagang X-1with amplitude peak response window length of 20 ms. Arbitrary section was taken into account to see the effect of the frequency content and amplitude together cumulative effect in the RMS slice view at sakaesar and chorgali where yellow color shows the presence of the high frequency content I this case spectral decomposition did not follow the lead trend over Talagang x-1.

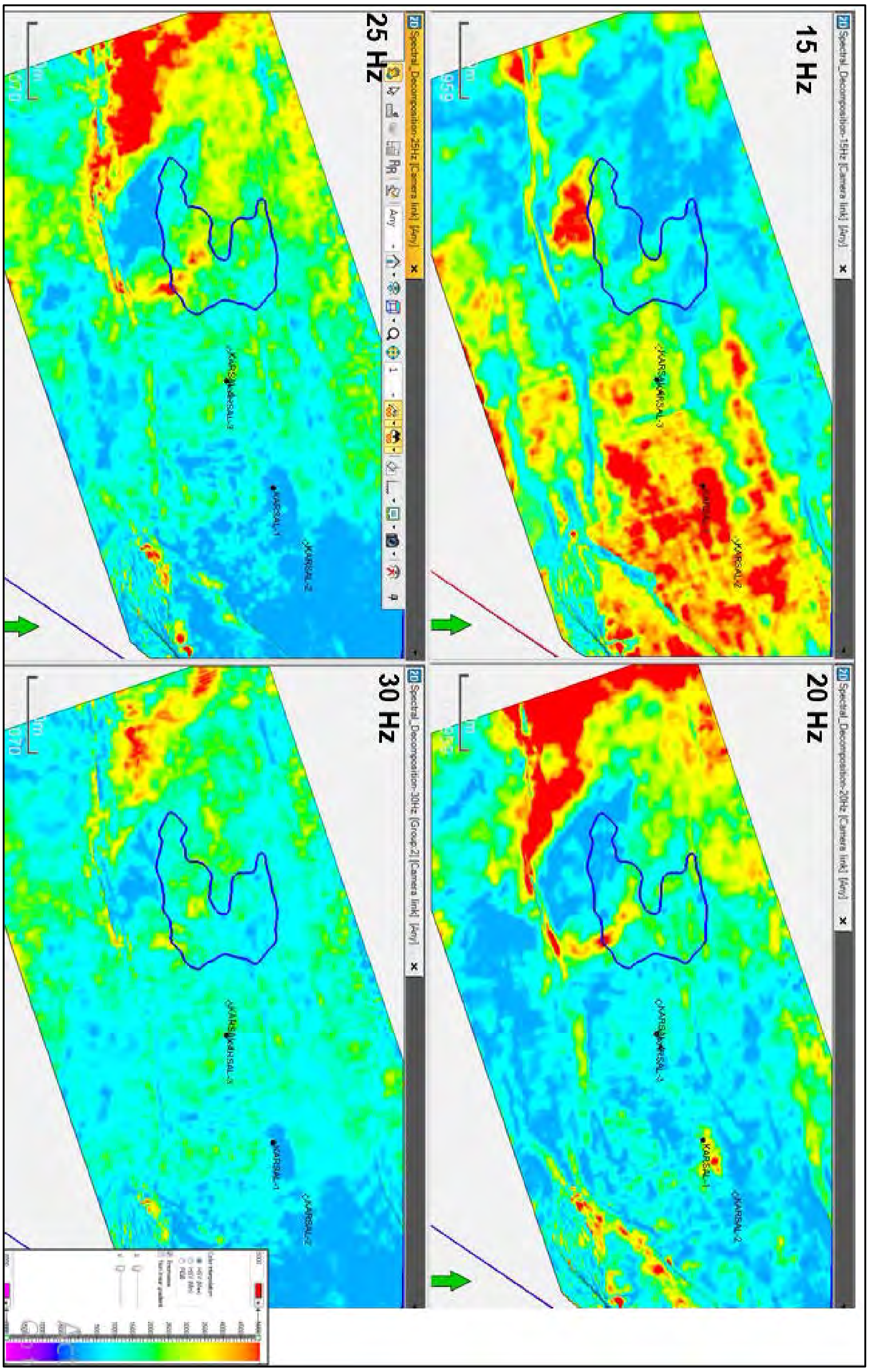

Figure 3.25: Time slice view for the 3D seismic Data of Karsal Study area Spectral Decomposition- Sakessar/ Chorgali with intensity of 15 HZ to 30 Hz. Frequency content and amplitude together cumulative effect in the RMS slice view at sakaesar and chorgali where yellow color shows the presence of the low frequency content In this case spectral decomposition did not follow the lead trend over Talagang x-1.

Figure 3.26: shows the ant track results from Petrel algorithm More Fractures at Karsal-3 (higher production) than Karsal-1 (less production). No Fractures at Karsal-2 and Karsal-4---non-Producer. Good Fractures network are evident on Karsal Prospect as well along with karsal 1 and 3 together which give strength to move for drilling because minute trending lines represent the fracture corridor network not single line for one set of fracture.

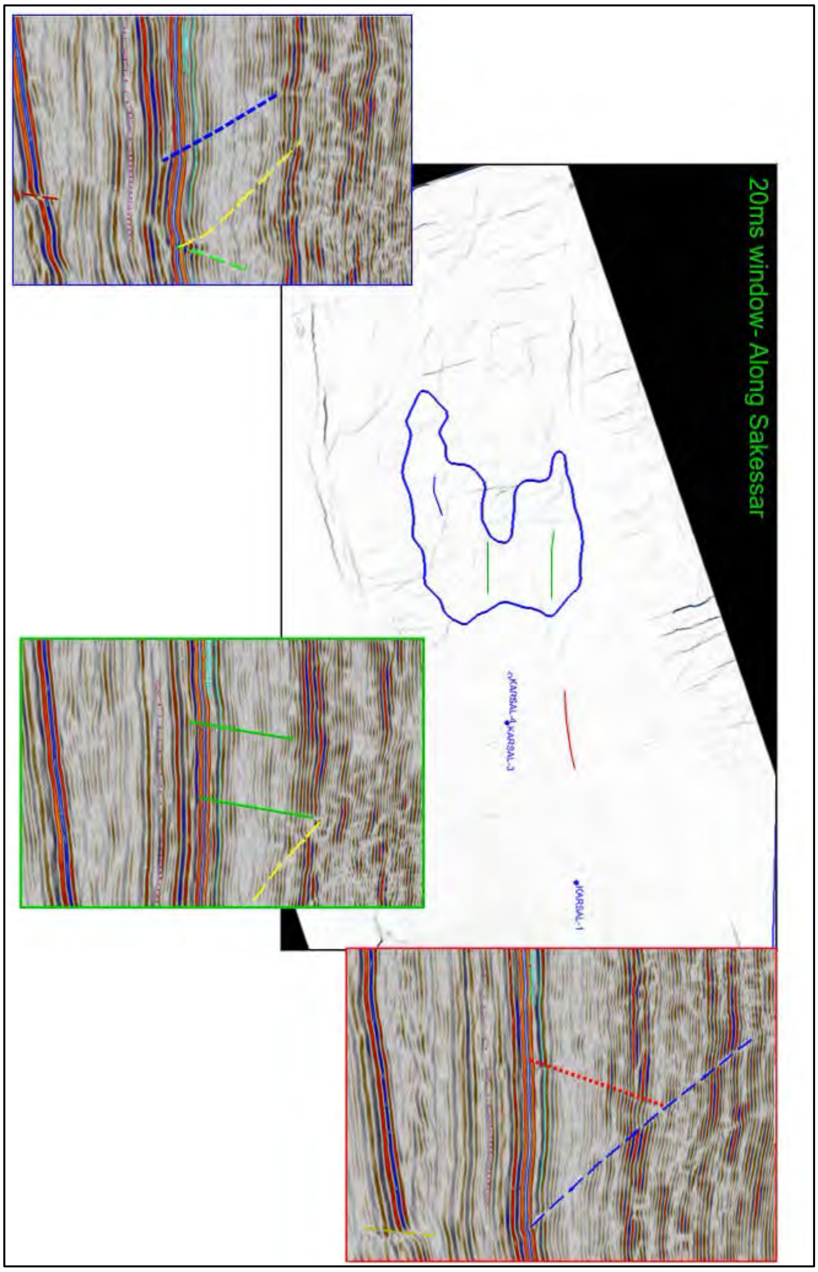

Figure 3.2: Number of faults present in Siwalik (Lower and upper), some of which extend deep into Eocene Package Limited/ No throw at most of locations along these faults Potential Source for fractures generation in Carbonate Reservoirs. Ant Track result correlation with seismic amplitude relativity data set which reflect the presence of the fault network evident of the fractures downward as well.

Chapter -04

Attribute Analysis

4.1 Introduction

A collection of characteristics defined as seismic attributes are drawn from seismic data. The usual attribute of the data is its amplitude, but other attributes can also be computed. The most common post-stack attributes are instantaneous attributes, which are computed for each sample of the seismic trace. These attributes can be calculated on both pre-stack and post-stack data. In essence, the seismic energy is a mechanical energy made up of both kinetic and potential energy elements. Experimental research has revealed that only the kinetic energy component can be quantified.

It is essential to calculate the seismic energy's artificial potential energy component to calculate the instantaneous attributes (Castagna, J. P., & Backus, M. M. 1993). The Hilbert transform can be used to calculate the imaginary component, which is a 90-degree phase-rotated version of the input seismic trace (Taner et al., 1979).3D seismic attribute analysis was performed to delineate lineaments corresponding to possible fracture corridors in Chorgali/Sakesar reservoir across Karsal field. Two seismic data cubes, PSTM and PSDM data volumes, were used for this analysis.

The goal of 3D seismic attribute analysis is to characterize locations and lateral/vertical extent of fracture corridors in the reservoir that may significantly contribute to hydrocarbon production in an otherwise low-porosity/low-permeability carbonate reservoir. Also, the computed seismic attributes and their interpretation served as input to the natural fracture prediction (NFP) workflow that is discussed Seismic data aids in imaging the subsurface through seismic reflections at interfaces of acoustic impedance contrast. Different lithologies and episodes of sedimentary deposition can be easily identified from the seismic data. Apart from the major events of deposition seismic data also captures the discontinuities (no reflection) or near vertical planes of reflection.

These events are mostly represented as faults. Faults are relatively large scale features in comparison to fractures, which are mostly captured through borehole images around the wells. To identify fractures from the seismic data it is necessary to extract the subtle features captured in the seismic which can represent fracture corridors. To achieve this objective various edge-detection attributes (or their combination) can be used to highlight these subtle discontinuities. Maximum curvature, consistent dip, variance, dip deviation and ant tracking are such attributes that are used in this study. These attributes are described in the following section.

4.2 Applications of Seismic Attributes

Uses of Seismic attributes include:

- To detect artefacts and assess the quality of seismic data.
- Mapping seismic facies to anticipate depositional habitats.
- Hydrocarbons detailed evaluation.
- Reservoir characterization.

4.3 Seismic Attributes and its variances

In spite of temporal migration, seismic attributes can be calculated from either pre-stack or post-stack data. In each of these scenarios, the calculation of characteristics is the same. It is possible to categories attributes into many distinct groups, and various authors have put forth their own classification schemes. We propose a classification in this context based on the attributes' characteristics (Taner, 1994).

4.3.1 Pre-Stack Attributes

CDP or image collect traces are used as input data. They will have details about offset and azimuth directions. These calculations produce enormous quantities of data, so they are not useful for preliminary research. They do, however, carry a significant amount of data that is pertinent to fluid content and fracture orientation. This class includes AVO, velocities, and azimuthal variation for all characteristics (Taner 1994).

4.3.2 Post-Stack Attributes

The stacked data is used to determine the post stack attributes. The characteristics obtained from the intricate seismic signal are what lead to the attribute related facts pertaining to azimuth. Data entry methods include CDP stacking and migration. It's important to keep in mind that time-migrated data will maintain its time relationships, which means that temporal factors like frequency will keep their original physical dimensions. In depth migrated sections, wave number, a function of propagation velocity and frequency, takes the role of frequency.

For early reconnaissance investigations involving significant amounts of data, post-Stack attributes offer a more manageable solution (Taner 1994).

4.3.3 Seismic Edge Detection Attributes

Seismic edge-detection attributes measure local dissimilarity between seismic waveforms or local variations in seismic amplitude in 3D. Most commonly used edge-detection attributes for structural interpretation include maximum curvature, variance and dip deviation. These attributes have found various applications in stratigraphic and structural interpretation of geological features that are detectable at seismic resolution (Chopra and Marfurt, 2007). These attributes are typically used to guide seismic interpretation and to provide inputs for reservoir characterization and modeling. Their common applications include structural interpretation of seismic data for identification of faults and fracture networks/corridors in the subsurface, building discrete fracture network (DFN) models, validation of natural fracture prediction methods, etc.

4.3.4 Seismic attributes used for fracture characterization

Seismic attribute used for the fracture characterization are listed below which are widely used for the limestone fracture network identification.

- Maximum Curvature
- Variance
- Dip Deviation
- Consistent Dip Model
- Ant Tracking

A seismic characteristic that emphasizes discontinuities and removes stratification from the 3D data (Figure-4.1). It is an indicator of the degree of local bending in a surface that is determined by the geometrical consistency of seismic amplitudes at a specific location inside a seismic cube.

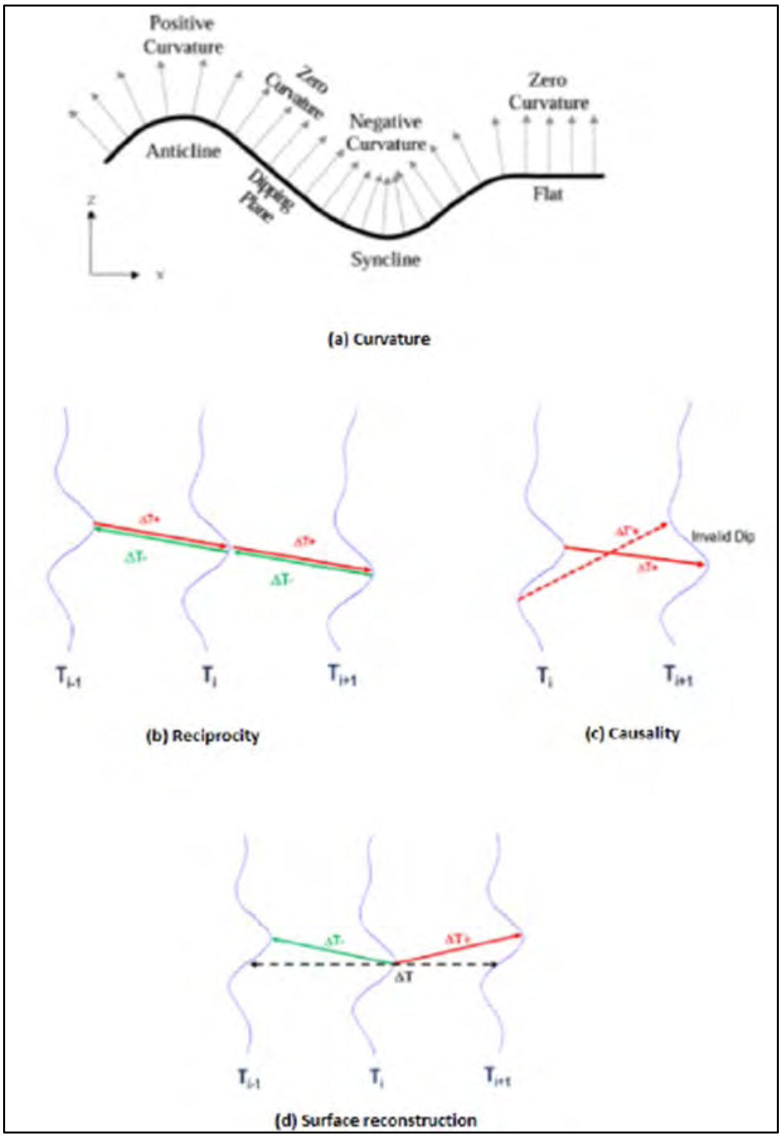

Figure 4.1: Description of seismic curvature and dip model attributes (Randen et al., 2001).In a seismic volume, it depicts the trace-to-trace variation over a specific 3D samples window. Thus, a seismic data cube's variance characteristic offers a local measurement of signal discontinuity. In contrast to geological discontinuities like faults or fracture corridors, which cause variations in seismic amplitude that lead to a higher variance, an unbroken reflection layer's variance is relatively modest (Randen et al.2001). The local variation is calculated for each voxel using horizontal sub-slices (Randen et al. 2001).While abrupt changes in amplitude caused by a discontinuity result in large variance, lateral continuity of amplitude creates a small variance. Finding fracture corridors and verifying fault patterns are both made easier by the variance attribute. It is used to find breaks in the amplitudes' horizontal consistency (Randen et al., 2001).

4.4 Ant Tracking

Edge enhancement is carried out by Schlumberger's proprietary ant tracking technology, which locates faults, fractures, and other linear anomalies within the seismic data volume (Cox, Tom, and Krista Seitz, 2007). In order to analyse the swarm's collective behaviour, swarm intelligence ideas are used to introduce a large number of agents (ants) into the data volume.

The behaviour of two ants arriving at the nest simultaneously in quest of food served as the model for the ant tracking attribute. The ant that takes the shorter route will get there before the ant that takes the lengthier route. As a result, the shorter path will be marked with more pheromone than the longer one, making it more likely that the next ant, who will be affected by the pheromone, will choose the shorter path. We are able to improve and recover fault-like replies in the attribute by encoding fault properties expectations as behaviour of intelligent software agent. In the foraging scenario mentioned above, an agent will behave very similarly to an ant by making choices based on its pre-coded behaviour and emitting "electronic pheromone" along its train. A large number of agents are to be dispersed throughout the volume, and each agent is to be allowed to travel along what appears to be a fault surface while emitting pheromones.

Agents that are deployed at locations with no surface, only unstructured noise, or surfaces that do not meet the requirements for a fault (such as the remains of a reflector) will be terminated soon after or immediately after being deployed. On the other hand, agents stationed at a fault should be able to locate the fault surface. We anticipate that surface fulfilling our expectation for fault will be traced by many agents deployed at various positions in the volume, and hence be strongly marked by "pheromone". Unmarked or faintly marked noise and surfaces that are unlikely to be faults will be covered up by the threshold.

The ant tracking attribute yields an enhanced discontinuity volume when compared to variance and dip deviation input volume; time slice at a specific time value shows the orientation and the distribution of the faults along the whole area.

Variance and dip deviation attributes are estimated from seismic amplitude data over voxels (seismic volume elements) defined by vertical window sizes and horizontal filter lengths. The optimum filter length depends on the data quality and objective. Smaller filter lengths are preferred for fracture characterization whereas larger filter lengths may be acceptable for interpreting faults. Too short window sizes tend to capture more of the lateral features in the data that are belongs to interfaces of reflection and dip, rather than steeply dipping features that may be related to faults and fracture corridors. Similarly, too large window sizes or lateral filter lengths reduce any random noise but also smear the response of steeply dipping features. This may result in reduction of sharpness of the detected edges and may obscure real discontinuties in the subsurface. Optimization of filter lengths is therefore required to ensure that any random noise in the data does not produce spurious features that might be interpreted as structural features / geological discontinuities. For this purpose, multiple variance attribute volumes were generated as virtual cubes in Petrel for a range of filter lengths: 3-7 traces for horizontal filter lengths and 6-16 samples for vertical window sizes. Based on detailed analysis of the produced virtual volumes, To calculate variance from the PSTM seismic cube, a frame size of 12 samples and a filter length of 5 traces were selected figure 4.2. The 3D view of the complete study area is highlighted in camera view figure 4.3. The PSTM seismic cube was found to have a poorer signal to noise ratio than the PSDM seismic cube. To compute variance from the PSTM seismic cube figure 4.4, a larger window size of 16 samples and a filter length of 7 traces were selected.

Variance and dip deviation attributes provide seismic discontinuity volumes from which lineaments may be extracted that may be related to structural features in the sub-surface such as faults and fracture corridors. The variance and dip deviation attributes are subjected to ant tracking in order to accomplish this. Ant tracking operates similarly to how ant colonies act to maximise their hunt for food, as was previously mentioned. By scattering "artificial ants" or "agents" as seeds on a seismic discontinuity volume in order to follow and capture lineaments, the ant tracking attribute is calculated.

Different parameters that work together to control these agents' behaviour are what fuel the ant tracking process. These factors also aid in distinguishing between small- and large-scale features, such as fracture networks and corridors, and large-scale features, such as faults. These variables are explained below. PSTM interpretation for the old school of mind and vintage processing revealed its results figure 4.2 and its PSDM new processed result were validate velocity variations with interpretation as shown in figure 4.4

The seismic structural characteristics that are used to characterise fractures are extremely susceptible to minute changes in seismic amplitude and frequency. The level of coherent noise in the data, such as the seismic acquisition footprint, may be comparable to the level of the signature of fracture corridors found in the data. In this situation, noise and fracture passageways can still be distinguished if:

(1) the level of noise is not significantly high and,

(2) the orientations of major fracture corridors do not align with the noise trend.

In order to assess this, seismic amplitudes were analyzed directly to identify any coherent noise present in the data and additional structural seismic attributes were computed for QC purpose such as dominant frequency, consistent dip model and maximum curvature. The seismic attributes and procedure used for seismic data quality assessment are described below.The cross section of the line passing through wells as shown in figure-4.5 and respectively figure4.6.

4.5 Dominant Frequency:

Dominant frequency refers to the frequency that has highest amplitude in the spectrum of seismic data. Large lateral variations in dominant frequency at the reservoir level indicates distortions in the seismic wavelet due to noise and applied strategy (Figure 4.10 and 4.11 respectively).

4.6 Consistent Dip Model:

Conventional dip estimation methods calculate the instantaneous dip only, ignoring the constraints of global consistency. The 'Consistent dip' model combines conventional volumetric dip computation methods with an understanding of the global dip consistency constraints, to produce an attribute that more accurately defines reflector dip consistency within the seismic volume. 'Inconsistent' dips can typically be attributed to geological complexities in the subsurface and used as a proxy for fault and/or fracture identification and the detection of salt/shale volumes. The 'Consistent dip' attribute accounts for the global consistency of the seismic waveform from trace to trace by employing x, y, and z-weighted computation methods. Using reciprocity as the foundation, a repeated optimization technique is used, causality and consistency of the waveform (V. Aarre, 2010), to take into account the global consistency constraints and to produce an improved representation of the true structural dip as shown in the figures 4.6 and 4.7 respectively constant dipping and azimuth of the strata can also be validated through state of the art algorithm opted for the selected results based on the geological information provided as show in the figures 4.12 and 4.13 respectively different colors represent the dip and azimuth of the structuration trend which also reflect the monocline behavior of the Karsal anticline previously names as based on the surface feature as highlighted in figures 4.14 and 4.15 respectively with ant track results integration along with variance cube as well.

4.7 Maximum Curvature:

a seismic characteristic that emphasises discontinuities in the 3D seismic data and removes stratification figure 4.1 component (a). It is an indicator of the degree of local bending in a surface that is determined by the geometrical consistency of seismic amplitudes at a specific location inside a seismic cube.

To evaluate the data integrity, seismic data cubes from PSTM and PSDM were both examined. Significant structural variations between the given Top and Base Sakesar surfaces, as deduced from the two cubes, were seen as shown in figure-4.8 and figure-4.9 respectively. Using the supplied velocity model, the PSDM cube was converted to two-way time (TWT), and the dominant frequency attribute was calculated from the two cubes. In both cubes, Top Sakesar' s dominant frequency changes primarily uniformly, and no discernible or coherent noise was present as shown in the figure 4.16.

4.8 variance-based Fracture logs:

As reflected the reverse strategy for the well FMI a same approach is used to calculate the PSTM based fracture set from variance cubes counted against the all-present wells (Figure 4.15) and its respective cross section of variance (Figure 4.16). PSDM variance is also calculated based on the Sakesar surface as shown in the figure 4.17 and cross section view of the seismic variance section along with line passing through the wells (Figure 4.18) and the same method used for the PSDM cube as well to generate the all wells passing through the fracture set from the variance cube as well about PSDM (Figure 4.19) from the top of the surface of the sakaesar as sown in the figure 4.20 and the bottom part is also shown in the surface of Sakesar as shown in the figure 4.21.

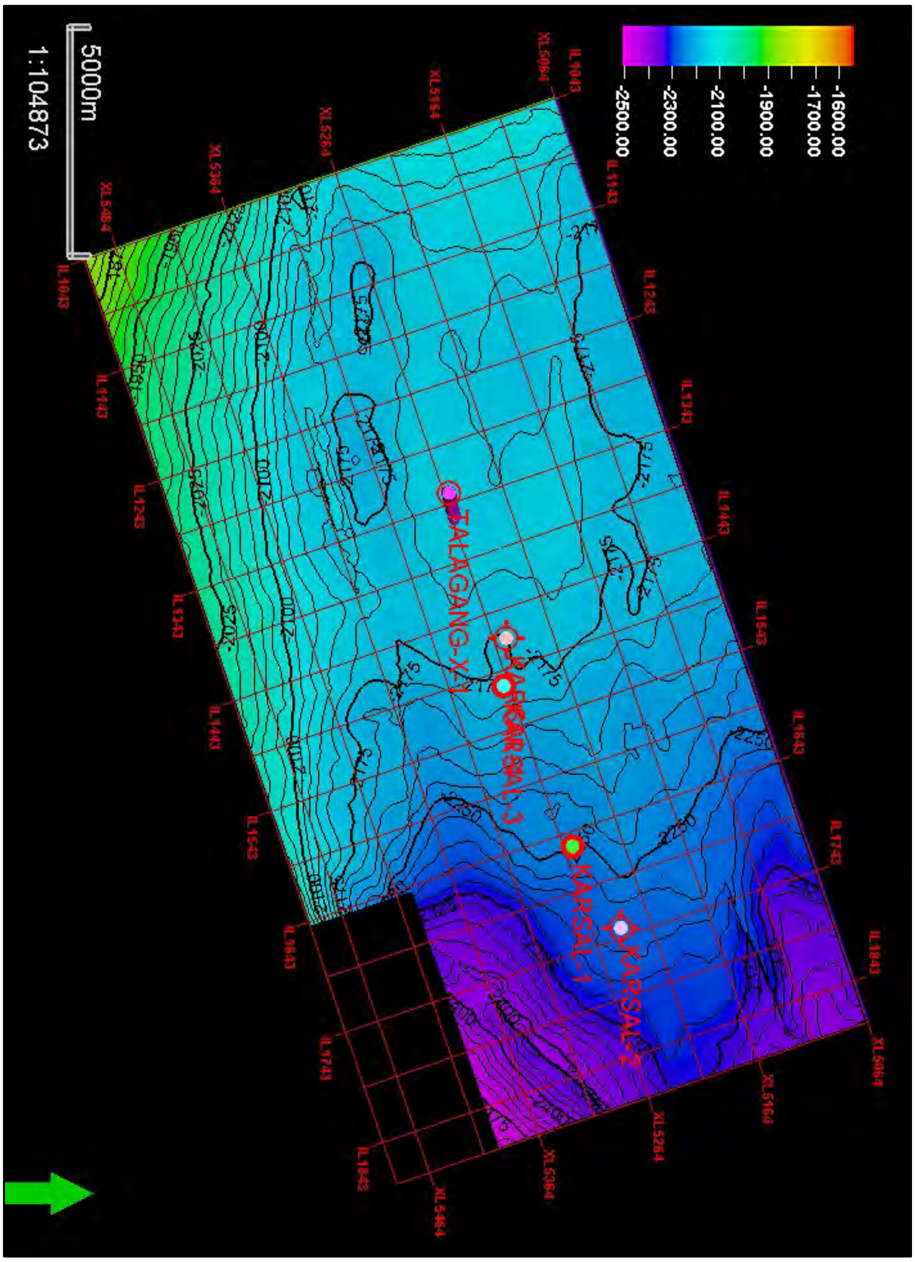

Figure 4.2: Top Sakesar surface - PSTM Two-way time map of Top Sakesar surface from PSTM seismic data.

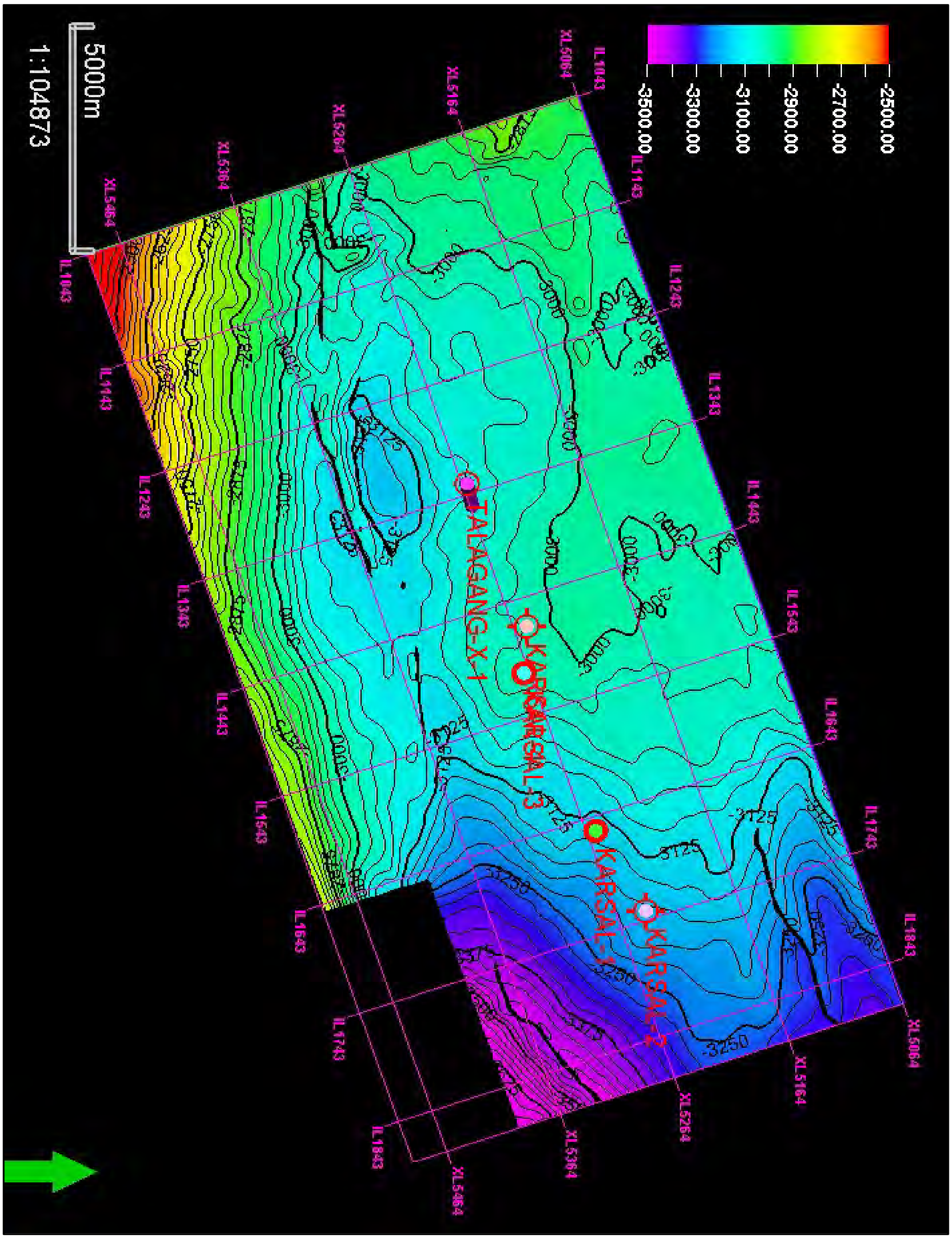

Figure 4.3: Top Sakesar surface – depth contour map from PSDM seismic data.

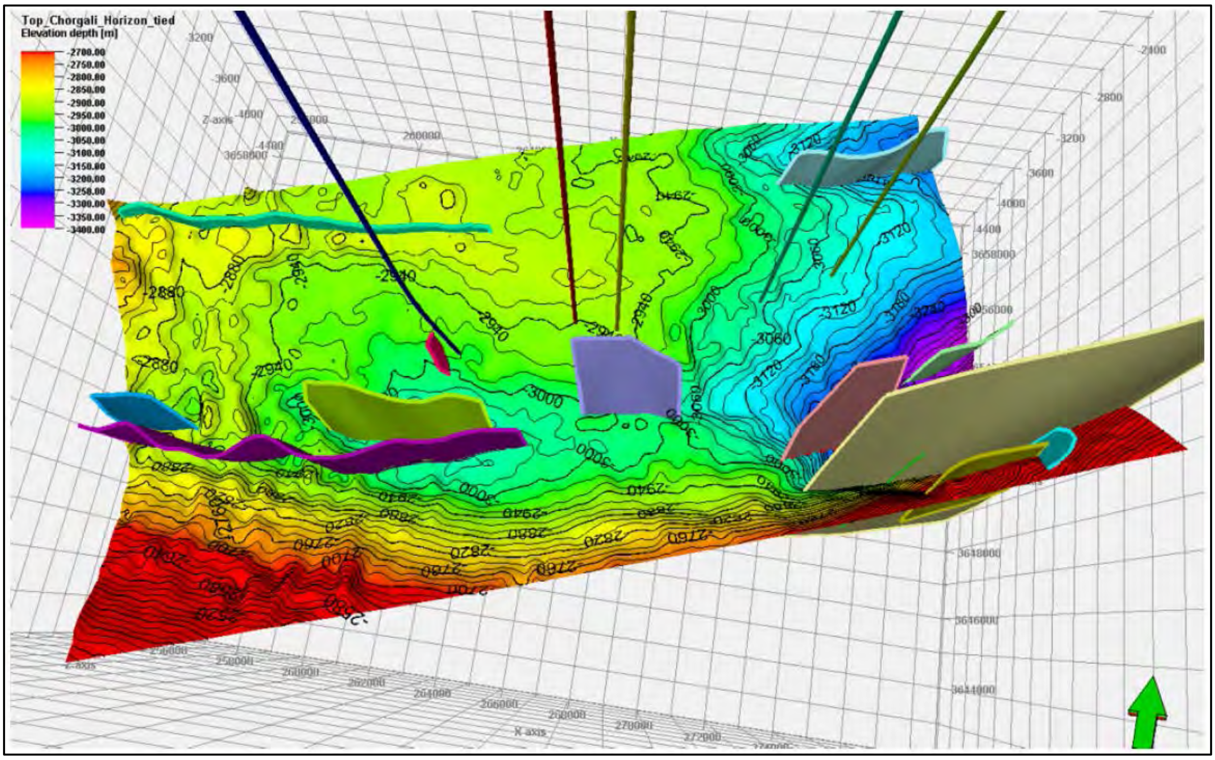

Figure- 4.4: Depth Map of Top Chorgali Surface -3D View Depth Map of Top Chorgali Surface -3D View

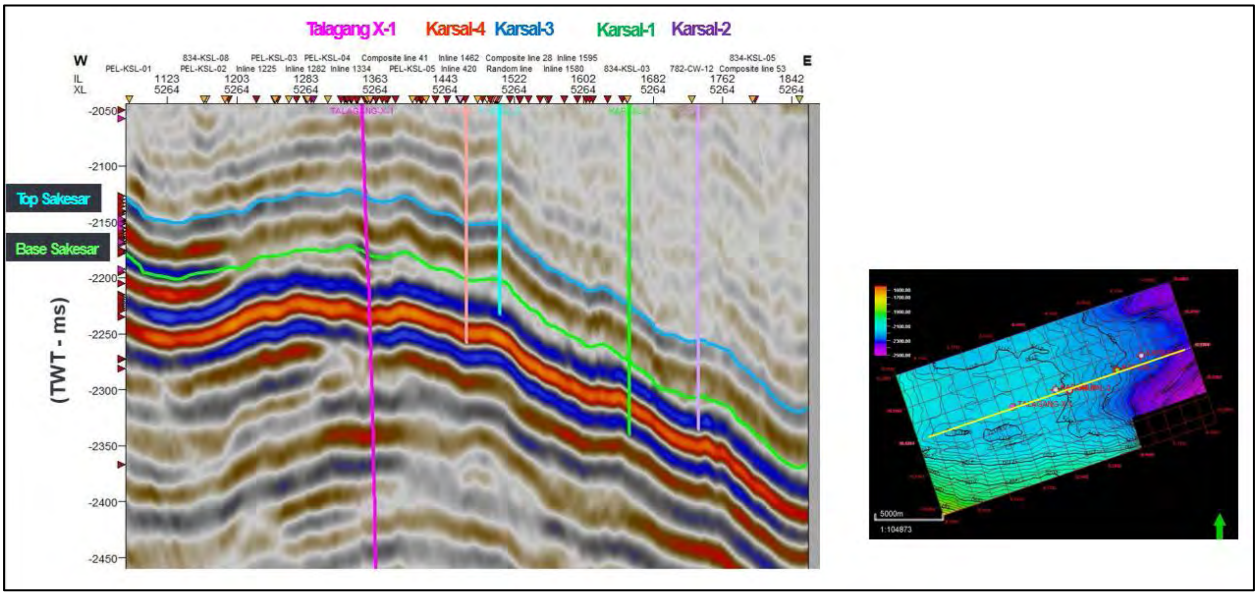

Figure- 4.5: PSTM – Crossline 5264 Top and Base Sakesar horizons interpreted on PSTM Seismic Data – Crossline 5264.

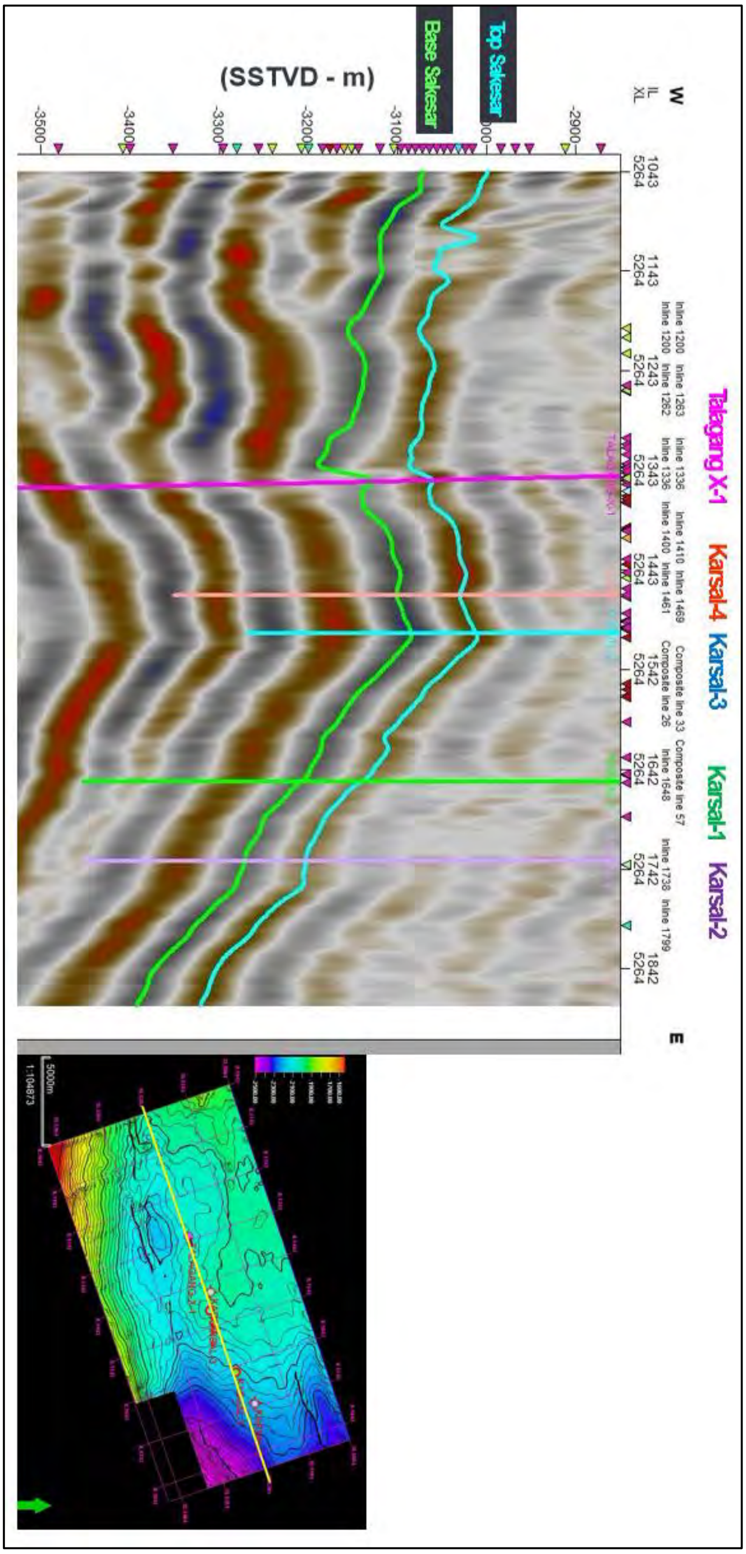

Figure -4.6: PSDM – Crossline 5264 Top and Base Sakesar horizons interpreted on PSDM Seismic Data – Crossline 5264.

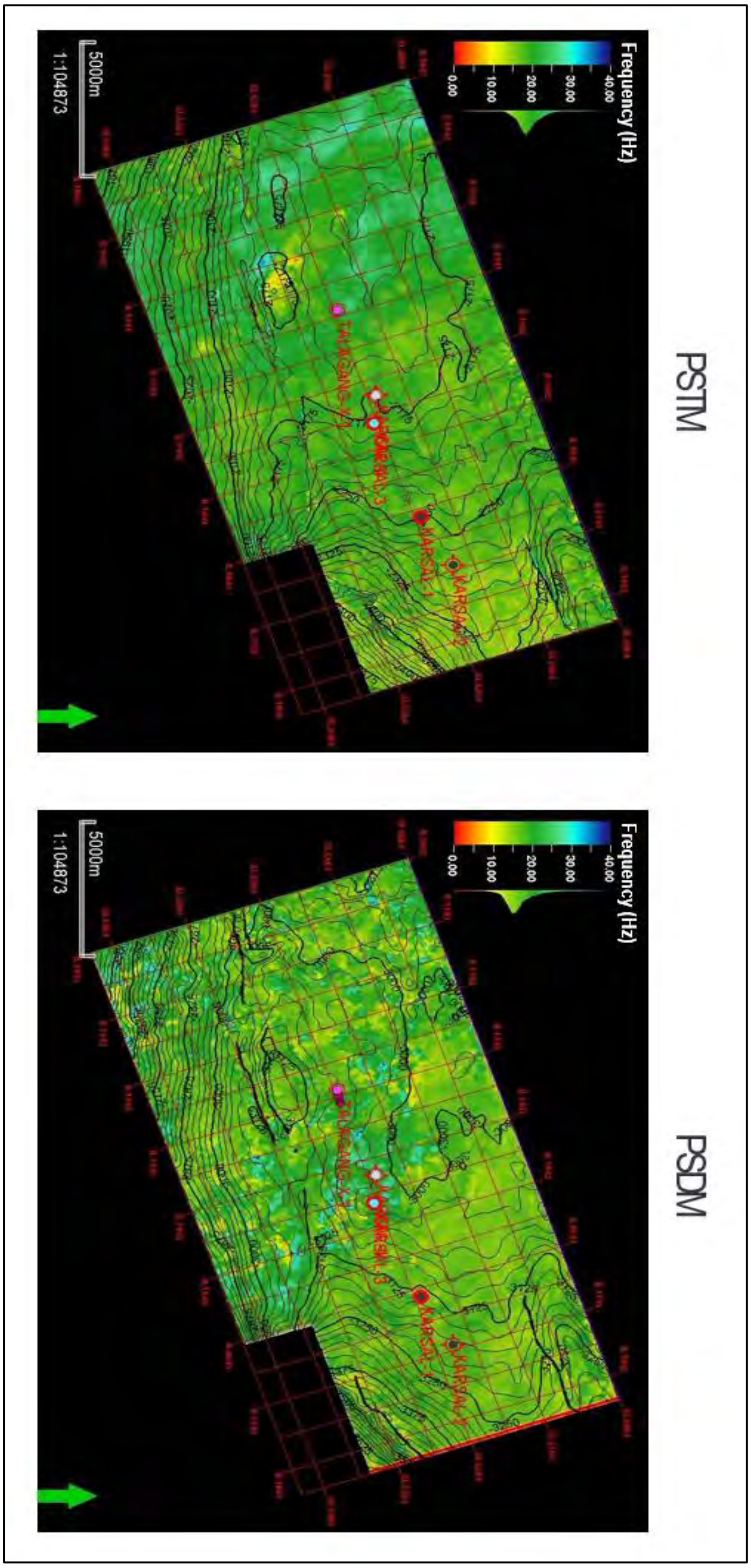

Figure 4.7: The dominant frequency mostly varies uniformly across top Sakesar. Some high-frequency noise is observed but it is not expected to impact quality of seismic attributes significantly.

Structural lineaments corresponding to the fracture corridors are typically too weak to be easily observable at the scale of recorded seismic amplitudes. However, if significant coherent noise such as acquisition footprint is present in the seismic data, it should be directly visible at the recorded seismic amplitude scale. To investigate if coherent noise is presence in the data, seismic amplitudes were directly analysed on the horizontal slices of the 3D seismic cubes while varying amplitude scaling as shown.

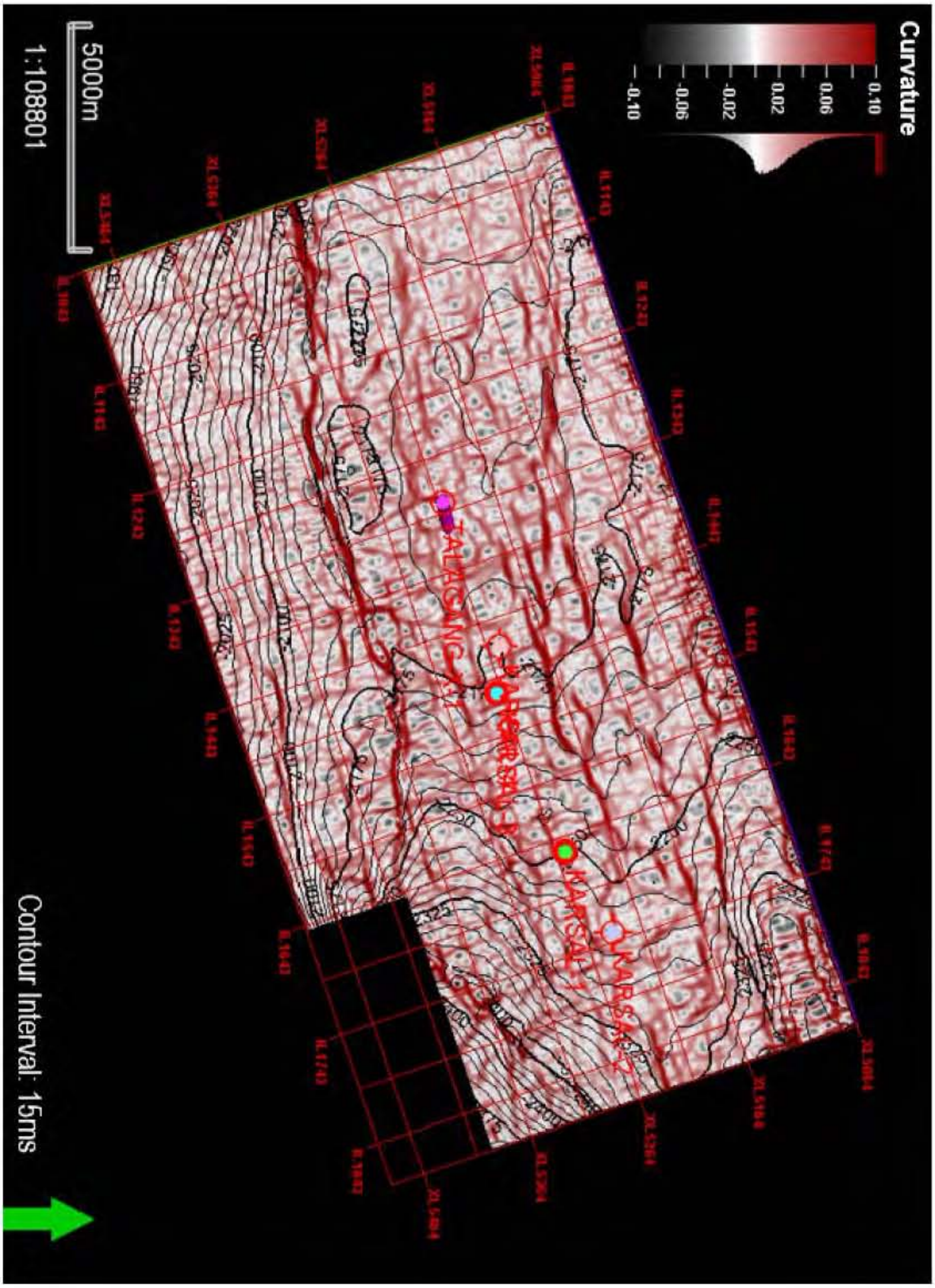

Figure 4.8: Top Sakesar surface - PSTM - Coarse scale max curvature Coarse scale (radius = 20 bins) maximum curvature attribute computed from PSTM seismic cube displayed at the Top Sakesar surface.

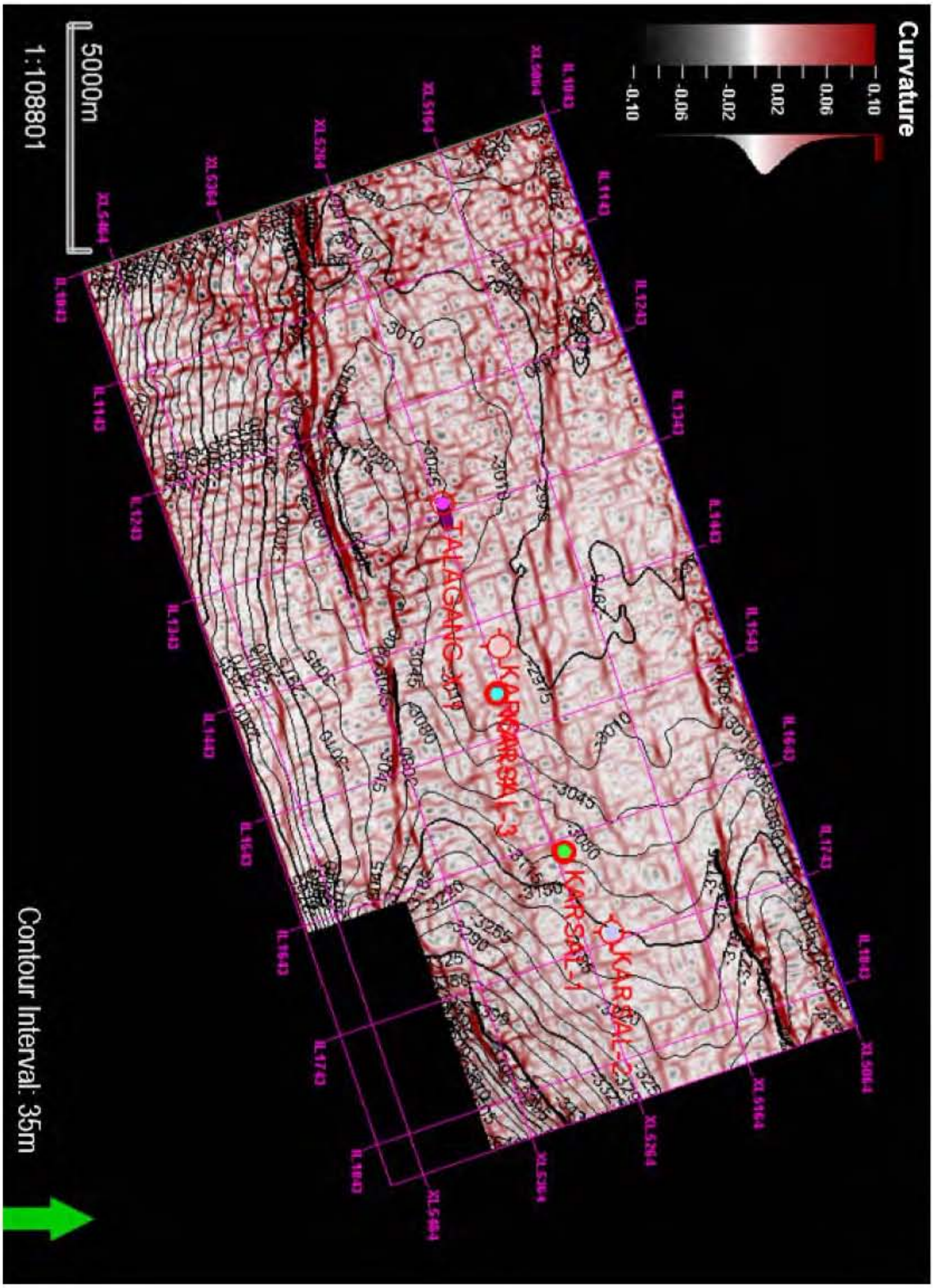

Figure 4.9: Top Sakesar surface - PSDM - Coarse scale max curvature Coarse scale (radius = 20 bins) maximum curvature attribute computed from PSDM seismic cube displayed at the Top Sakesar surface.

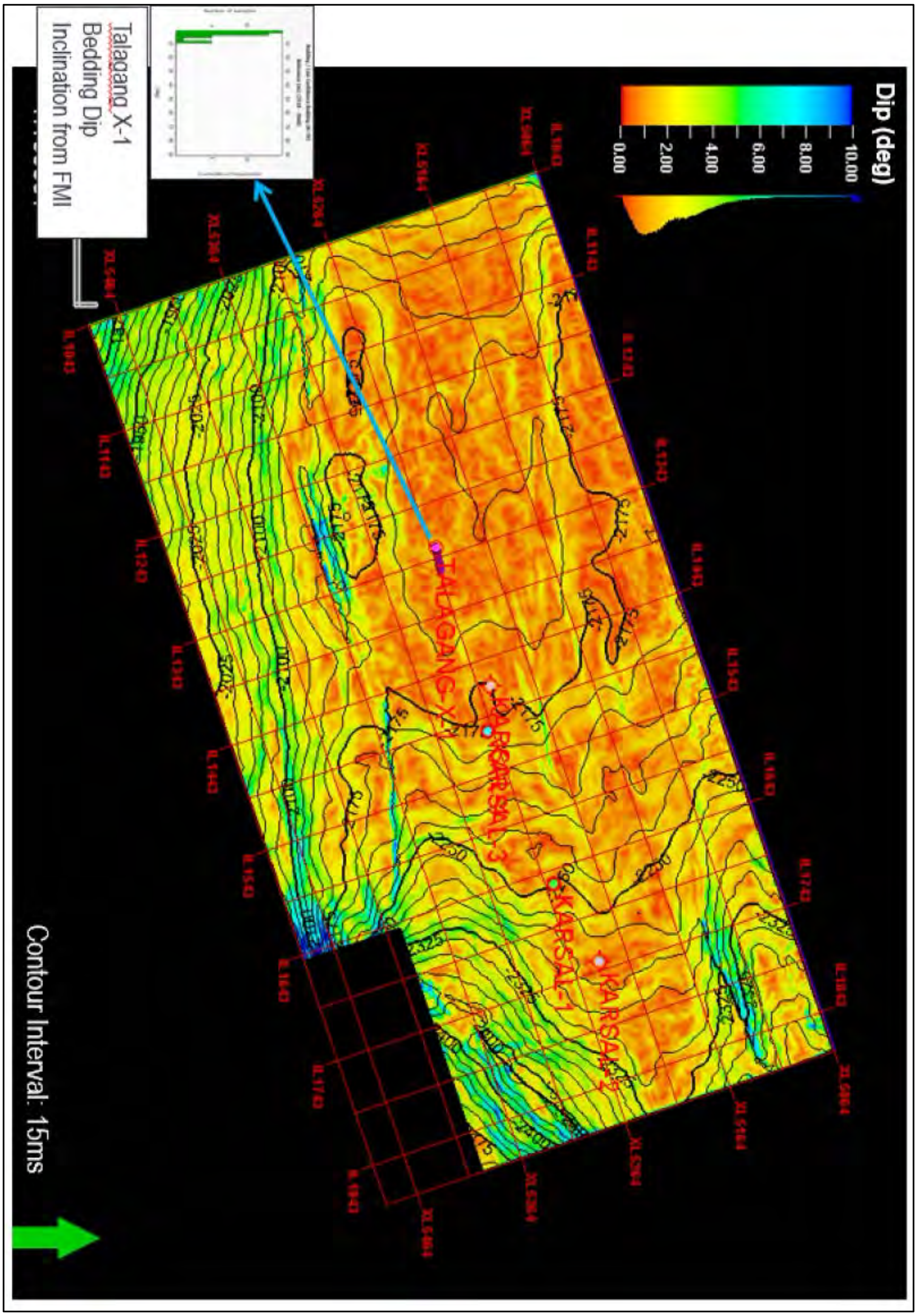

Figure 4.10: Top Sakesar surface - PSTM - Fine scale consistent dip Fine scale (radius: horizontal = 2 bins, vertical = 2 bins) consistent dip attribute computed from PSTM seismic cube displayed at the Top Sakesar surface.

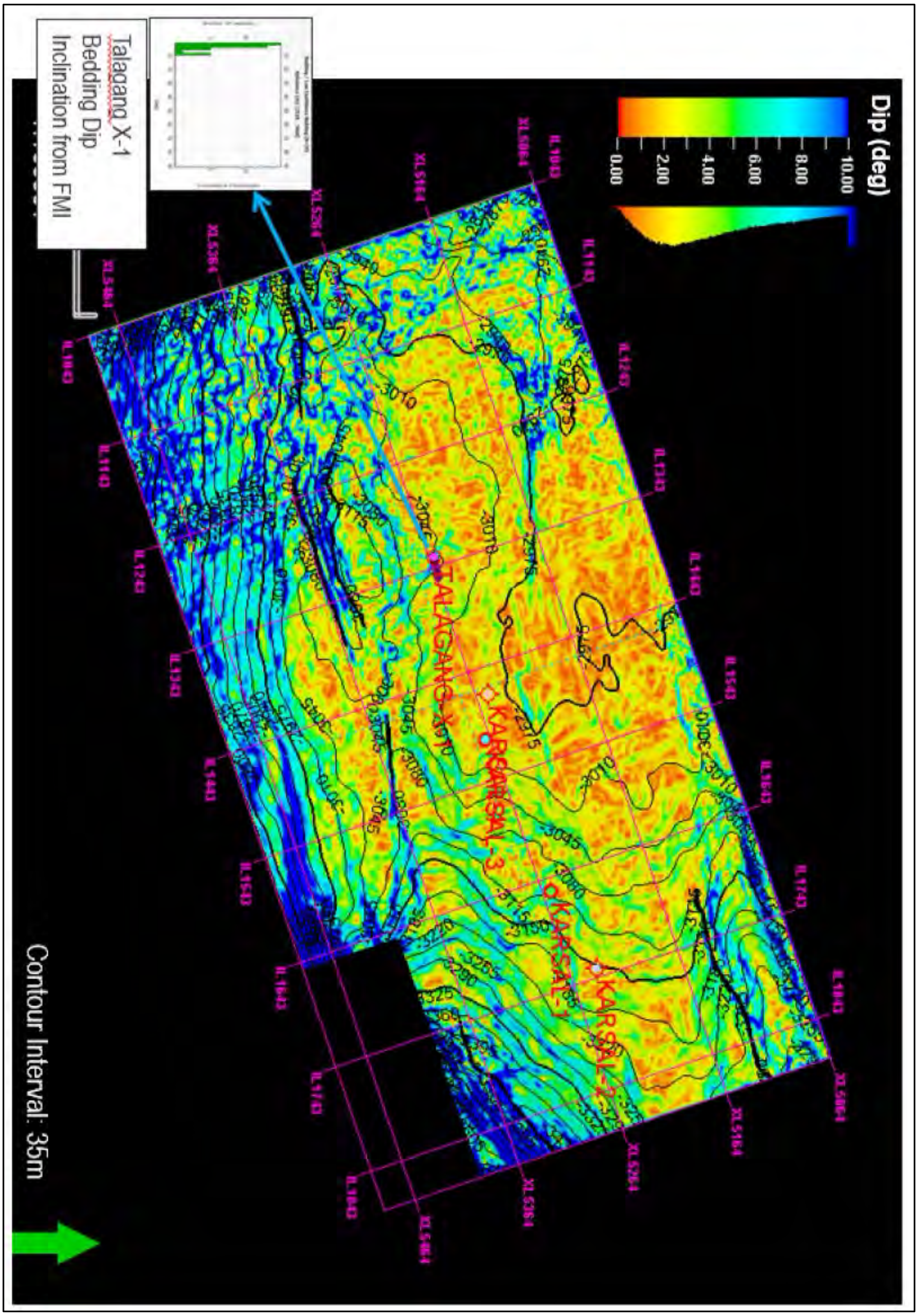

Figure 4.11: Top Sakesar surface - PSDM - Fine scale consistent dip Fine scale (radius: horizontal = 2 bins, vertical = 2 bins) consistent dip attribute computed from PSDM seismic cube displayed at the Top Sakesar surface.

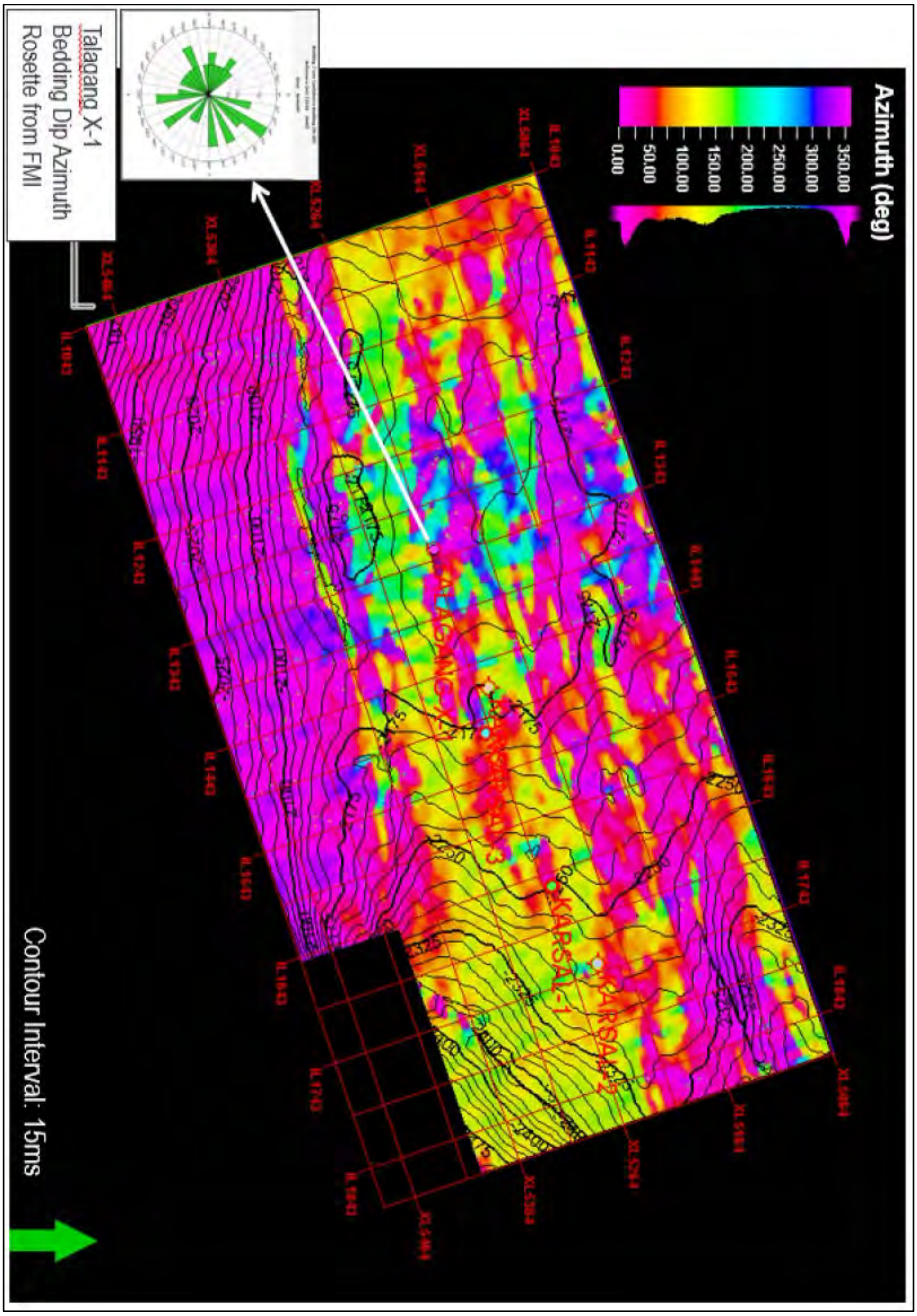

Figure 4.12: Top Sakesar surface - PSTM - Coarse scale dip azimuth model Coarse scale (radius: horizontal = 10 bins, vertical = 5 bins) consistent dip azimuth attribute computed from PSTM seismic cube displayed at the Top Sakesar surface.

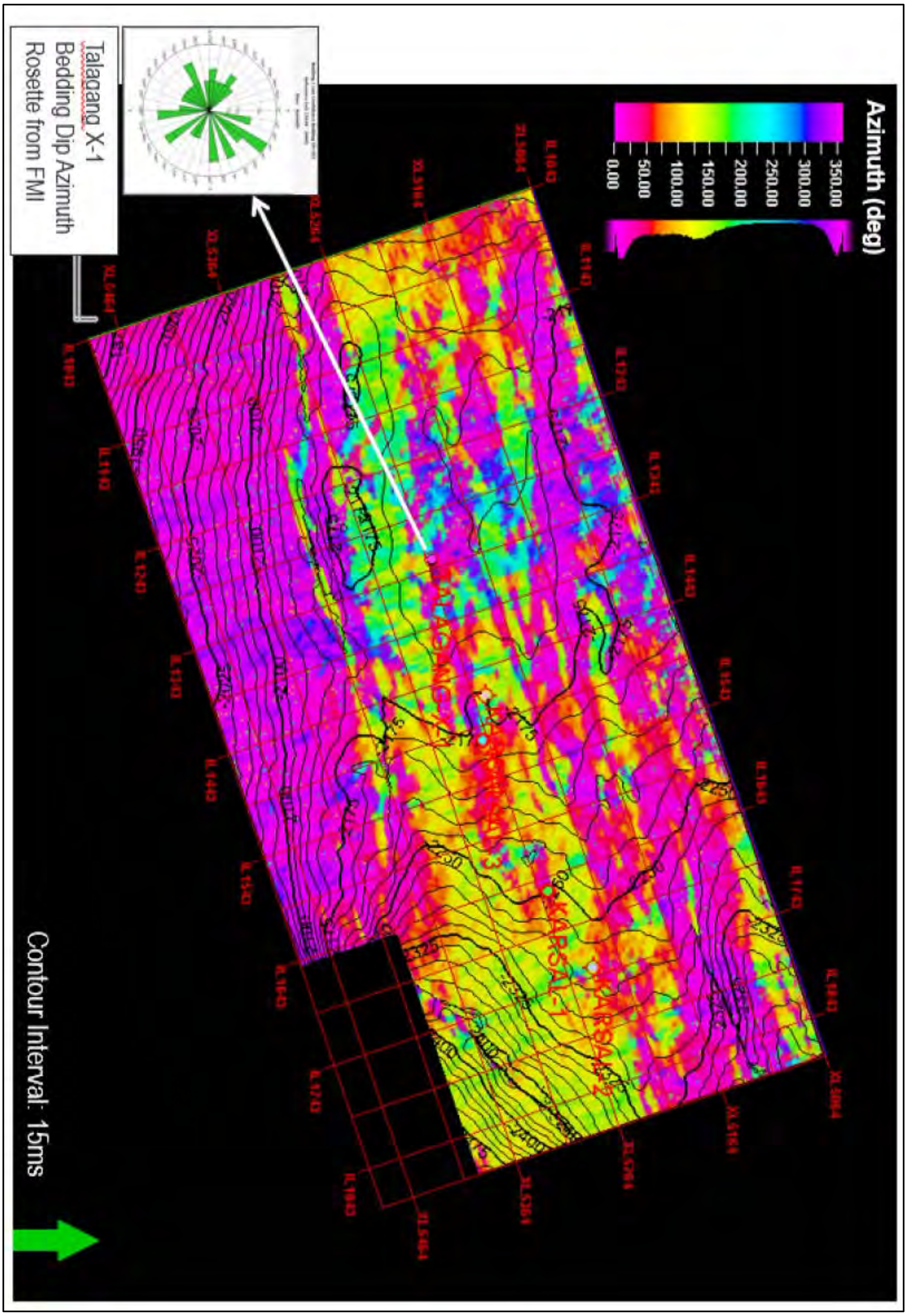

Figure 4.13: Top Sakesar surface - PSTM - Fine scale dip azimuth model Fine scale (radius: horizontal = 2 bins, vertical = 2 bins) consistent dip azimuth attribute computed from PSTM seismic cube displayed at the Top Sakesar surface.

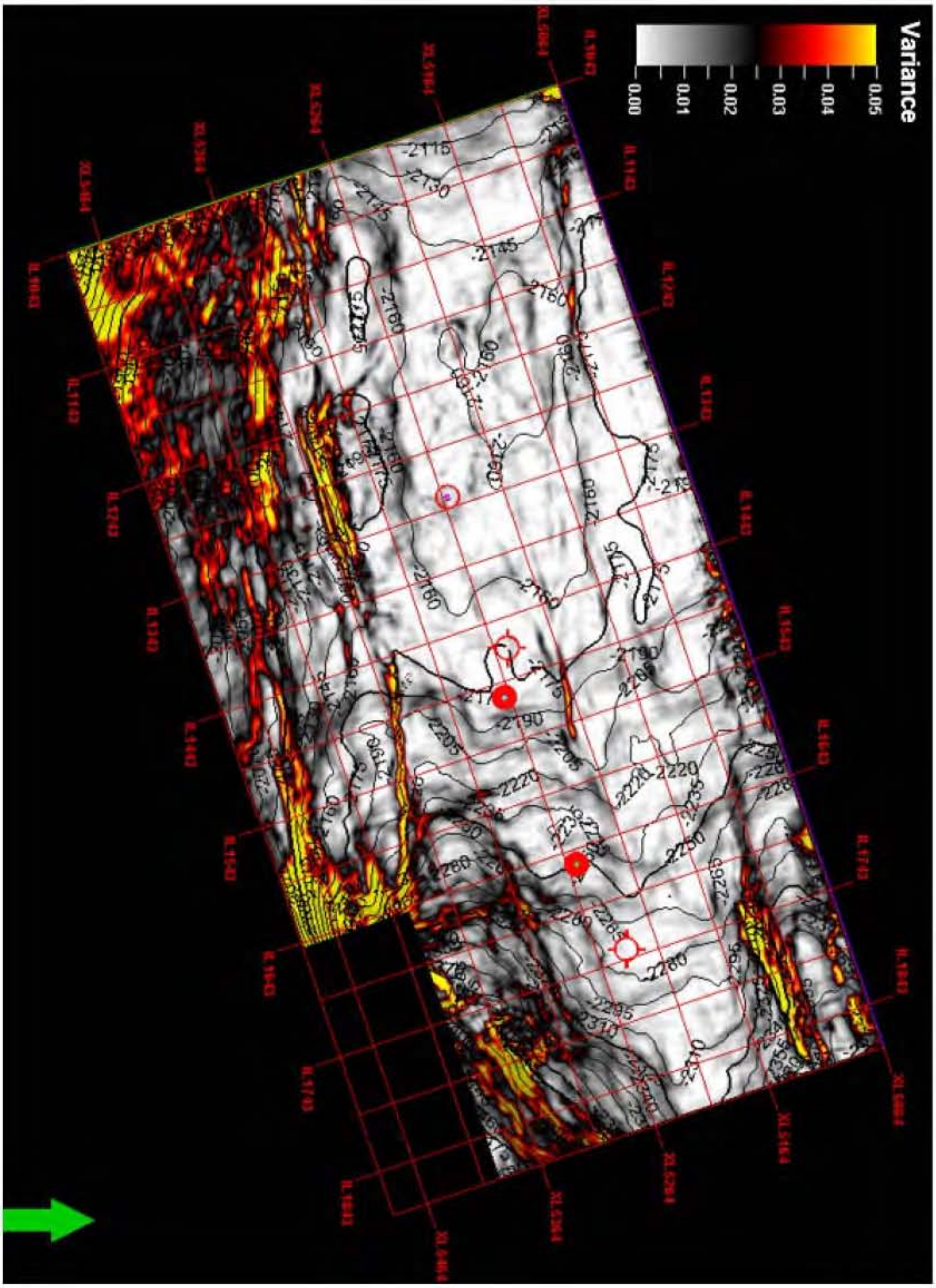

Figure 4.14: Top Sakesar surface - PSTM - Variance attribute Variance attribute computed from PSTM seismic cube displayed at the Top Sakesar surface.

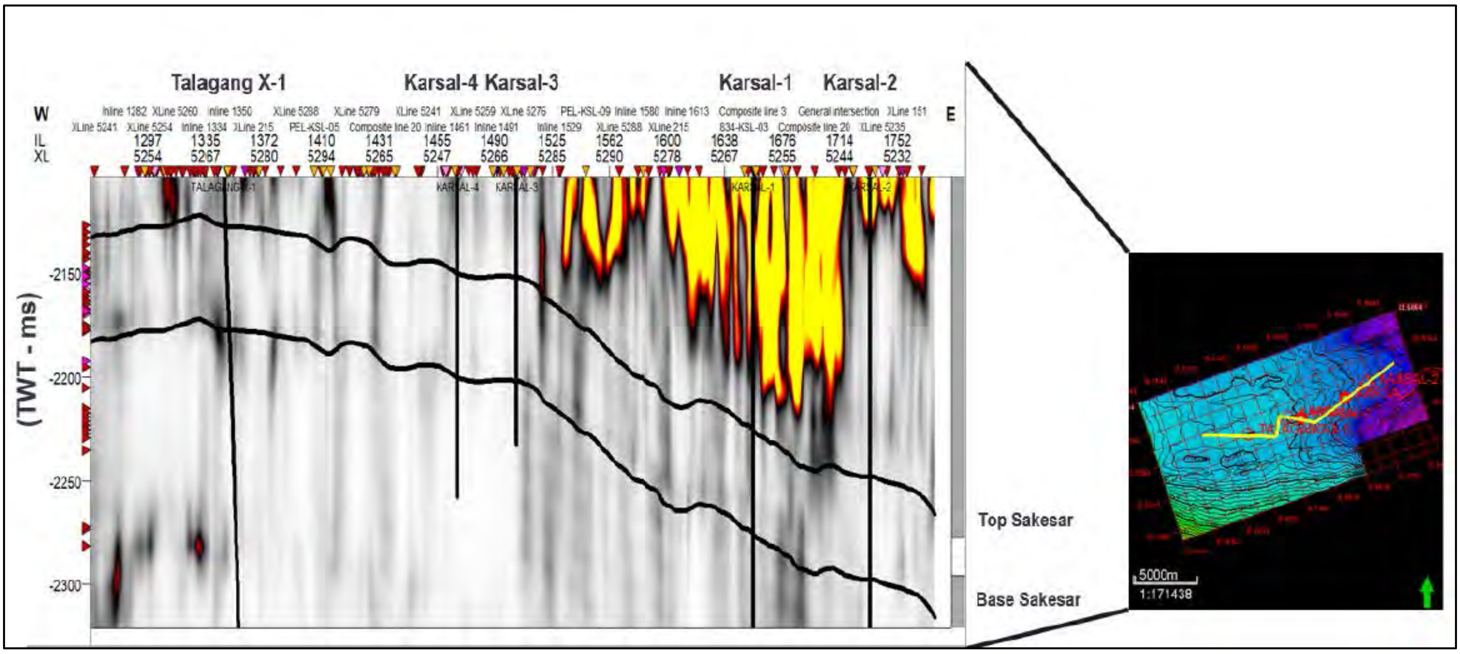

Figure 4.15: Arbitrary section - PSTM - Variance attribute Variance attribute computed from PSTM seismic cube displayed along an arbitrary section passing through Talagang X-1 and Karsal 1-4 Wells.

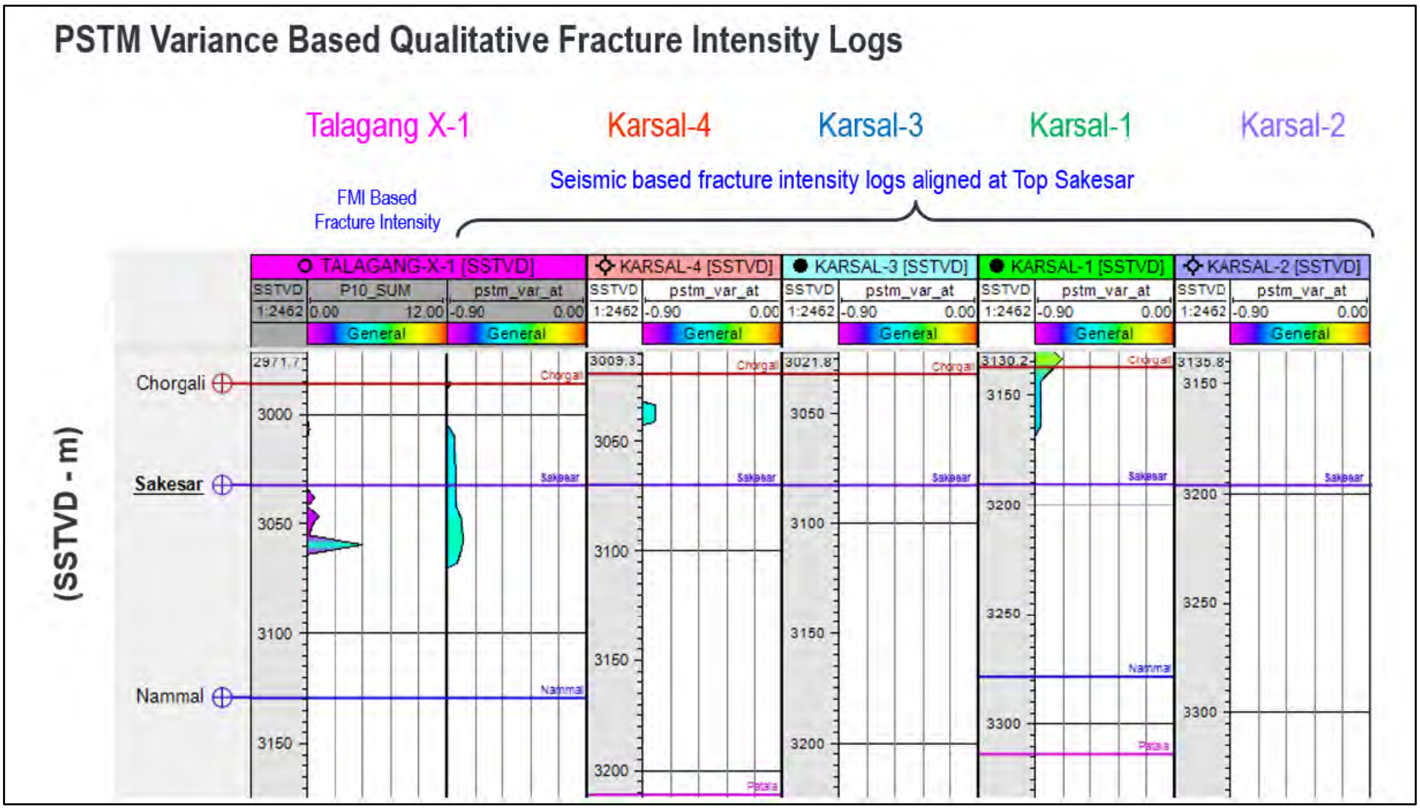

Figure 4.16: PSTM Variance - Fracture intensity logs Fracture intensity logs derived from PSTM seismic variance attribute cube at the well locations.

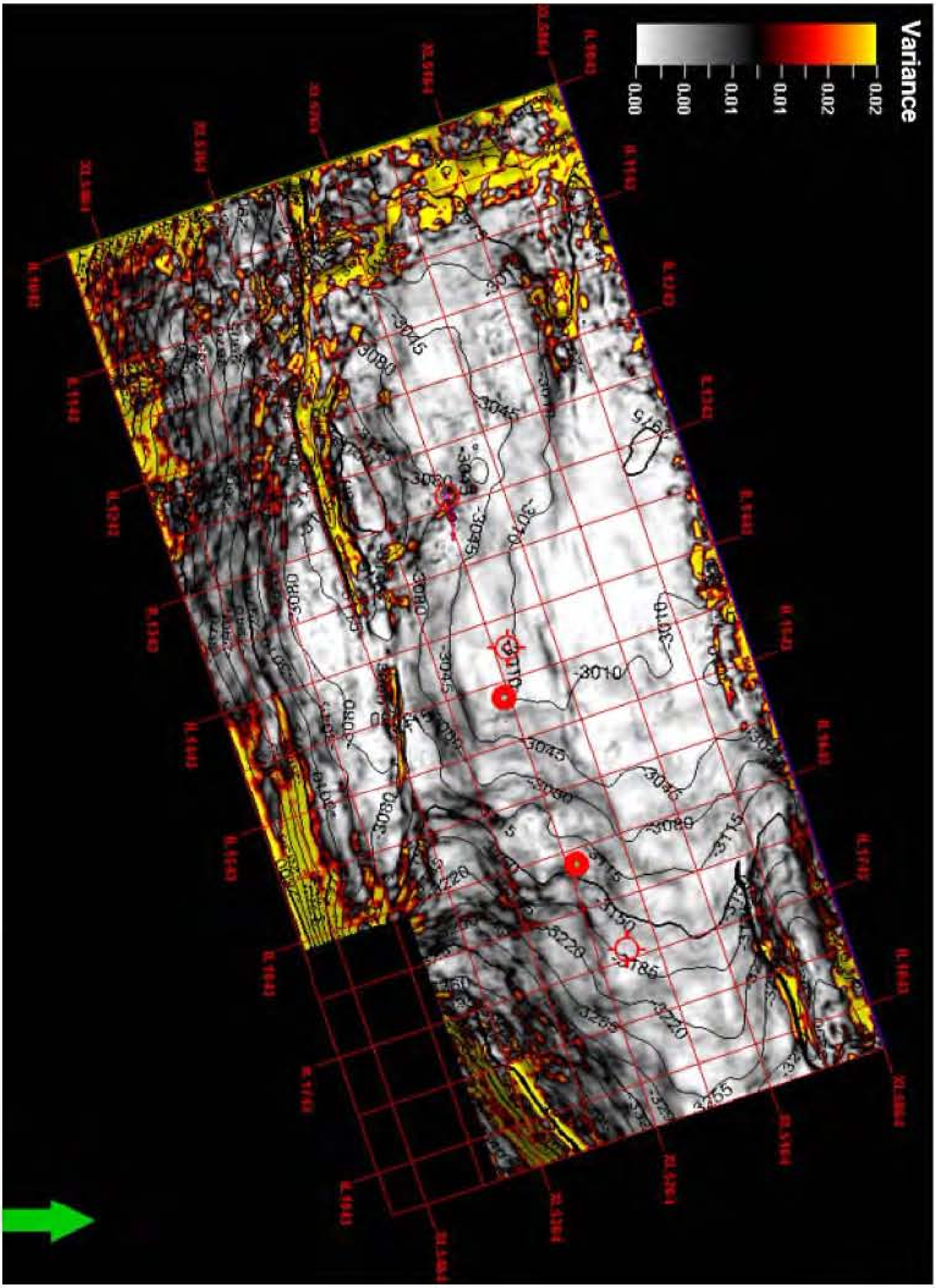

Figure 4.17: Top Sakesar surface - PSDM - Variance attribute Variance attribute computed from PSDM seismic cube displayed at the Top Sakesar surface.

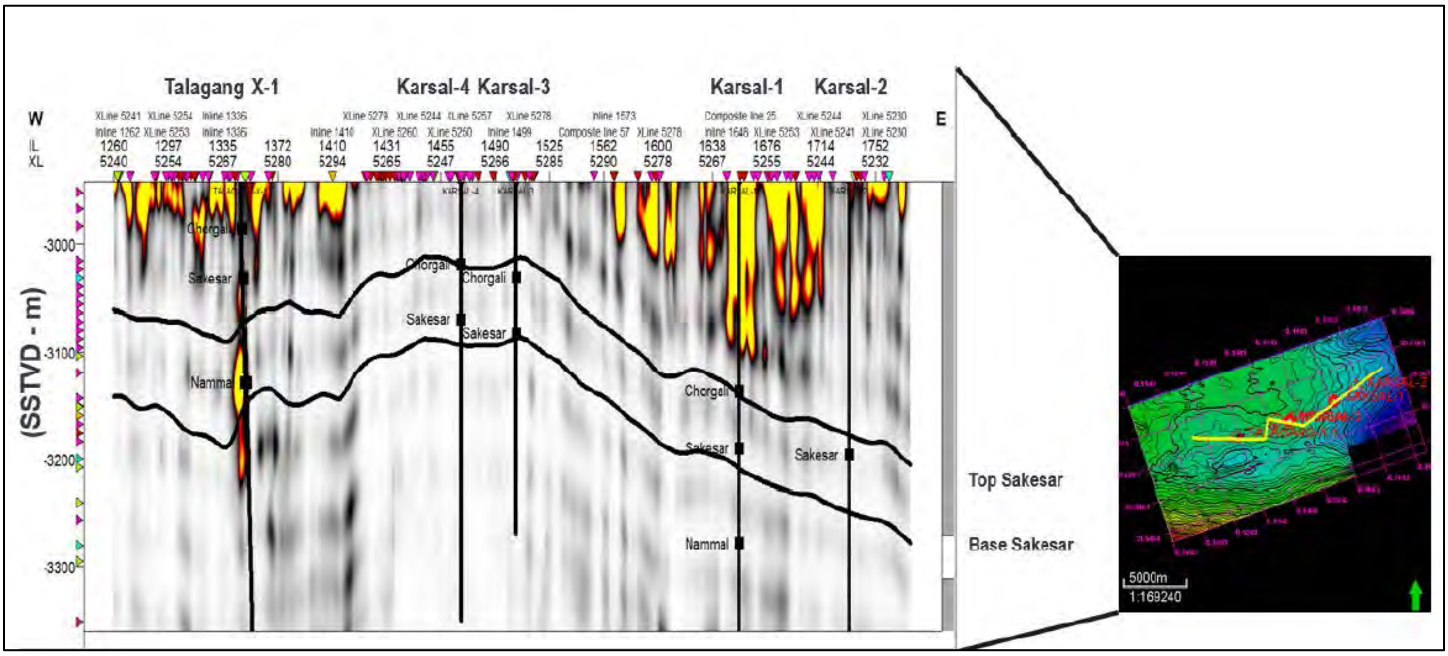

Figure 4.18: Arbitrary section - PSDM - Variance attribute Variance attribute computed from PSDM seismic cube displayed along an arbitrary section passing through Talagang X-1 and Karsal 1-4 Wells.

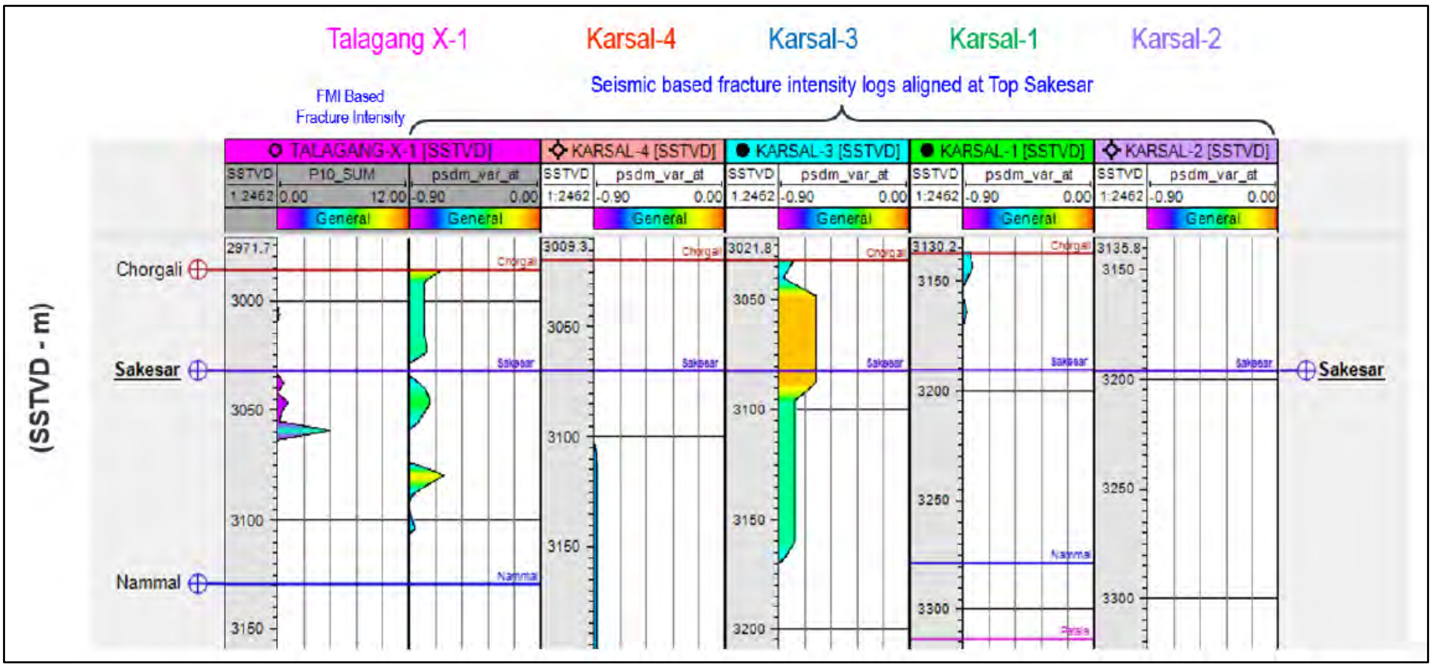

Figure 4.19: PSDM Variance - Fracture intensity logs Fracture intensity logs derived from PSDM seismic variance attribute cube at the well locations.

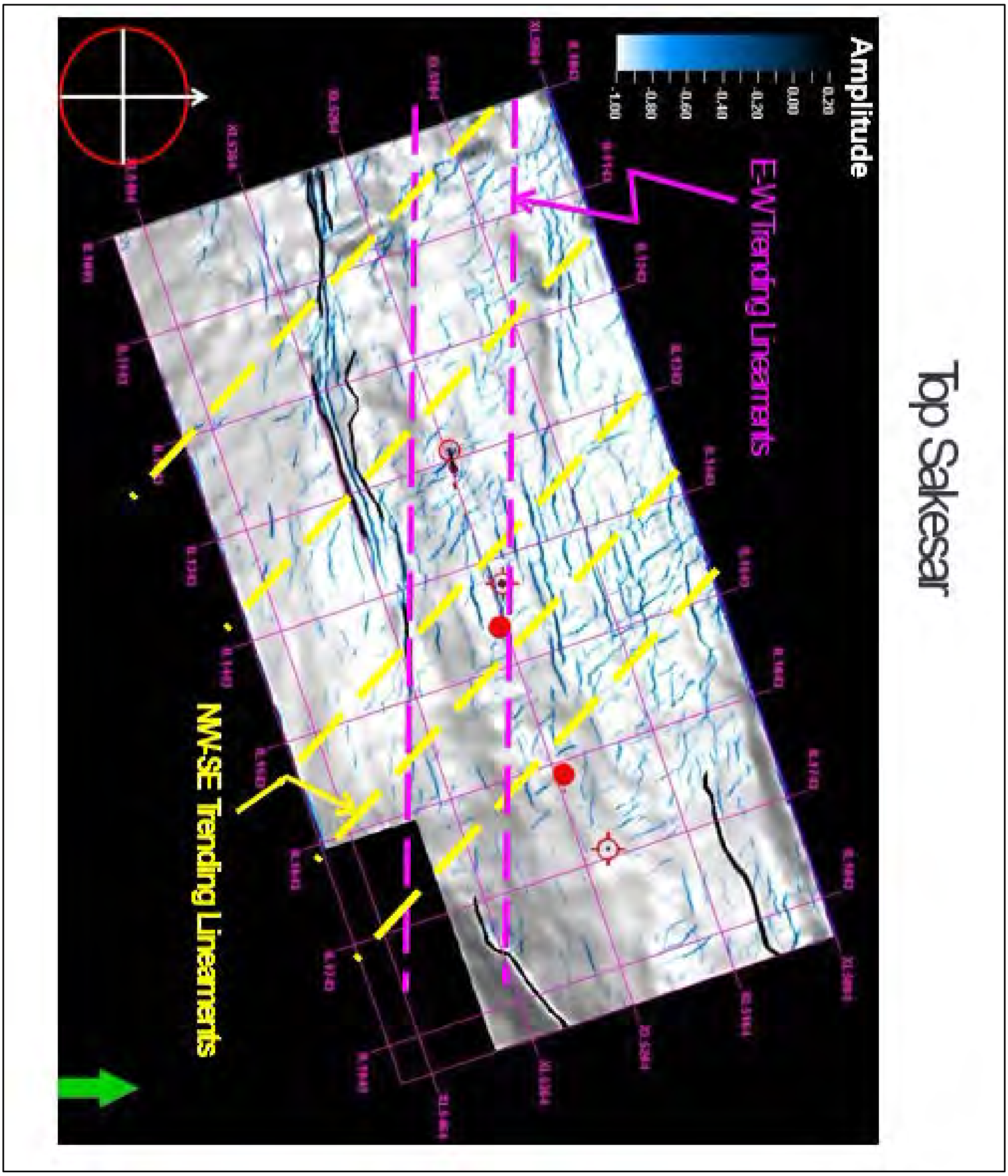

Figure 4.20: Ant Tracking Results from PSDM Variance Attribute mapped over Top Sakesar

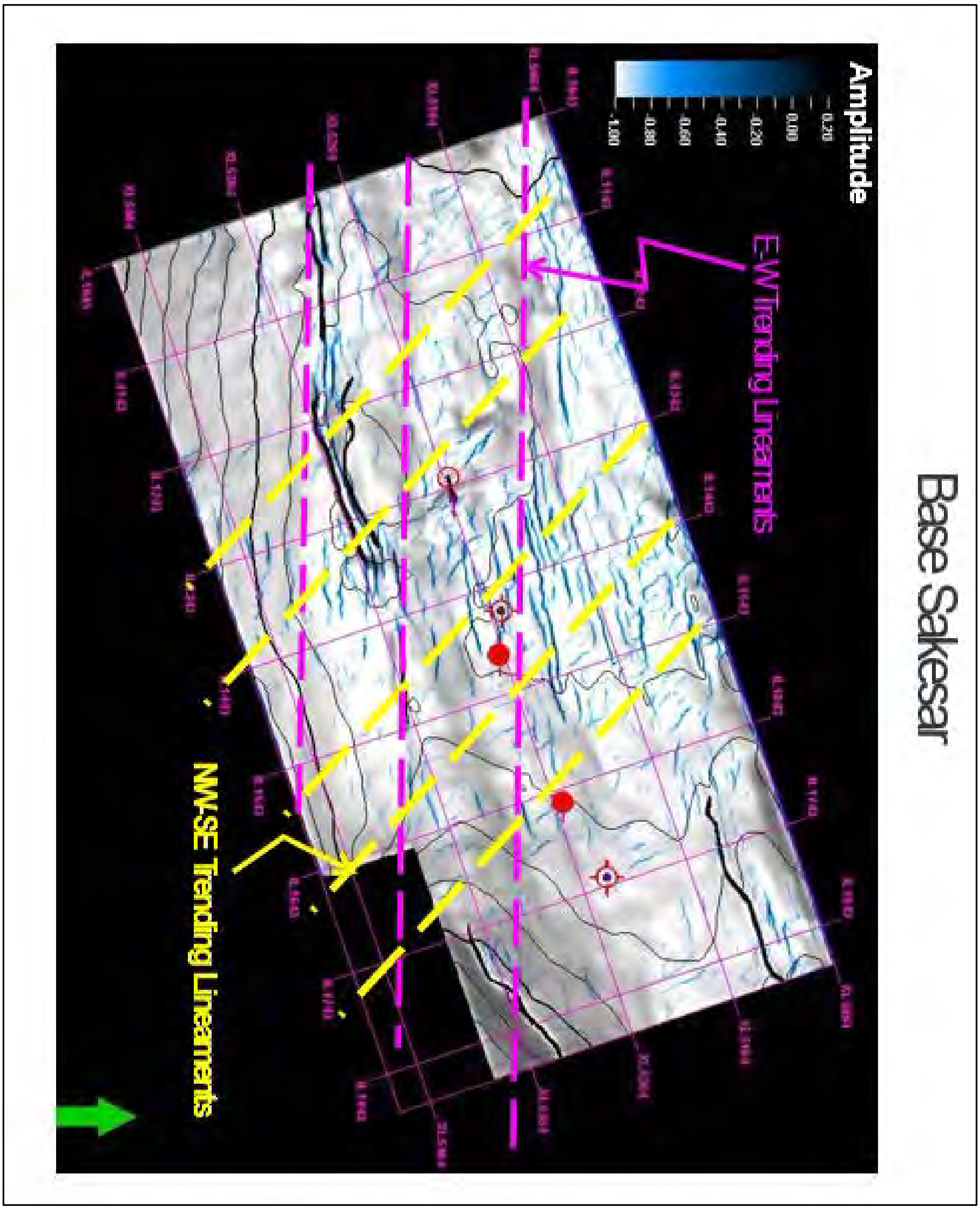

Figure 4.21: Ant Tracking Results from PSDM Variance Attribute mapped over Base of Sakesar.

Chapter -05

Anisotropic data interpretation

Anisotropic data interpretation

The presence of fractures in limestone reservoirs can significantly affect the properties of hydrocarbons, Nelson. R. A, 2001 including their density and API gravity. This thesis aims to investigate the relationship between geological features and the API gravity of hydrocarbons in fractured limestone reservoirs. The study will use pre-stack anisotropic data to identify and characterize fractures in the reservoir and relate these features to the quality of the hydrocarbons. The thesis will also investigate the impact of other reservoir properties, the effect of factors at the API gravity of hydrocarbons in fractured limestone formations, inclusive of porosity, permeability, and fluid kind.

The study deals the awareness of a fracture limestone reservoir in a specific geological setting, using data from well logs, seismic surveys, and laboratory analyses of hydrocarbon samples. The thesis will explore the use of different pre-stack anisotropic attributes, such as azimuthal velocity variation in offset (VVO) & azimuthal variation in amplitude with offset (AVO), identify and quantification about the presence of fractures within the limestone reservoir. The thesis will also investigate the use of other seismic attributes, such as acoustic impedance and attenuation, to characterize the properties of the hydrocarbons and their relationship to the geological features. This represents undulation on azimuthal gathers. relationships between fracture direction, fast/slow azimuths of P-wave velocity, and fast/slow S-wave propagation. After Bratton et al. (2006).

The research will employ numerical simulations, data analysis, and statistical modeling to provide a comprehensive understanding of the relationship between geological features and hydrocarbon quality in fractured limestone reservoirs. The thesis will look at the effect of various kinds of fractures upon API gravity of hydrocarbons and their contribution to reservoir porosity, permeability, and fluid flow. The study will also examine the impact of other factors, such as reservoir temperature and pressure, on the API gravity of hydrocarbons in fractured limestone reservoirs. After Rüger, A. (1998).

The findings of dissertation will contribute to the field of petroleum geology by providing a better understanding of the relationship between geological features and hydrocarbon quality in fractured limestone reservoirs. The study's findings can be used to inform reservoir modeling and drilling strategies, helping to optimize hydrocarbon recovery and reduce exploration risks.

The results of this study will be of particular interest to geoscientists and reservoir engineers working in the exploration and production of hydrocarbons from limestone reservoirs.

The API gravity is a measure of crude oil density and is important for determining its commercial value. The relationship between pre-stack anisotropic data and API gravity is complex and depends on several factors. Three potential ways that anisotropic pre-stack data may be related to API gravity are:

API gravity is generally inversely proportional to the viscosity of crude oil. Anisotropic pre-stack attributes will be used to estimate reservoir porosity, permeability, and saturation, which provide information about the type and quality of hydrocarbons. More permeable reservoirs are more likely to contain lighter, higher API gravity oils.

The lithology of the reservoir can also influence API gravity. For example, carbonate reservoirs often contain lighter oils with higher API gravities, while sandstone reservoirs may contain heavier oils with lower API gravities. Anisotropic pre-stack attributes can help identify the lithology of reservoir and guide about the properties of mechanical & elastic in nature, which can affect the properties of the hydrocarbons. However, the quality and effectiveness of the derived attributes are directly related to the quality of the seismic imaging used in the inversion (Johnson and Dorsey, 2010).

Structural complexity: Geological features like fractures and faults can affect API gravity by influencing reservoir permeability and fluid flow. Anisotropic pre-stack attributes can be used to identify and characterize these features and provide information about their orientation and density, which can help understand the impact of structural complexity on hydrocarbon quality.

To fully understand the relationship between pre-stack anisotropic data and API gravity, a thorough analysis of the data and consideration of other factors like reservoir temperature and pressure is necessary.

Interval velocity is a crucial parameter in seismic imaging, which involves creating a subsurface image of the Earth from reflected or refracted seismic waves. It measures the speed of seismic waves as they travel through rock layers between two depths or horizons. By analyzing seismic data collected during exploration, it is possible to estimate interval velocity and create an image that shows reflections from different depths.

Interval velocity is calculated through dividing the rock layer thickness by the time travel through it. This results in an average velocity for that layer, which is useful for predicting the time travel of future waves through the same layer.

Interval velocity fastness refers to the degree of variation in interval velocity between different rock layers. A higher interval velocity fastness indicates rapid changes in velocity with depth, while a lower interval velocity fastness indicates more uniform changes.

Knowledge of interval velocity fastness is important in seismic imaging, as it affects the accuracy of the resulting image. High interval velocity fastness can lead to imaging artifacts and distortion, making it more difficult to interpret the data and identify subsurface features accurately.

Interval velocity is a key parameter in seismic imaging, as it provides information about the speed at which seismic waves travel through the subsurface rock layers. The accuracy of interval velocity estimation is critical in interpreting seismic data and identifying subsurface structures accurately.

Fomel, Sergey (2007) assessed the impact of interval velocity variations on seismic imaging in one of their studies. It was discovered that differences in interval velocity fastness produced noise and image distortion, which could result in mistakes when identifying subsurface structures. It came to the conclusion that minimizing these imaging artefacts requires an exact estimation of interval velocity.

The effects of anisotropy on the determination of interval velocity Wang, Peng, Feng Zhang, (2022). It was discovered that anisotropy had the potential to significantly alter interval velocity, producing unreliable subsurface pictures. It was suggested that in order to produce more precise subsurface images, the impacts of anisotropy should be taken into account when estimating interval velocity.

Time-lapse seismic monitoring was the subject of a research by Al-Khodary et al. (2019) that concentrated on the impact of interval velocity variations. It had discovered that variations in interval velocity over time could result in inaccurate subsurface structure tracking and reservoir change detection. It was suggested that time-lapse seismic monitoring could be more accurate if monitoring intervals had comparable interval velocity characteristics.

Overall, it emphasize the importance of accurate interval velocity estimation and its impact on seismic imaging and subsurface structure identification. Factors such as anisotropy and interval velocity fastness should be considered in the estimation of interval velocity to obtain more accurate subsurface images.

5.1 Data Set Integration

Pre-Stack Time Migration and Pre-Stack Depth Migration are two widely used seismic imaging techniques that are used to create images of subsurface structures for oil and gas exploration.

PSTM is a technique that involves migrating the 2D or 3D seismic data from time to depth domain. In PSTM, model of the velocity is used for migration which is taken from well logs, seismic velocities, and other geological data. The process involves creating a grid of seismic traces and then moving each trace vertically to its correct depth position in the subsurface based on the velocity model. 3D image of the subsurface structures comes as a result, but with limitations in resolution and accuracy in areas of complex geology (Figure 5.1).

PSDM is a more advanced technique that involves migrating 2D or 3D seismic data from time to depth domain using a more detailed velocity model that is derived from well logs and other well data. PSDM also cover the angle of incidence of the seismic waves, which results in accuracy of subsurface imagining. Structures with better resolution and imaging quality, especially in complex geology as highlighted in figure 5.2.

Well data integration play the vital role for both PSTM and PSDM. The velocity model used for migration is typically derived from well log data, which provides information about the geological properties of the subsurface. Integration of well data with seismic data refine the velocity model and result in the accuracy for final image as highlighted in figure 5.3. This integration can also help identify areas of interest for exploration and production, such as hydrocarbon reservoirs, faults, and other geological features.

Seismic data integration with anisotropic data involves including information about the directional dependence of seismic wave velocities and other rock properties in the subsurface, which is referred to as anisotropy. This can significantly affect the accuracy and quality of seismic images. Various types of anisotropy can exist in the subsurface, such as HTI, VTI, TTI, and orthorhombic anisotropy. Integrating anisotropic data into seismic processing workflows can improve the accuracy of the velocity model used for migration, resulting in higher-quality seismic images.

One approach to integrating anisotropic data is through inversion techniques, where anisotropic properties of the subsurface are estimated from well data. The estimated parameters, such as Thomsen parameters, are then incorporated into the velocity model used for migration to improve the final image's accuracy. Another approach is using PSDM techniques that account for anisotropy, such as TTI-PSDM. These algorithms use anisotropic velocity models to consider the directional dependence of seismic wave velocities, producing higher-quality seismic images in areas with complex anisotropic properties.

Incorporating anisotropic data into the processing and imaging workflows of seismic data stands as a pivotal step towards elevating the precision and quality of seismic images, as illustrated in Figure 5.4. Employing inversion techniques or specialized algorithms tailored for anisotropic conditions in the subsurface proves instrumental in seamlessly integrating anisotropic data into the broader spectrum of seismic processing workflows.

The utilization of such advanced techniques acknowledges and accommodates the inherent anisotropic characteristics of the subsurface, ensuring that seismic images accurately reflect the complex geological structures. By integrating anisotropic data, seismic processing workflows can capture a more nuanced understanding of the subsurface, unveiling intricate details that might be obscured when employing conventional processing methods.

This integration not only enhances the accuracy of seismic imaging but also contributes to the overall quality of the interpreted data. The incorporation of anisotropic considerations in seismic data processing is a testament to the commitment to refining and optimizing workflows for a more comprehensive and faithful representation of the subsurface geological features.

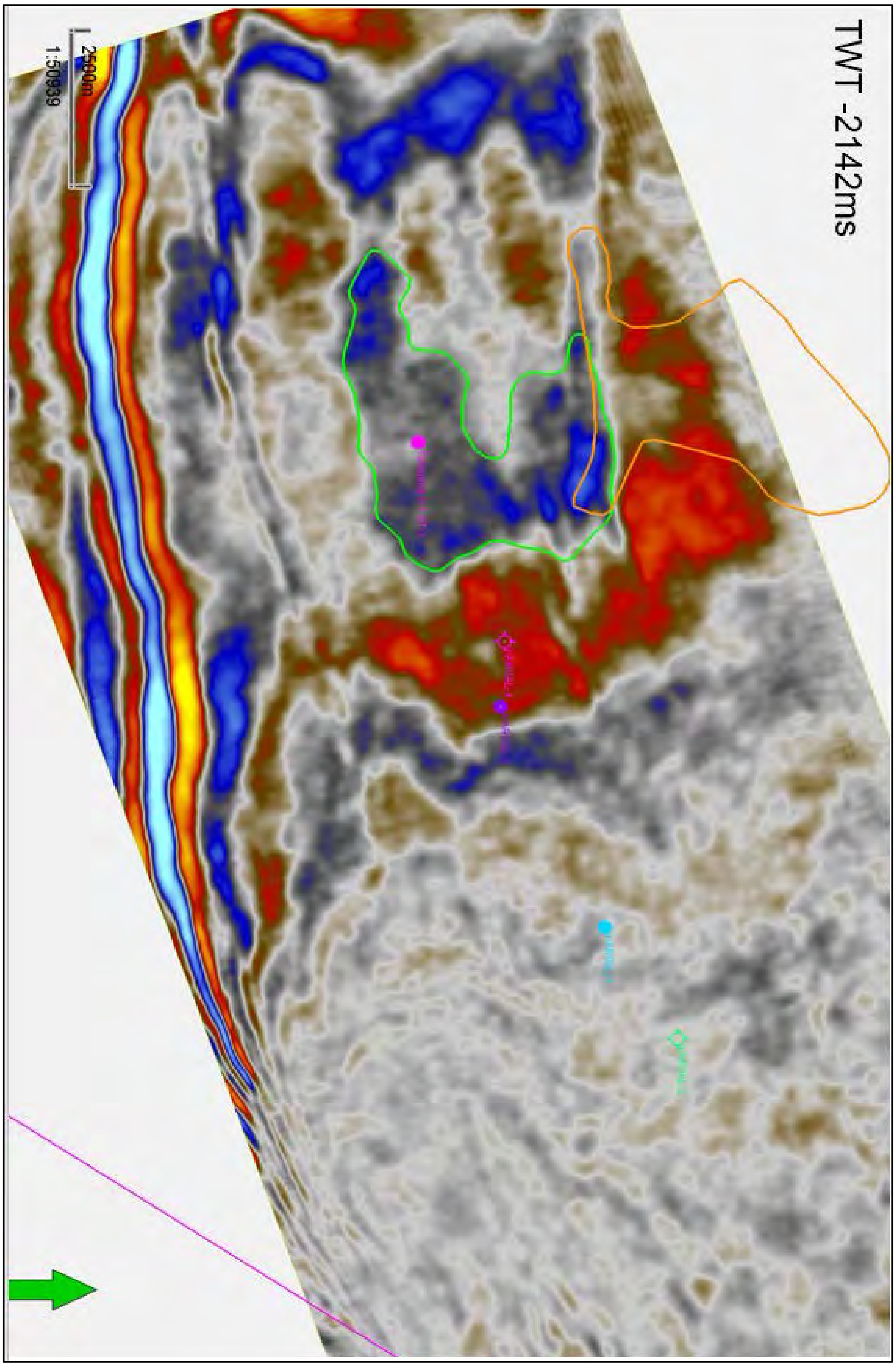

Figure 5.1: PSTM time slice view for the anomalous behavior of amplitude data green polygon is PSTM and orange representing PSDM amplitude area.

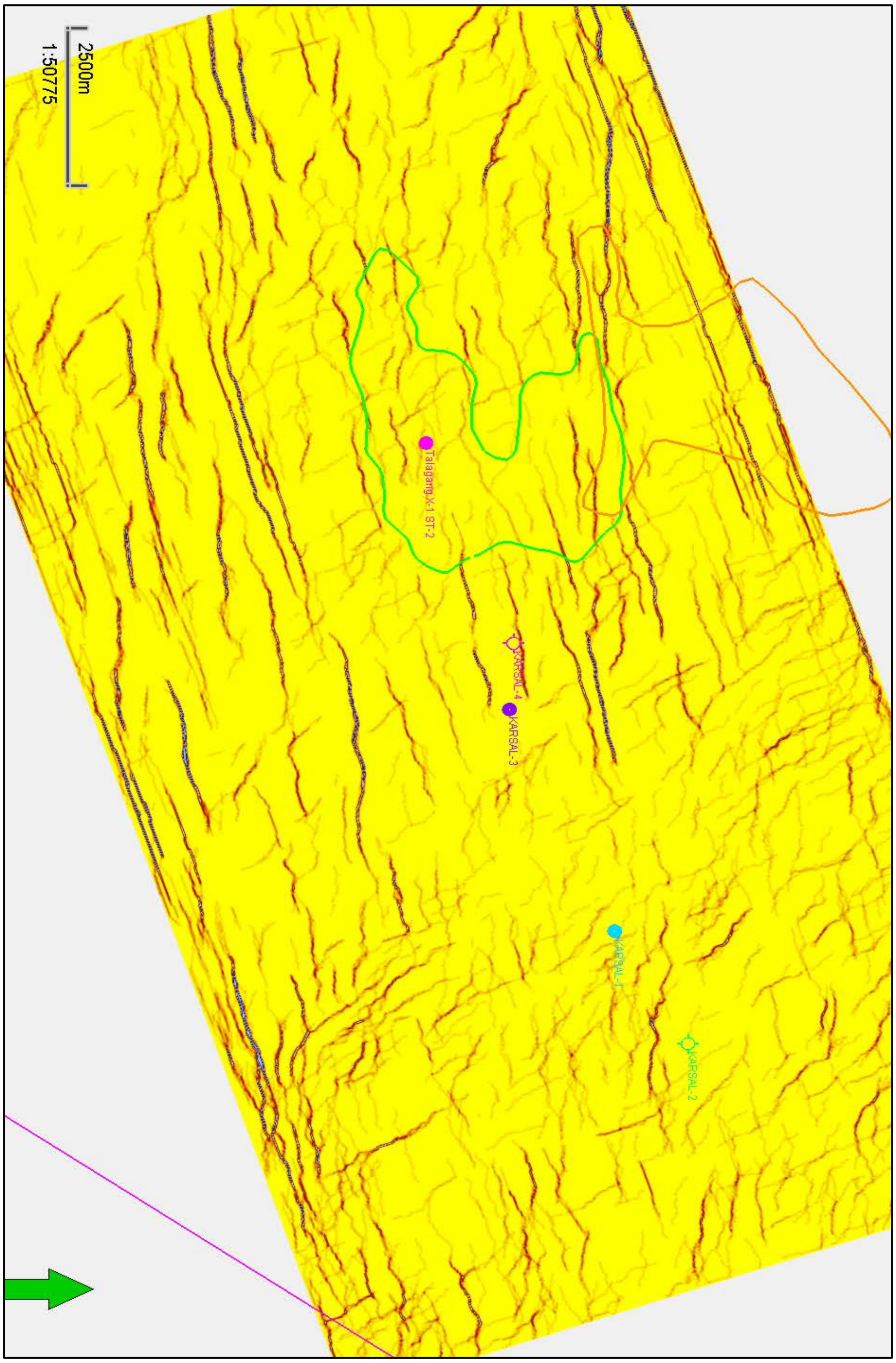

Figure 5.2: variance time slice view at sakaesar for the anomalous behavior of amplitude data green polygon is PSTM and orange representing PSDM amplitude area.

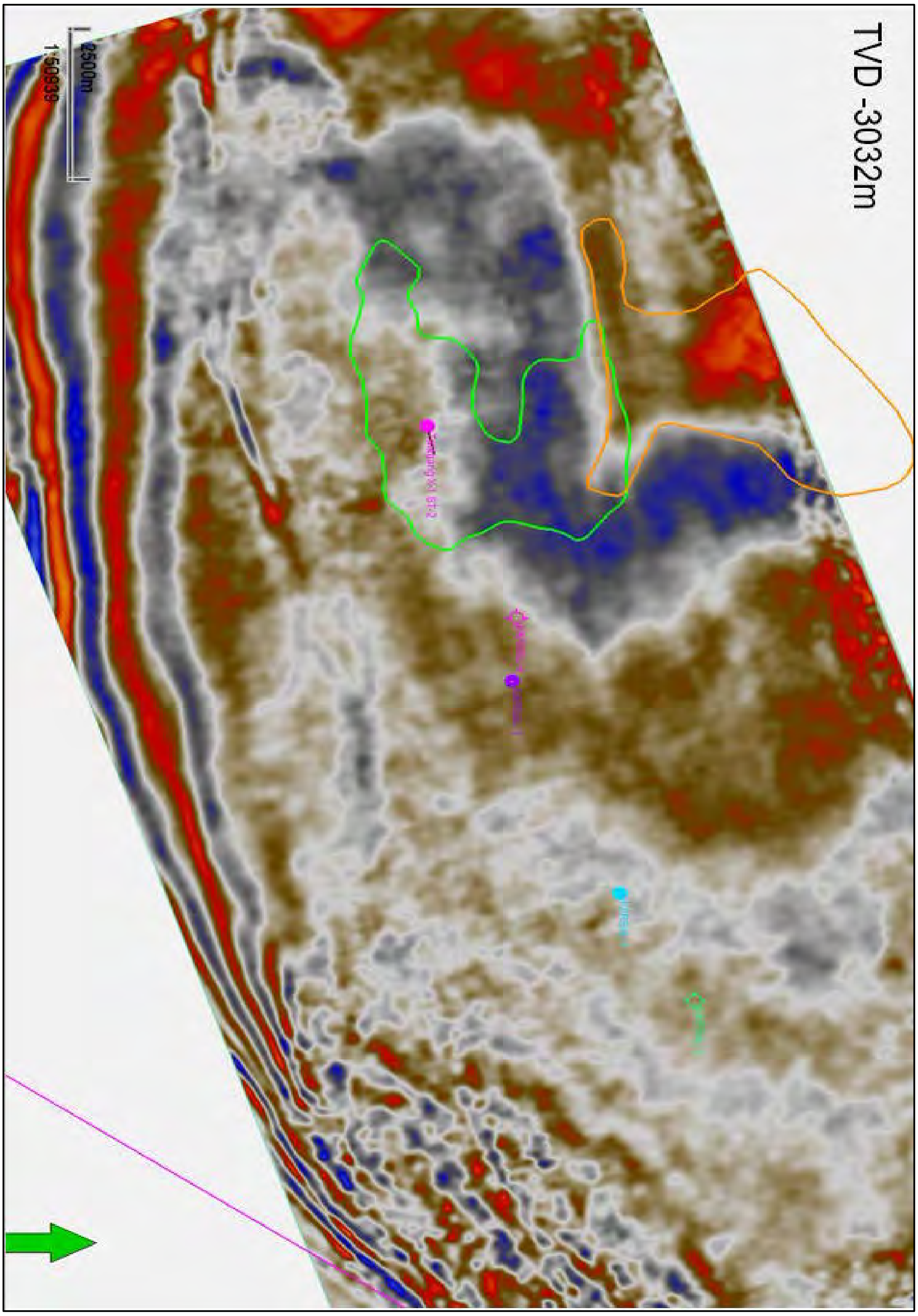

Figure 5.3: PSDM time slice view slice for the anomalous behavior of amplitude data green polygon is PSTM and orange representing PSDM amplitude area.

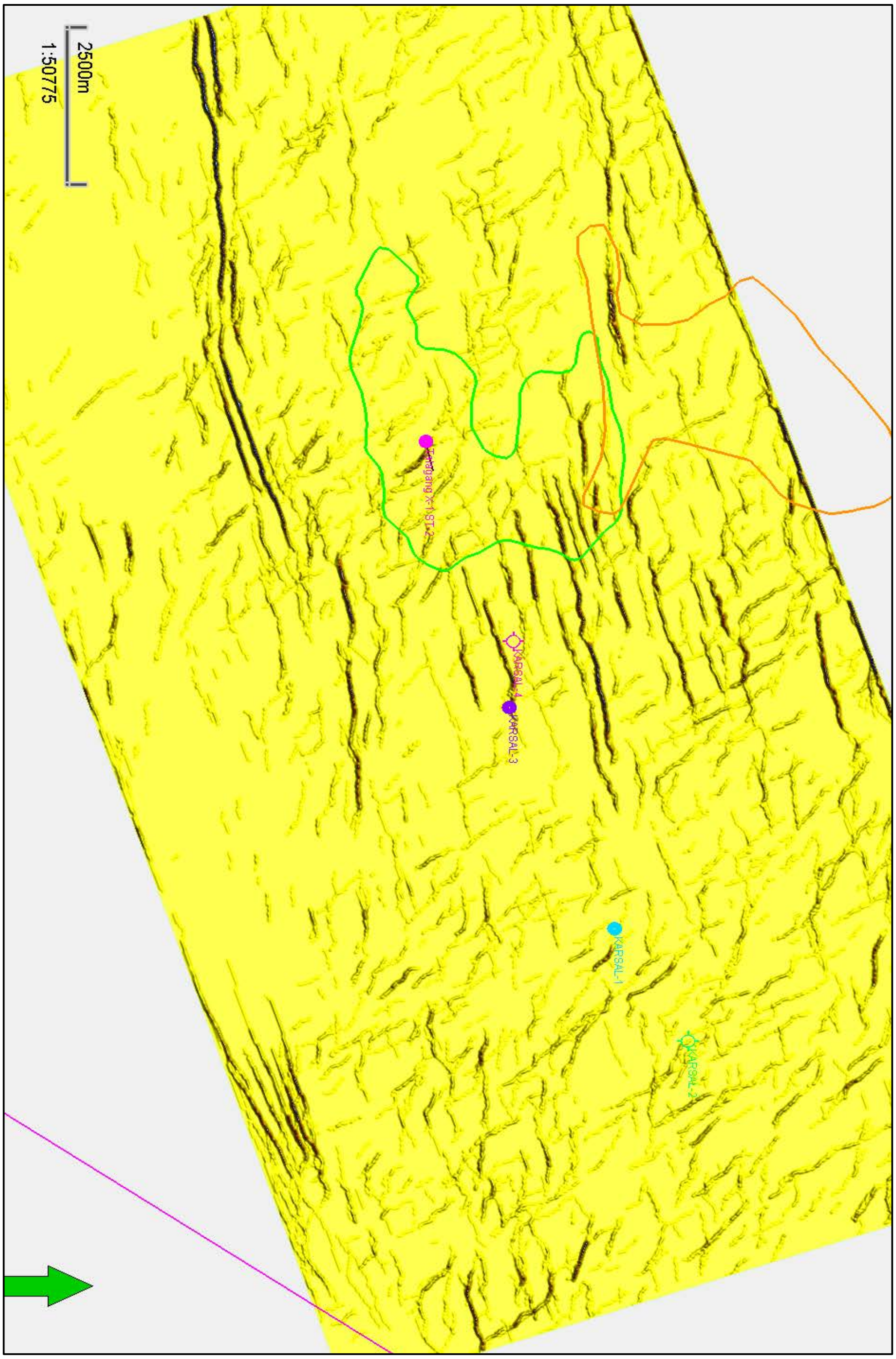

Figure 5.4: PSDM Variance Ant Track on Sakesar surface level for the anomalous behavior of amplitude data green polygon is PSTM and orange representing PSDM amplitude area.

5.2 Fitted elliptical anisotropy by travel times analysis (FEATT, Intensity and direction)

The technique of fitted elliptical anisotropy by travel times is utilized in seismic data processing to estimate the anisotropic properties of subsurface rocks based on recorded seismic travel times. Anisotropy denotes the directional dependence of seismic wave velocities and other rock properties in the subsurface, which can significantly impact the accuracy of seismic imaging. This approach involves analyzing seismic data to extract travel times of seismic waves, which are then resulted into the anisotropic properties of subsurface. The technique assumes that the subsurface is anisotropic with an elliptical symmetry, implying properties of anisotropic in nature are the same in all directions even in perpendicular to the axis of symmetry. Based on this assumption, the anisotropic properties can be described by two parameters: the fast velocity direction and the anisotropy strength.

Intensity and Direction involves

1- V-fastness
2- V-slowness
3- RMS-Fitting error
4- Percentage Anisotropy

The technique encompasses fitting the observed travel times to the travel times predicted by a theoretical model that assumes elliptical anisotropy. An iterative algorithm is utilized to adjust the fast velocity direction and anisotropy strength until the predicted travel times align with the observed travel times as closely as possible. The fast velocity direction and anisotropy strength determined using this technique can be utilized to update the velocity model used for seismic imaging. This can result in higher-quality seismic images. The fitted elliptical anisotropy from travel times is commonly used in seismic data processing workflows to estimate anisotropic properties from seismic travel time.

5.2.1 V-interval Fast

P-wave interval velocity fastness pertains to the consistency or uniformity of P-wave interval velocities within a specific subsurface region. P-wave interval velocity fastness characterizes how comparable these interval velocities are throughout a particular depth range. When the P-wave interval velocities are relatively uniform across the subsurface, this is referred to as P-wave interval velocity fastness. Seismic data processing and imaging workflows often assume this condition as it simplifies the velocity model used for imaging. However, the subsurface conditions can be heterogeneous and complex, leading to varying P-wave interval velocities.

In such cases, assuming P-wave interval velocity fastness may result in incorrect seismic images. To address this, seismic data processing workflows may adopt methods to estimate and incorporate variations in P-wave interval velocities during model building which is used for imaging.

These techniques may include inversion methods by well or seismic data and the computation of state of the art velocity model building algorithms like FWI. Interval velocity fastness pertains about consistency of interval velocities in a particular subsurface area. While assuming fastness simplifies the velocity model used for imaging, subsurface conditions can be complex and diverse as shown in figure 5.5.

Hence, seismic data processing workflows can employ diverse methodologies to estimate and integrate variations in P-wave interval velocities into the velocity model utilized for the imaging process. This multifaceted approach is crucial for refining and optimizing the velocity model, ensuring that it accurately represents the subsurface conditions and contributes to the enhancement of imaging results.

In the pursuit of an effective seismic data processing strategy, the consideration of various techniques becomes essential to adequately capture and incorporate the nuances in P-wave interval velocities. The estimation methods employed in this context play a pivotal role in refining the velocity model, which, in turn, significantly influences the precision and reliability of the final imaging outcomes.

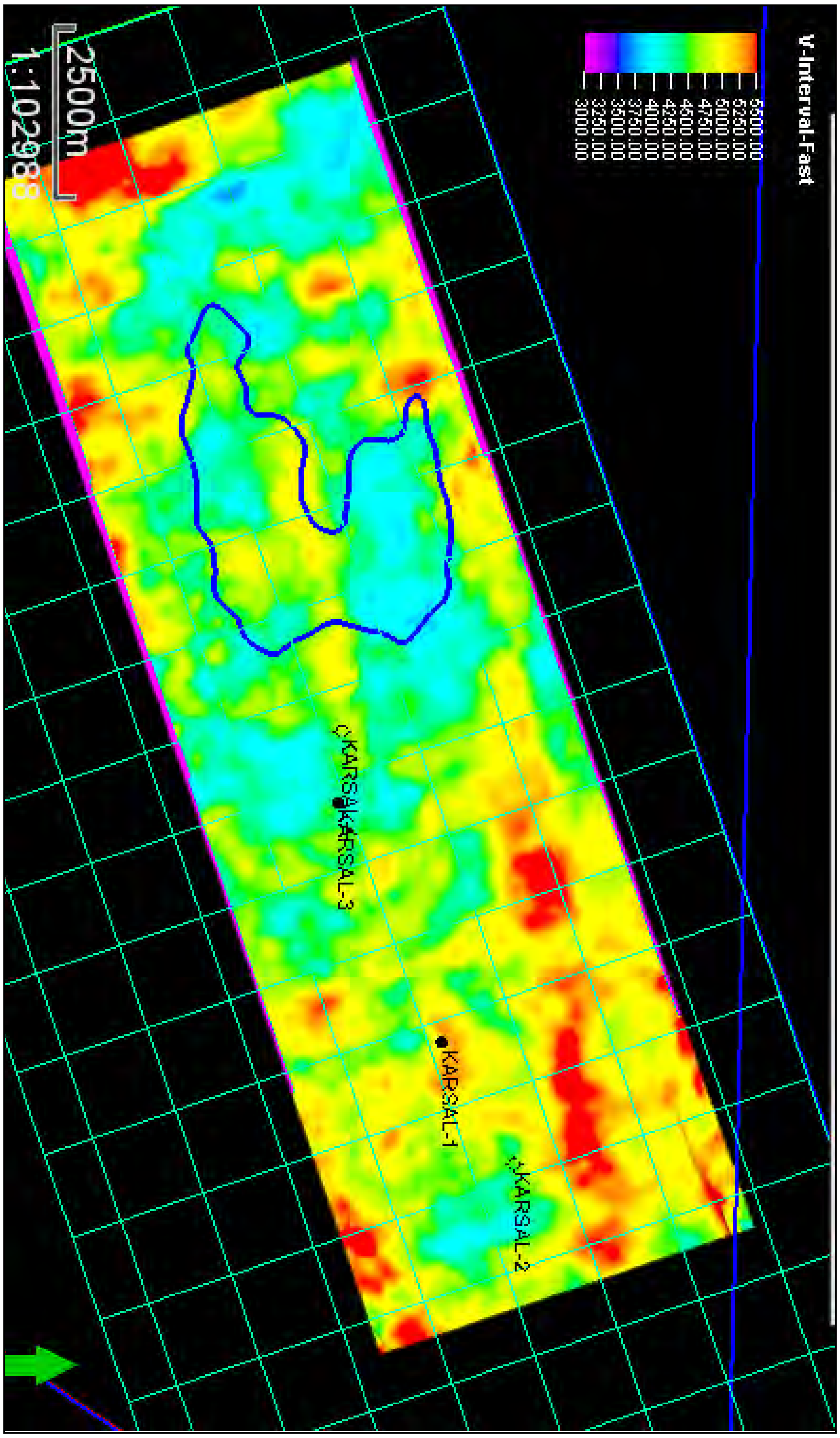

Figure 5.5: V-interval Fastness an azimuthal velocity analysis attribute run over 20 millisecond window of Eocene carbonates in study area which is a range from 3200 to 3500 meter/sec for less fracture area and 4700 to 5000 for highly fracture area. Red is the maximum V-interval fastness and Pink is the lowest for fastness.

5.2.2 V-interval Slow

P-wave interval velocity slowness refers to the decrease in the velocity of P-waves with increasing depth in the subsurface. The interval velocity is the average velocity of seismic waves between two depth levels, and it is calculated by dividing the distance travelled by the travel time between the two depths. When the P-wave interval velocity decreases with increasing depth, it is known as P-wave interval velocity slowness. This phenomenon depends upon on various factors, like changes in rock properties, the presence of geological structures. Understanding P-wave interval velocity slowness is crucial in seismic data processing because it impacts the velocity model accuracy which then used for imaging and can cause distortions and artifacts in the seismic images. To account for P-wave interval velocity slowness, methods such as interval velocity analysis and tomography can be used to estimate the velocity model and incorporate variations in P-wave velocity with depth. By doing so, the accuracy of seismic images can be improved, and potential subsurface targets such as hydrocarbon reservoirs can be identified more accurately (Figure 5.6).

P-wave velocity anisotropy. This horizontal slice at reservoir depth (inset) is color coded with azimuthal velocity anisotropy, calculated as the difference between VP, int, fast and VP, int, slow divided by VP, int, fast. The direction and length of the red lines indicate the orientation of VP, int, fast and P-wave velocity anisotropy expressed as a percentage, respectively. Velocity anisotropy in this field has been shown to be directly proportional to the local in situ principal stress anisotropy.

The black lines are existing horizontal wells. The two wells on the left are oriented in the direction of minimum stress predicted by seismic azimuthal anisotropy; the well on the right was drilled almost parallel to the maximum stress direction and hydraulic fractures are likely to propagate parallel to the well. The dark blue zone (white circle) to the left of the leftmost well is a possible fault. On the west side of this fault, the maximum stress orientation is SW–NE and parallels the fault plane; on the east side, it is NW–SE and orthogonal to the fault. Geomechanical studies have revealed that faults may alter the stress field near them.

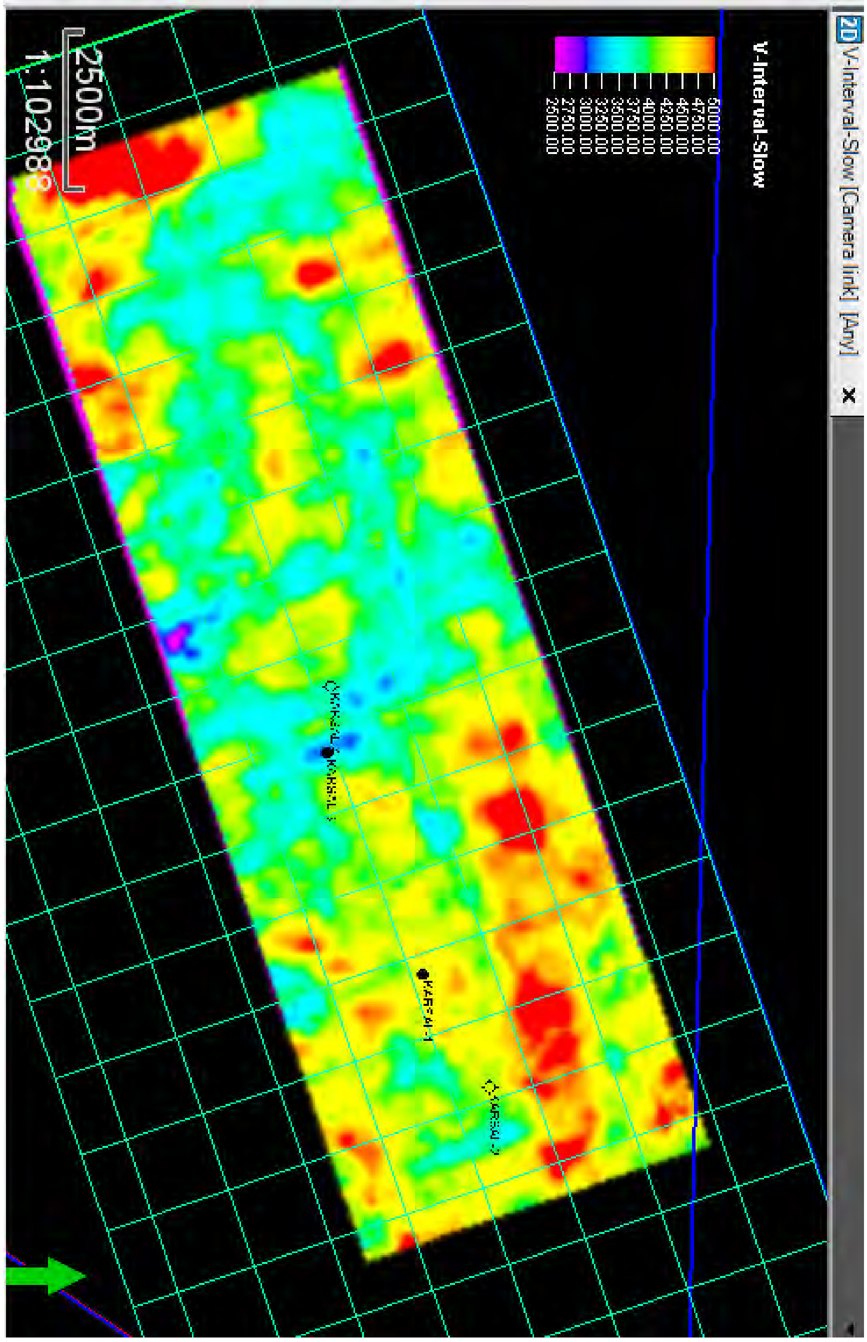

Figure 5.6: V-interval Slowness is an azimuthal velocity analysis attribute run over 20 millisecond windows of Eocene carbonates in study area which is a range from 2800 to 3100 meter/sec for less fracture area and 4200 to 4500 for highly fracture area. Red is the maximum V-interval fastness and Pink is the lowest for fastness.

5.2.3 RMS-Fitting error

In seismic data processing, RMS fitting error refers to the root-mean-square error in the observed and the synthetic seismic data generated by a forward modelling algorithm. The forward modelling algorithm uses a velocity model of the subsurface to simulate the propagation of seismic waves through the subsurface and generate synthetic seismic data.

The RMS fitting error is the calculation of velocity model fits in the observed seismic data. A lower RMS fitting error indicates a better fit and a more accurate velocity model, while a higher RMS fitting error indicates a poorer fit and a less accurate velocity model.

Reducing the RMS fitting error is an important goal in seismic data processing because it leads to more accurate subsurface images and helps identify potential hydrocarbon reservoirs. Methods such as velocity analysis, tomography, and inversion which is used to update the velocity model and reduce the RMS fitting error. These methods iteratively adjust the velocity model to improve the observed and synthetic seismic data until RMS fitting error is minimized.

To encapsulate, the Root Mean Square (RMS) fitting error serves as a metric gauging the dissimilarity between observed and synthetic seismic data in the realm of seismic data processing. A diminished RMS fitting error becomes indicative of a more precise velocity model, carrying significant implications for discerning subsurface structures, notably hydrocarbon reservoirs. Techniques such as velocity analysis, tomography, and inversion emerge as instrumental methodologies employed to mitigate error in RMS fitting, thereby enhancing the accuracy of the velocity model, as illustrated in Figure 5.7.

In essence, the RMS fitting error serves as a critical parameter in evaluating the fidelity of the velocity model, which is pivotal for identifying and characterizing subsurface features, especially those of economic importance such as hydrocarbon reservoirs. The employment of advanced methods, including velocity analysis, tomography, and inversion, becomes paramount in the concerted effort to minimize errors and refine the velocity model, ultimately

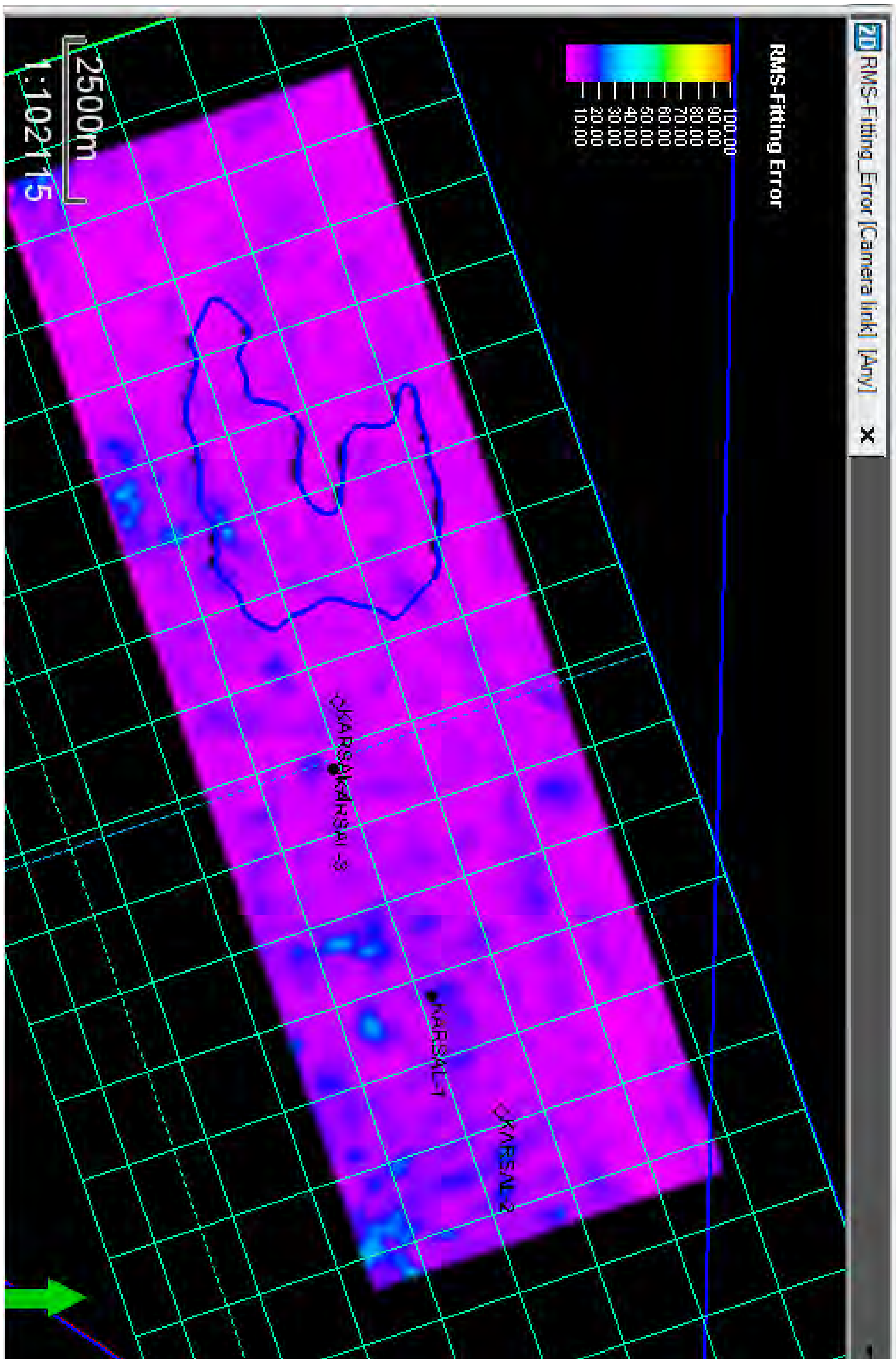

Figure 5.7: RMs fitting error normally ranging from < 15 percent for highly fracture area and > 20 for less fracture area and Azimuthal velocity analysis attributes run over 20 millisecond windows of Eocene carbonates. Less error chances is reflected with blue color and high level of error is with pinkish area.

5.2.4 Percentage anisotropy Azimuthal P-wave velocity anisotropy

Percentage anisotropy is a metric used to evaluate the directional dependence of seismic wave velocities within the subsurface during seismic data processing. Seismic anisotropy describes the phenomenon where seismic waves propagate through the Earth at varying velocities based on the direction in which they are traveling. By analysing the maximum and minimum velocities of seismic waves measured along different directions, geophysicists can calculate percentage anisotropy. For instance, if the maximum 4000 m/s velocity and the minimum 3000 m/s.

Percentage anisotropy is essential in seismic data processing as it allows geophysicists to obtain a more precise understanding of subsurface geology as shown in figure-5.10 and figure-11 respectively. A high percentage anisotropy may indicate the presence of directional heterogeneity such as fractures, whereas a low percentage anisotropy may suggest more isotropic conditions. Additionally, seismic anisotropy can improve seismic imaging and inversion techniques by considering the directional dependence of wave velocities, leading to more accurate and detailed subsurface images.

P-wave velocity anisotropy. This horizontal slice at reservoir Sakaesar Time (2140ms) is color coded with azimuthal velocity anisotropy, calculated as the difference between VP, int, fast and VP, int, slow divided by VP, int, fast. The direction and length of the red lines indicate the orientation of VP, int, fast and P-wave velocity anisotropy expressed as a percentage, respectively. Velocity anisotropy in this field has been shown to be directly proportional to the local in situ principal stress anisotropy.

The in-situ stress orientation data from borehole and hydraulic stress analyses were correlated to the FEATT velocity anisotropy findings (Figures 5.8 and 5.9 respectively). Monitoring micro-seismicity demonstrated that the direction of fast interval velocity coincided with the current highest principal stress. Zones with low minimal horizontal principal stress were also characterised by high VP, int, which is calculated as VP, int, fast minus VP, int, slow.

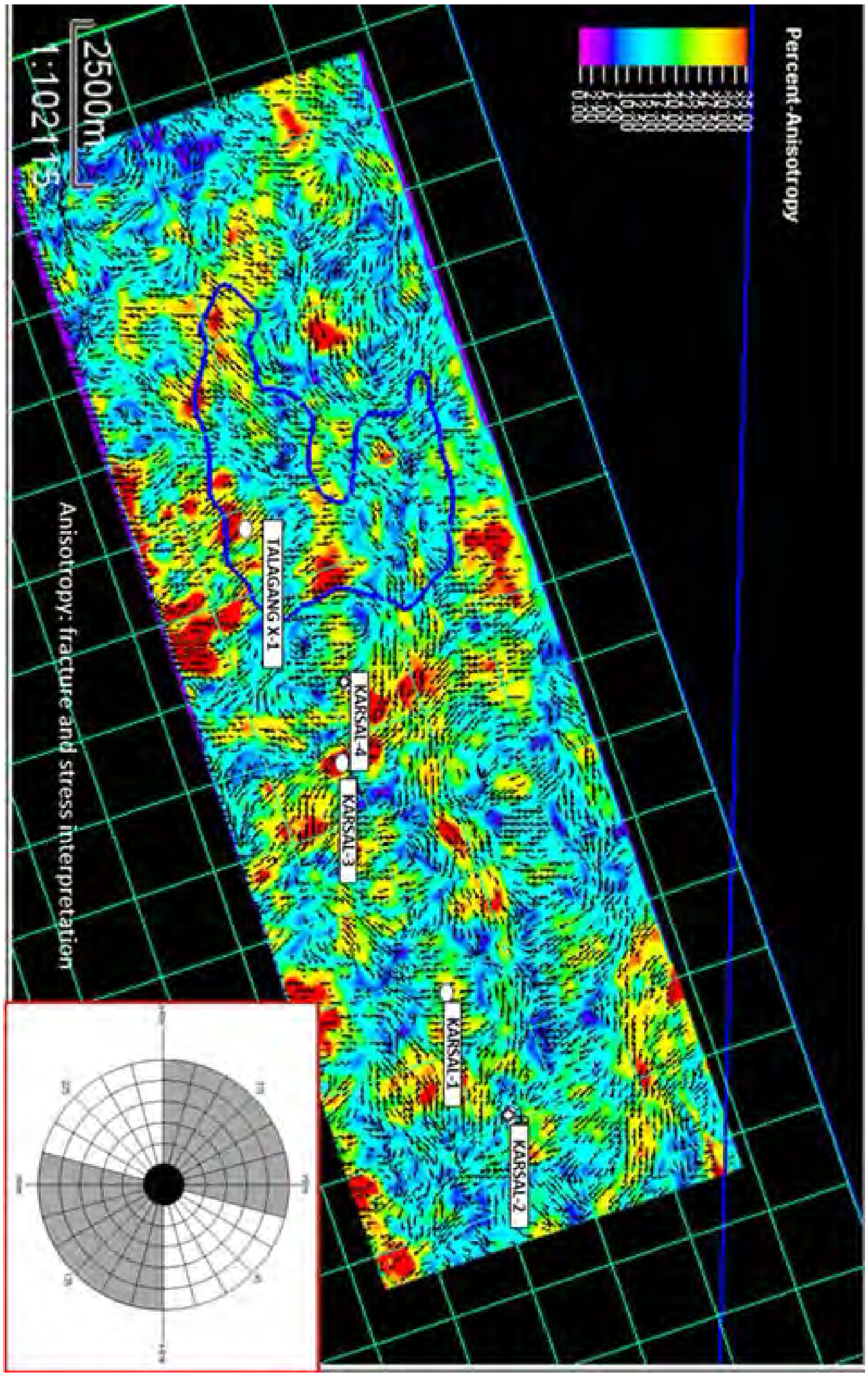

Figure 5.8. Percentage Anisotropy representation of the Eocene carbonate with fracture orientation (Arrow shoes direction of stress) & intensity (quantity of material) red color shows high level and blue is for low level however Grey part of Stereo net shows the producing fracture orientation. Attribute run over 20 millisecond window of Eocene carbonates.

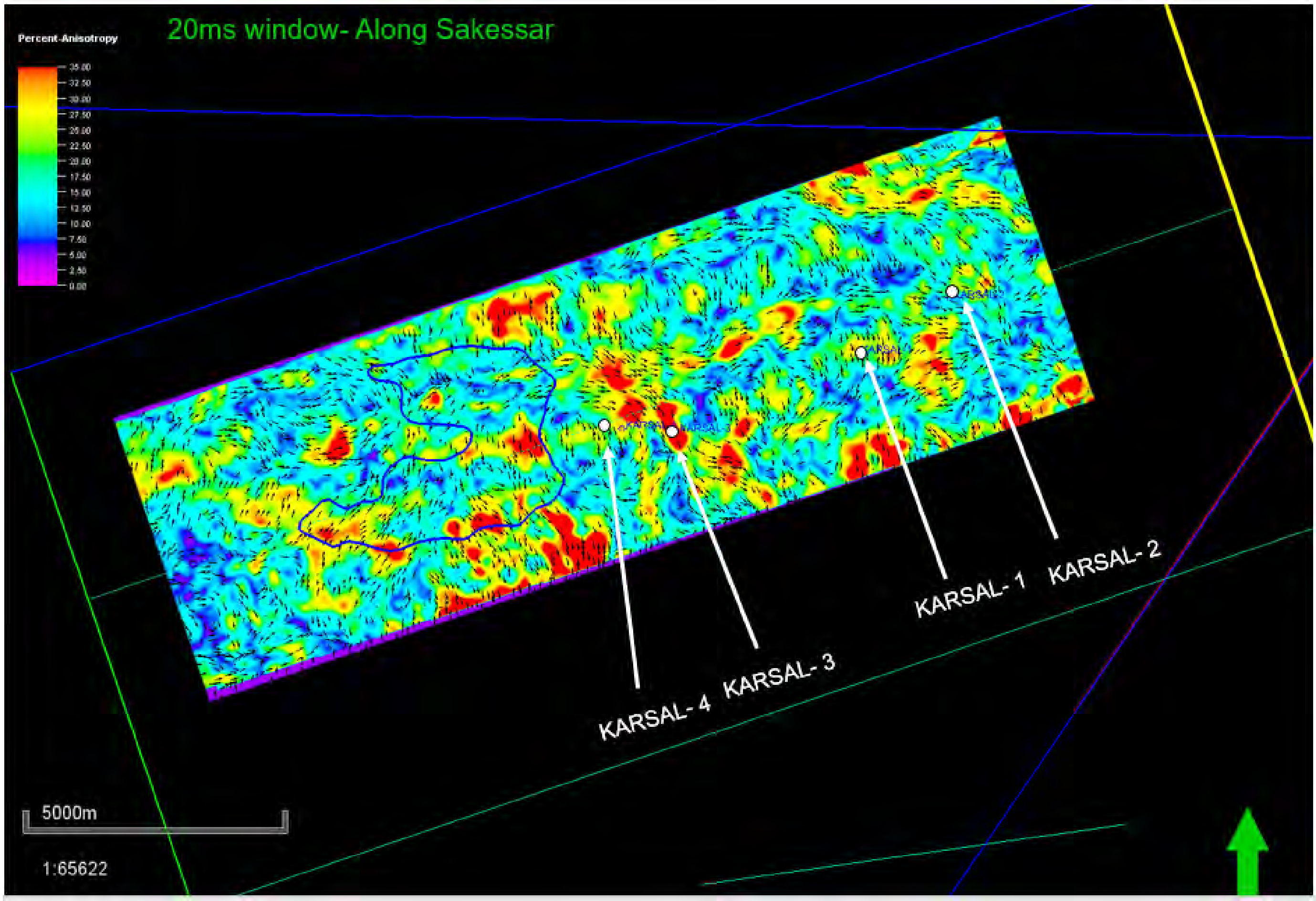

Figure 5.9: More Fractures at Karsal-3 (higher production) than Karsal-1 (less production) No Fractures at Karsal-2- non-Producer Karsal-4 located at edge of anomaly- non-Produce. Good Correlation of FEATT Anisotropy (intensity and direction) with Post Stack Attributes. Anomalies are present at on Karsal Prospect Zones as highlighted in the polygon. The black lines are existing horizontal wells. The two wells on the left are oriented in the direction of minimum stress predicted by seismic azimuthal anisotropy; the well on the right was drilled almost parallel to the maximum stress direction and hydraulic fractures are likely to propagate parallel to the well. The dark blue zone (white circle) to the left of the leftmost well is a possible fault. On the west side of this fault, the maximum stress orientation is SW–NE and parallels the fault plane; on the east side, it is NW–SE and orthogonal to the fault. Geomechanical studies have revealed that faults may alter the stress field near them.

5.3 Correlation of FEATT Anisotropy (intensity and direction) with Post Stack Attributes

Based on the integration of both post stack and anisotropic data integration attributes fracture interpretation has been carried out. Fractures were encountered in Sakesar Formation as was predicted in predrill models and the actual fracture trend found in FMI data is well matched with attributes.

Figure 5.10: Ant track attribute of Eocene carbonate with dark lines of highly intense fracture zones in the inset conductive producing zones from Eocene carbonates are shown by tadpole. From Ant track trend, it is hence proved Karsal 01 & 03 are falling in fracture intense zones and Karsal-02 & 04 missing the fracture zones.Moreover, the generated probs results has also matched with Sakesar core of Talagang X-1. Table-3 shows different calculated parameters based on interpretation of azimuthal velocity analysis and ant tracking.

Parameters	Talagang X-1	Karsal-4	Karsal-3	Karsal-1	Karsal-2
Sakesar Depth (m) SS	3032	3061	3080	3191	3189
No. of Fractures on Ant Track	6	0	2	1	0
Fracture Corridor Length (m) Based on Ant Track	1049	Nil	330	132	Nil
Fracture Hight (m) Based on the seismic core	3	0	4	2	0
Oil Production (BPD)	313	Nil	382	101	Nil
Oil (API)	14.5	Nil	26	26	Nil
V_{int} Fast (m/sec)	5200	3500	5500	4700	3200
V_{int} Slow (m/sec)	4700	3000	5000	4200	2800
Percentage Anisotropy	34	15	32	30	5
Fracture connectivity	Medium to limited	Nil	Medium	Low	Nil

Table 3: Different parameters calculated based on interpretation of azimuthal velocity analysis and ant tracking attribute.

5.3.1 ANT- Track- Sakesar / Chorgali- Overlay by Percent Anisotropy

Ant track result is overlain by the percentage anisotropy to understand the presence of the fracture corridor which were confirm by the drilling of the well Talagang X-1. Percentage anisotropy is calculated only in the well path area selected 100 Sq.km instead of the whole 3D volume. This will give more confidence to drill the fracture corridor-oriented anomaly over non structure mapping as well. As the percentage anisotropy reflect the amount of the fracture corridor to be present in one set of given area over the surface mapping of the Sakesar in Karsal Area as shown in the figure 5.11

Figure 5.11: Overlain of the percentage anisotropy over the ant-track results in karsal field wells area.

5.3.2 Api Relationship with Anisotropic Integration

The relation between API of hydrocarbon and the anisotropic data is merely established based on the well data porosity match with fracture corridor encountered in Ant track result plus the integration of the percentage anisotropic data it reflects that old well postmortem / well failure analysis and the new well location as shown n figure-5.12 can be sort out for the future prospectivity of the karsal field area. Location was identified based on the mark values of anisotropic sweet spots for the old wells already drilled API known and same sweet spots nature new location for the future wells as per the identification highlighted part in figure-5.12.

Gravity of the hydrocarbon based on the American system of the petroleum geoscientist ranges from the low quality of the hydrocarbon from 6 to 14 API and for the high-quality API ranges 26 to 50 for the good octaves and the hydrocarbon nature. Anisotropy refers to variations in the properties of a rock formation depending on the direction in which they are measured.

The integration of anisotropic data with hydrocarbon API grading can provide valuable insights for exploration and production in the oil and gas industry. Here are some recommendations.

5.3.2.1 Collect comprehensive anisotropic data:

To fully leverage the benefits of integrating anisotropic data with hydrocarbon API grading, it is essential to collect comprehensive and high-quality anisotropic data. This may include G&G data.

5.3.2.2 Utilize advanced analysis techniques:

Advanced analysis techniques such as AVO analysis, inversion, and rock physics modeling can help extract valuable information from anisotropic data and integrate it with hydrocarbon API grading. These techniques can help identify the nature, distribution, and quality of hydrocarbons.

5.3.2.3 Collaborate across disciplines:

Effective integration of anisotropic data and hydrocarbon API grading requires collaboration across different disciplines, including geoscience, engineering, and data analysis. Collaboration can help ensure that all aspects of the exploration and production process are considered.

5.3.2.4 Use integrated software tools:

Integrated software tools that can incorporate both anisotropic data and hydrocarbon API grading can help streamline data analysis and facilitate collaboration across disciplines. Such tools can help improve decision-making and increase efficiency in the exploration and production.

The best tool for integration from one domain to other domain and find out the best of the matched results likewise PSTM/PSDM and FMI data will be integrated and cross validated against the Ant Tack result well match from FMI side to the seismic section over the wells for under investigation is calculated figure 5.12.

Talagang-x-1 cross matching over seismic and FMI together with anisotropic data integration well described in the figure 5.13 and past well analysis was carried out for the already drilled wells without seismic and even without the presence of the surface geological features as well. This 3D is of great importance that also resolved the problems of the old myth about the karsal field over wells produced oil in Karsal-1 and Karsal-2 as shown its best integration in the figure 5.14 and same as for wells behavior on the ant track data as shown in figure 5.15 for the wells Karsal-3 and Karsal-4 respectively.

Overall, the integration of anisotropic data with hydrocarbon API grading can provide valuable insights to the E&P industry. By collecting comprehensive data, utilizing advanced analysis techniques, collaborating across disciplines, and using integrated software tools, exploration and production companies can effectively leverage this integration to improve decision-making and In the case of heavy oil production, anisotropic data can be used to better understand the spatial distribution and orientation of the oil reservoirs, as well as the flow pathways within them. This can help in optimizing the placement of production wells and designing effective production. Some examples of anisotropic data that can be used in heavy oil production include seismic data, well logs, and core samples. By analyzing these data sets, geoscientists and reservoir engineers can identify patterns and correlations between anisotropic properties and heavy oil production and use this information to make more informed decisions about production operations.

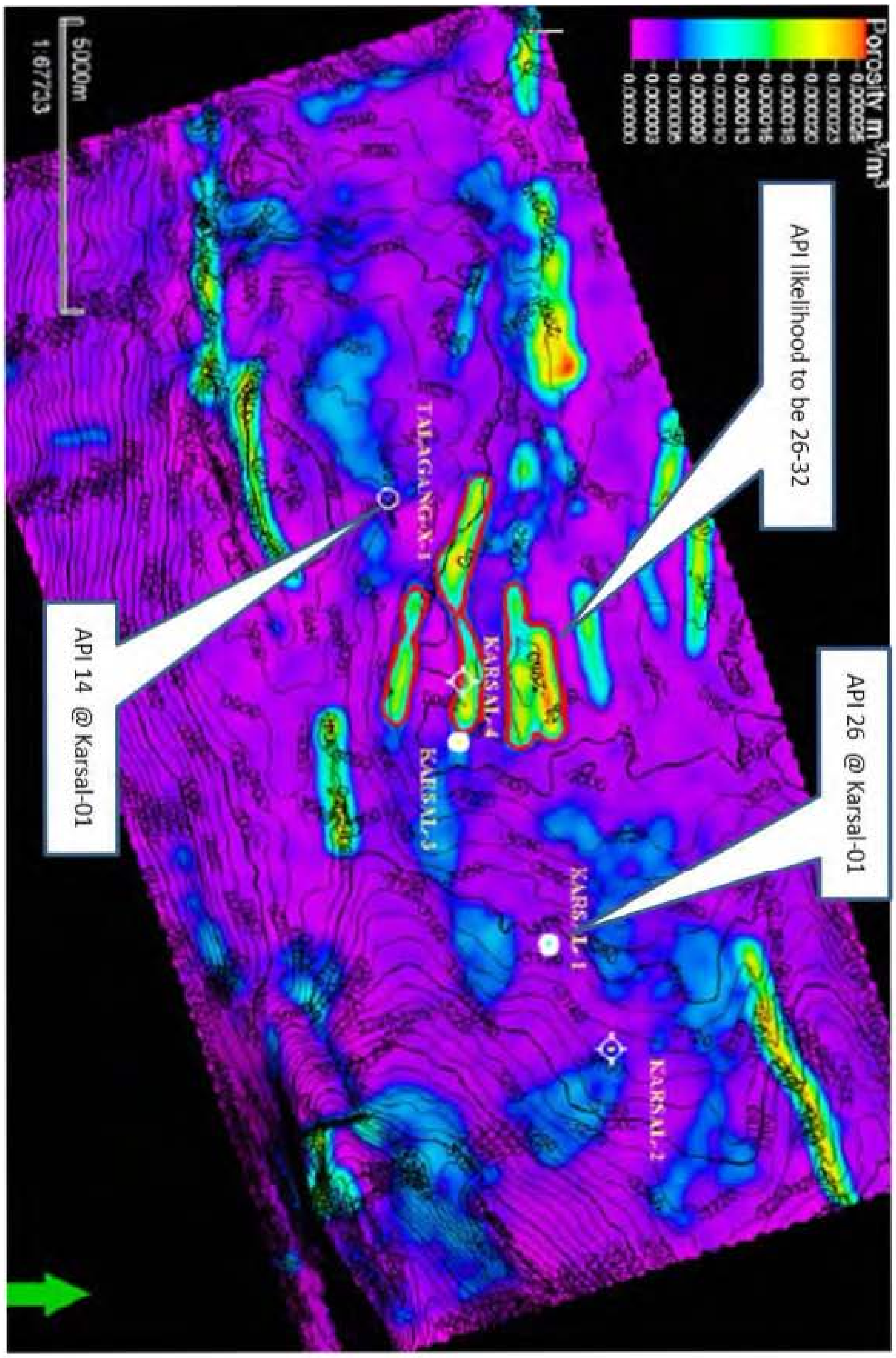

Figure 5.12: Correlation of the API with anisotropic data and well data integration of Sakesar limestone.

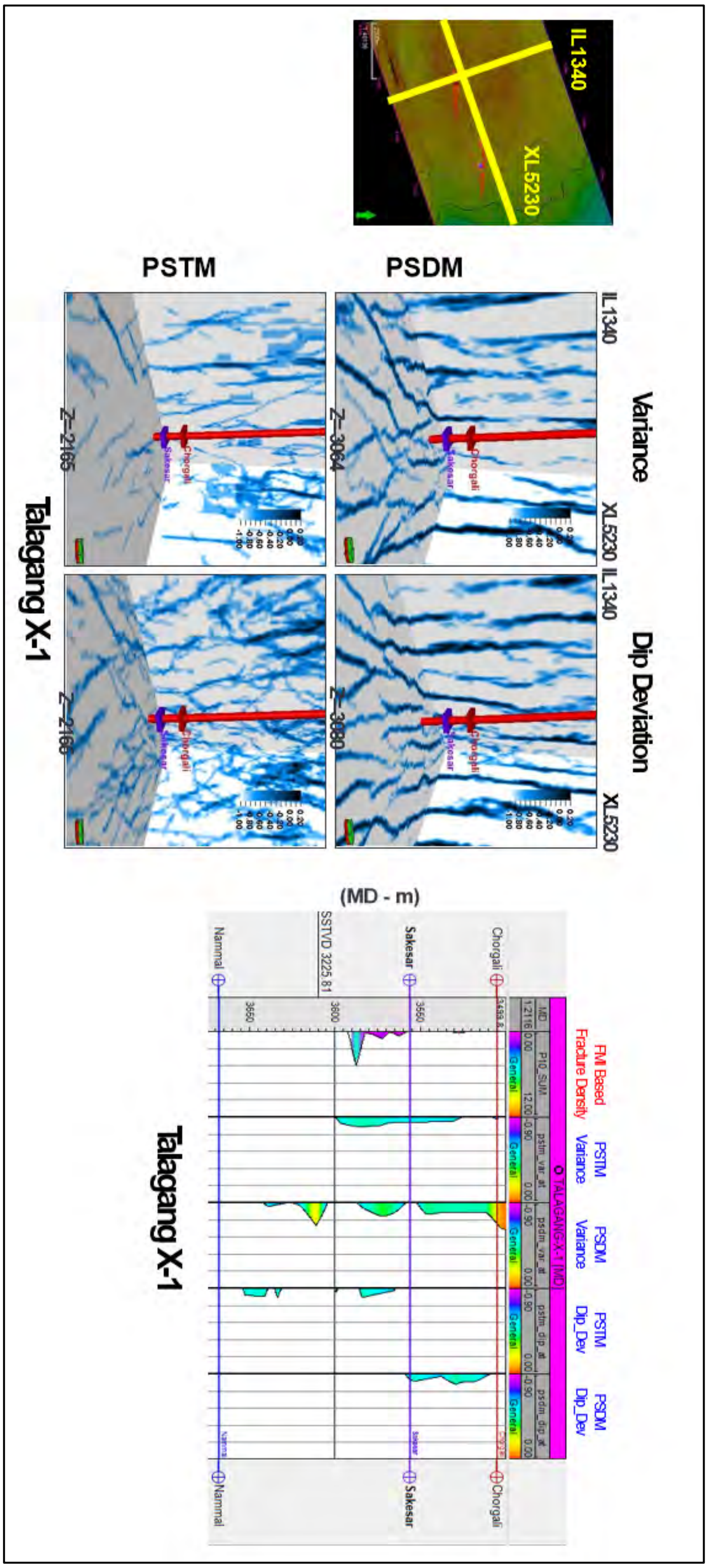

Figure 5.13: Ant tracking results around the well location Talagang X-1 which resulted with seismic amplitude derived fracture integration right corner of well panels.

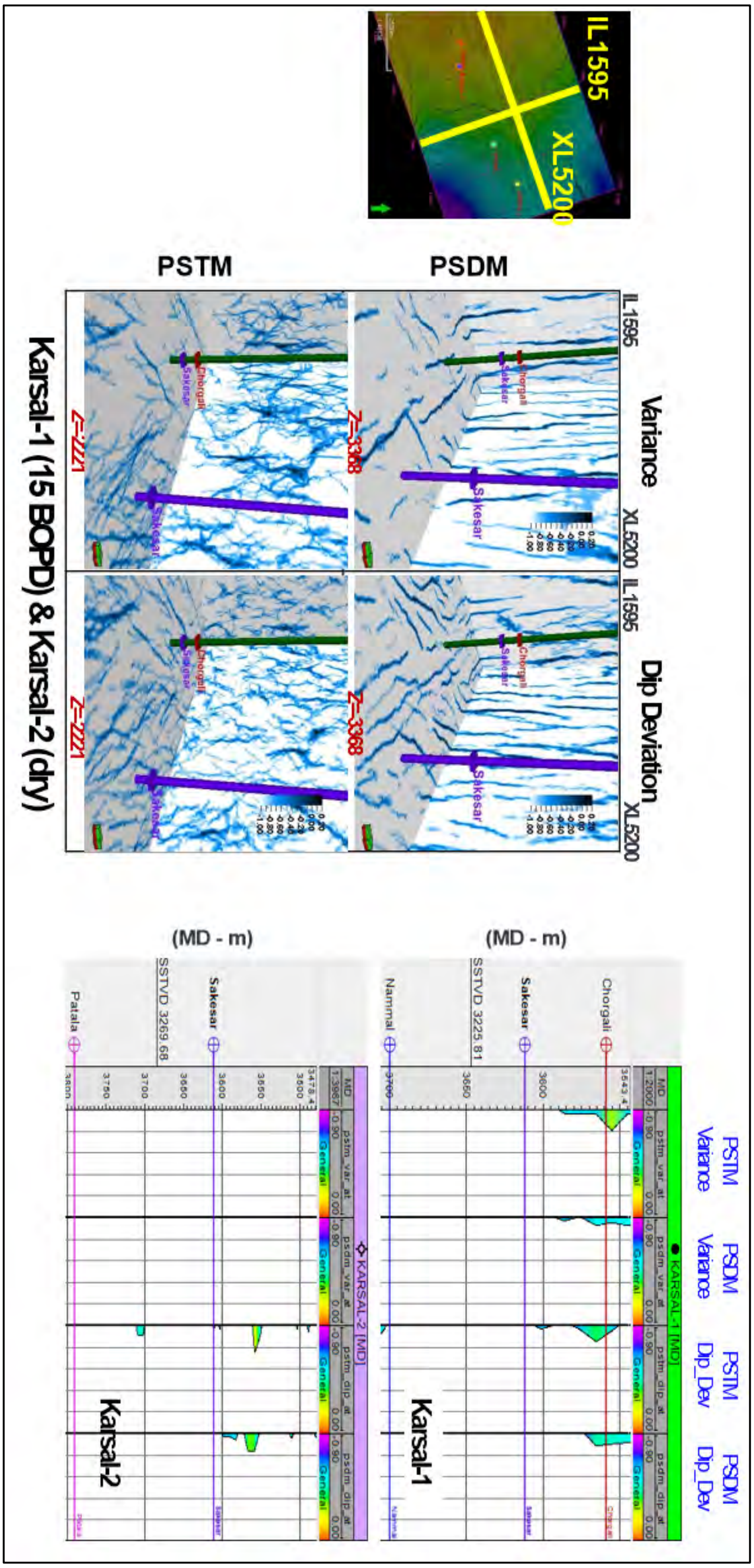

Figure 5.14: Ant tracking results around the well location Karsal-1 and Karsal-2 which resulted with seismic amplitude derived fracture integration right corner of well panels.

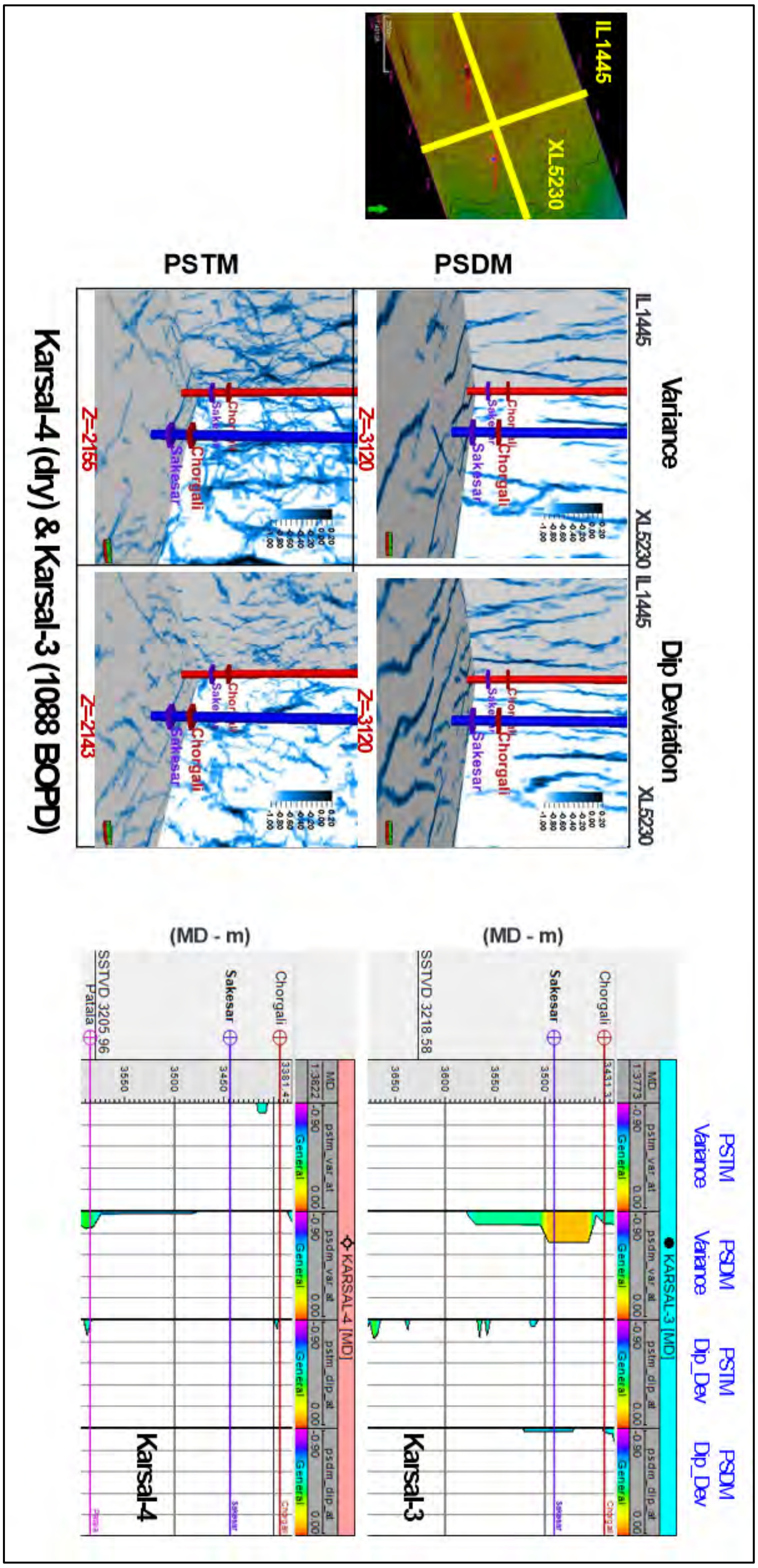

Figure 5.15: Ant tracking results around the well location Karsal-3 and Karsal-4which resulted with seismic amplitude derived fracture integration right corner of well panels.

5.4 Recommendation and new window for E & P industry

Integrating anisotropic data with hydrocarbon API grading can provide significant insights for the E&P of hydrocarbons. To fully utilize the benefits of this integration, it is crucial to acquire comprehensive and high-quality anisotropic 3D data. This may include high fold seismic, well logs, core samples to gain a better understanding of the subsurface.

Furthermore, advanced analysis techniques such as AVAZ analysis, inversion, and rock physics modelling can help extract valuable information from anisotropic data and integrate it with hydrocarbon API grading. These techniques can assist in identifying the nature, distribution, and quality of hydrocarbons present in a reservoir. For example, AVAZ analysis can be used to identify areas of high oil saturation and distinguish between oil and gas deposits.

Effective integration of anisotropic data and hydrocarbon API grading requires collaboration across different disciplines, including geoscience, engineering, and data analysis. Working together can ensure that all aspects of the exploration and production process are considered and optimized. By collaborating across disciplines, teams can enhance their understanding of the subsurface, optimize drilling and completion activities, and improve production outcomes.

Moreover, integrated software tools that can incorporate both anisotropic data and hydrocarbon API grading can help streamline data analysis and facilitate collaboration across disciplines. Such tools can assist in improving decision-making and increasing efficiency in the exploration and production process. These tools can also help in predicting hydrocarbon properties and facilitate.

Integrating anisotropic data with hydrocarbon API grading can offer valuable insights for the oil and gas industry. However, this requires a comprehensive approach that involves collecting high-quality anisotropic data, utilizing advanced analysis techniques, collaborating across different disciplines, and using integrated software tools. By following these key recommendations, exploration and production companies can make informed decisions and optimize.

Traditionally, exploration efforts have focused on obtaining 3D data for conventional sources of hydrocarbons. However, there is now a growing trend towards exploring larger non-structures such as the Potwar province, which contains abundant limestone formations with some extent of biodegrading properties that have significant potential as shown in figure-5.18. Instead of investing in costly deep well drilling, it may be more prudent to perform API and anisotropic grading prior to drilling dry wells. By doing so, exploration efforts can be directed.

To achieve this, it is important to identify the key features that are indicative of favourable hydrocarbon reservoirs as shown in figure-5.16. These may include the properties of the surrounding rock formations porosity and permeabilities distribution within the reservoir, the presence of fractures, and the API and anisotropic grading of the reservoir. By analysing these features using advanced techniques and collaborating with experts from different fields, exploration companies can better understand the geology of the region and make informed decisions on where to focus as shown in figure-5.16.

Integrating software tools that can process and interpret large amounts of data can greatly enhance the efficiency and accuracy of the exploration process. Such tools can be used to perform simulations, generate predictive models, and identify areas with the highest potential for hydrocarbon reservoirs.

By adopting these strategies and leveraging the benefits of integrating anisotropic data with hydrocarbon API grading, exploration and production companies can maximize their returns and optimize their operations in the oil and gas industry.Small producing zones identified based on the outcomes of this technique as clearly mentioned in details over figure-5.17 as prospect “A” 2D arial view and figure-5.18 for its 3D respective view, respectively prospect “B” is shown in the figure-5.19 in 2D aerial view and in figure-5.20 its 3D images while identified prospect “C” represent by the figure-5.21 for its 2D aerial view and figure-5.22 for its 3D view for non-structure exploration strategy for the oil and gas companies to follow.

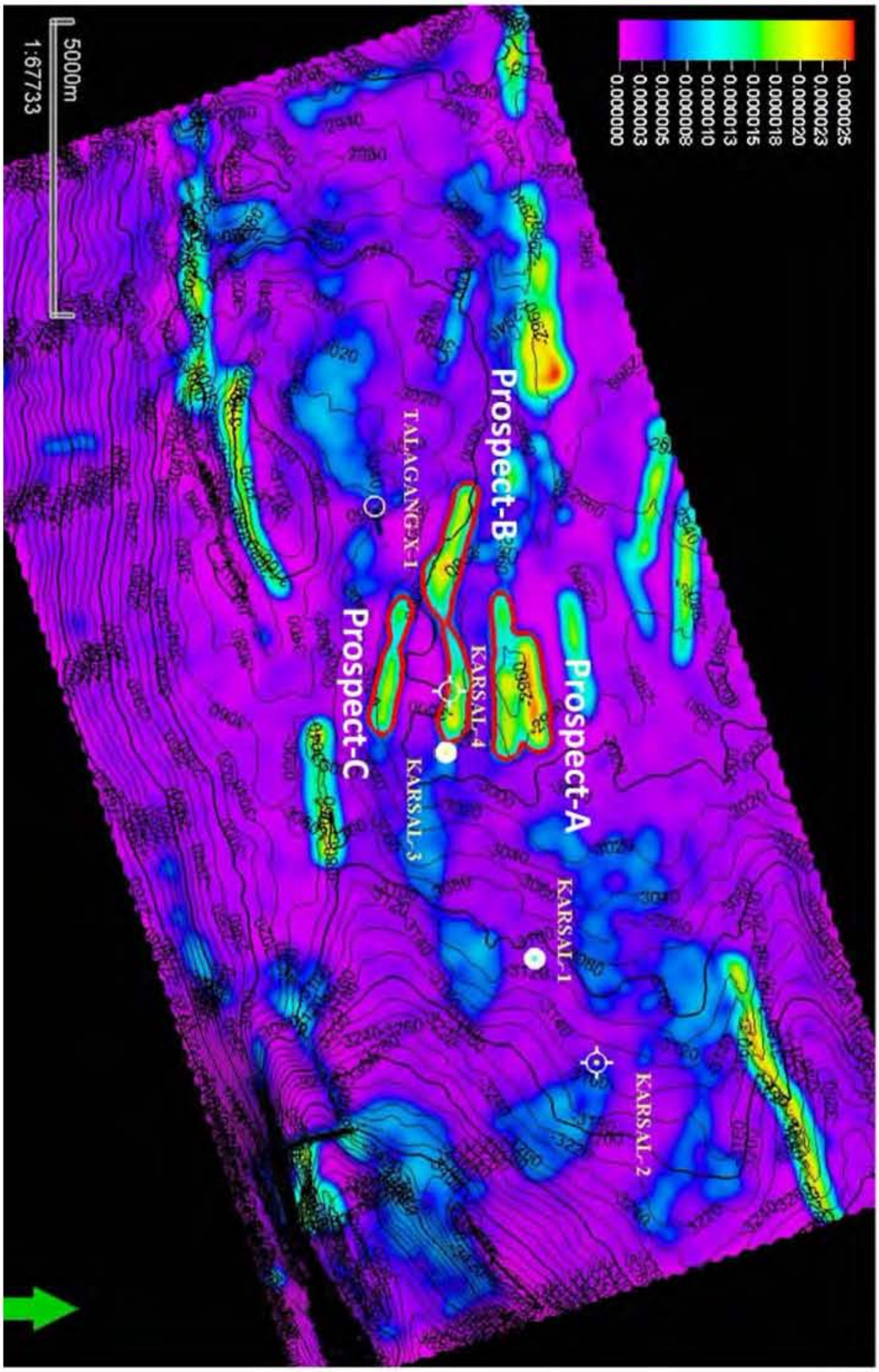

Figure 5.16: Location of the sweet spots and the future drilling locations based on the API and anisotropic interpretation zones of fracture corridors instead of structure closures.

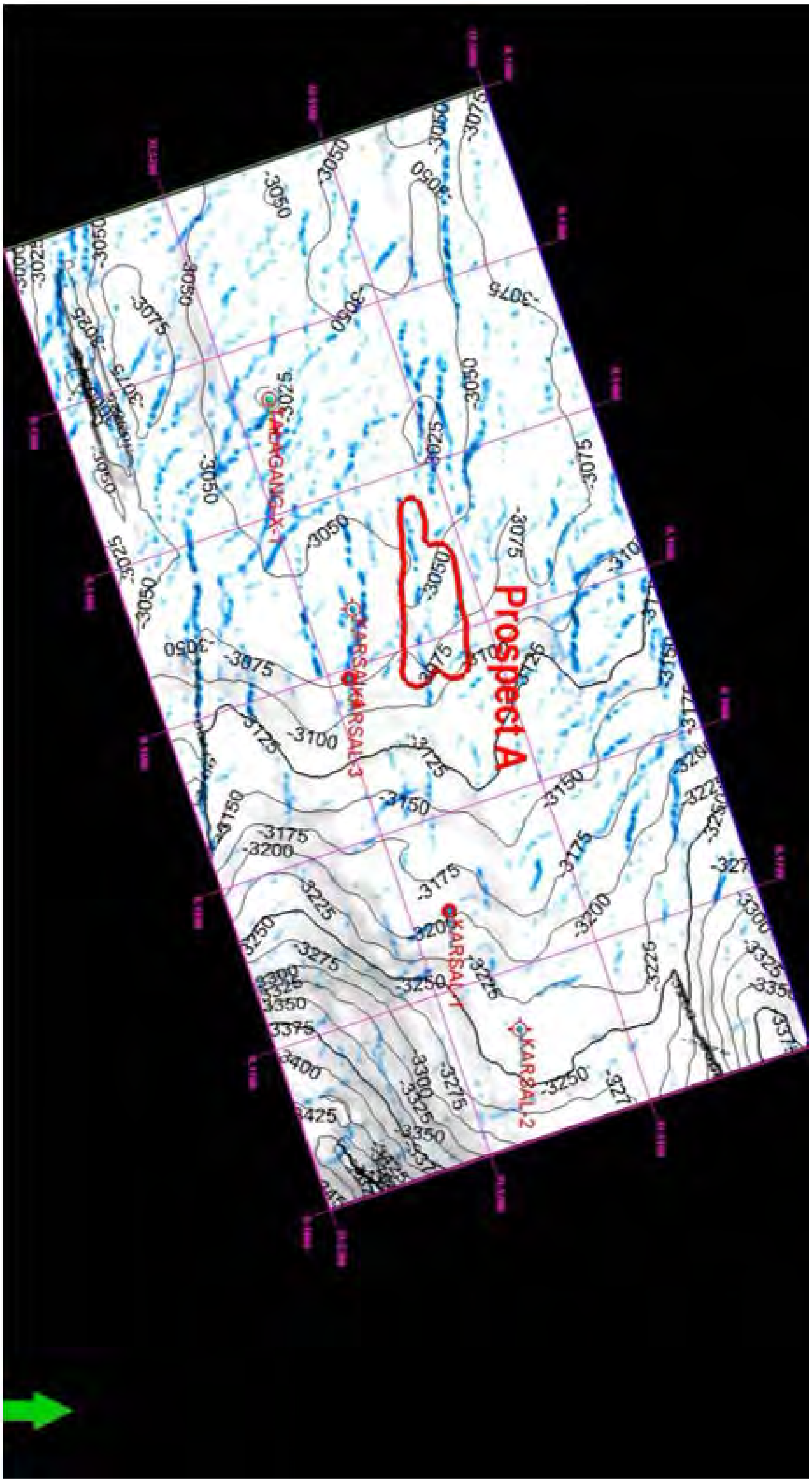

Figure 5.17: Map view of the prospect area A based on the ant track and the anisotropic integration well location with prognosis. 2D contours overlaid on the sakaesar surface ant-track results and monocline trend is reflection the data nature at sakaesar level with highlighting orange color polygon with anisotropic based data integration marked at the PSDM a level.

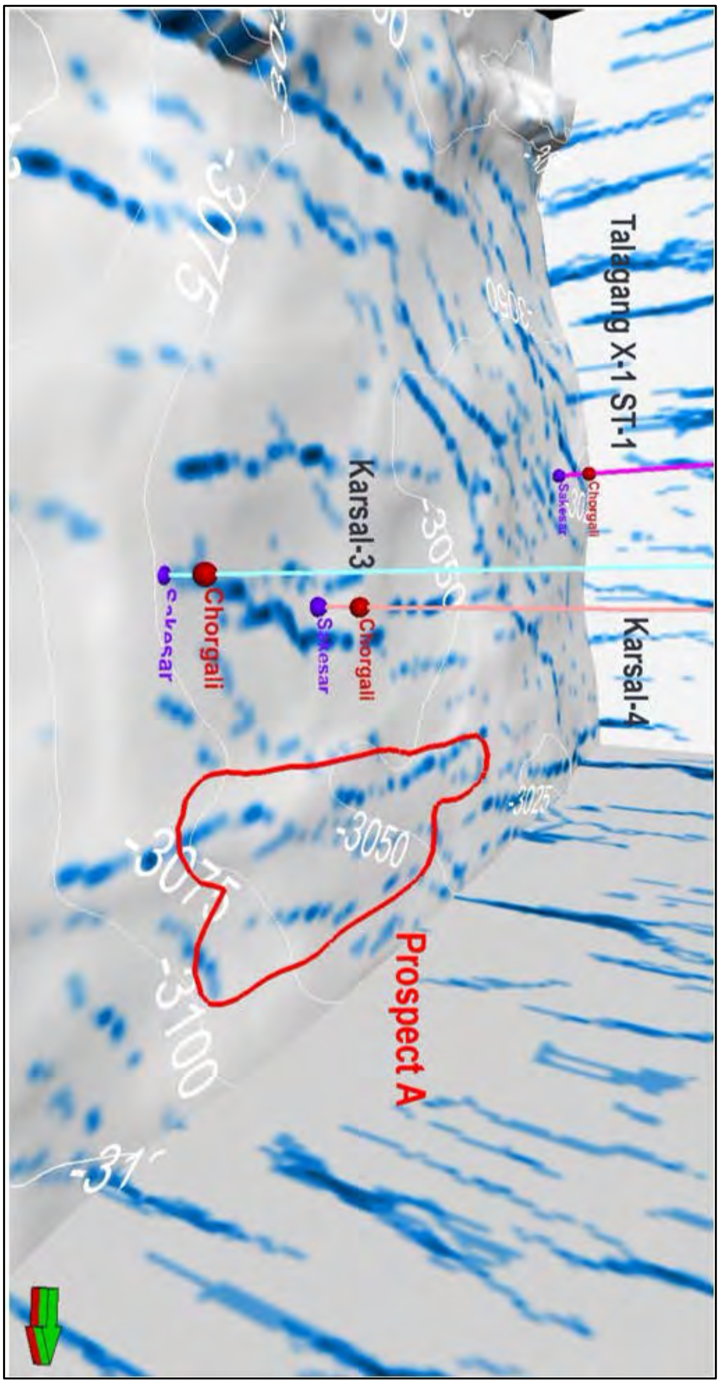

Figure 5.18: 3D view of the prospect area A based on ant track and the anisotropic integration.In the figure 5.18, the blue color lines represent the fracture corridors aligned in the maximum stress direction as per the integration of the anisotropic and post stack attribute at the sakaesar level surface with INLINE, XlINE in the triangle view 3D Orange color polygon represent the prospect area **A** with respect to the anisotropic and Api behavior of the hydrocarbons just stabled and shown above.

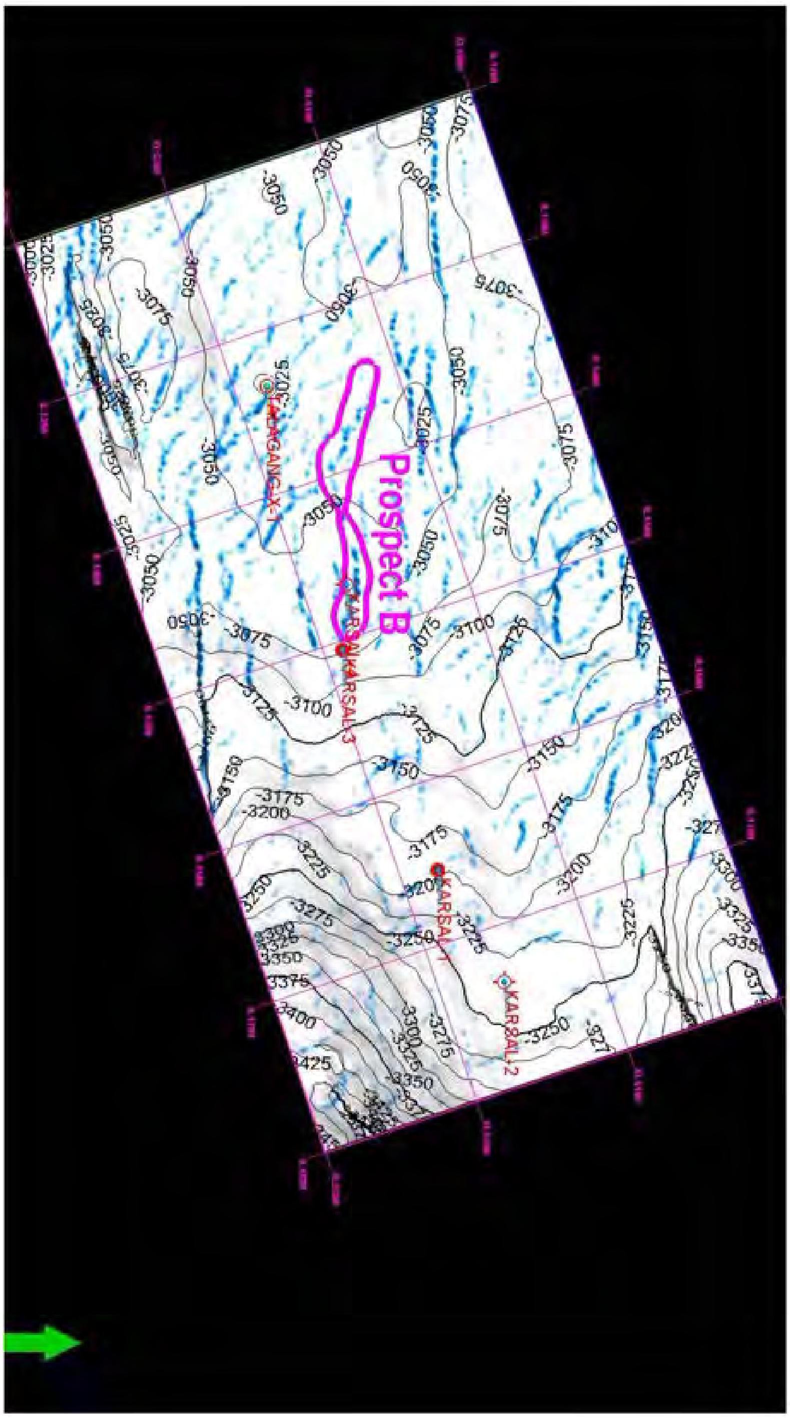

Figure 5.19: Map view of the prospect area B based on ant-track and the anisotropic integration proposed. 2D contours overlaid on the sakaesar surface ant-track results and monocline trend is reflection the data nature at sakaesar level with highlighting orange color polygon with anisotropic based data integration marked at the PSDM a level.

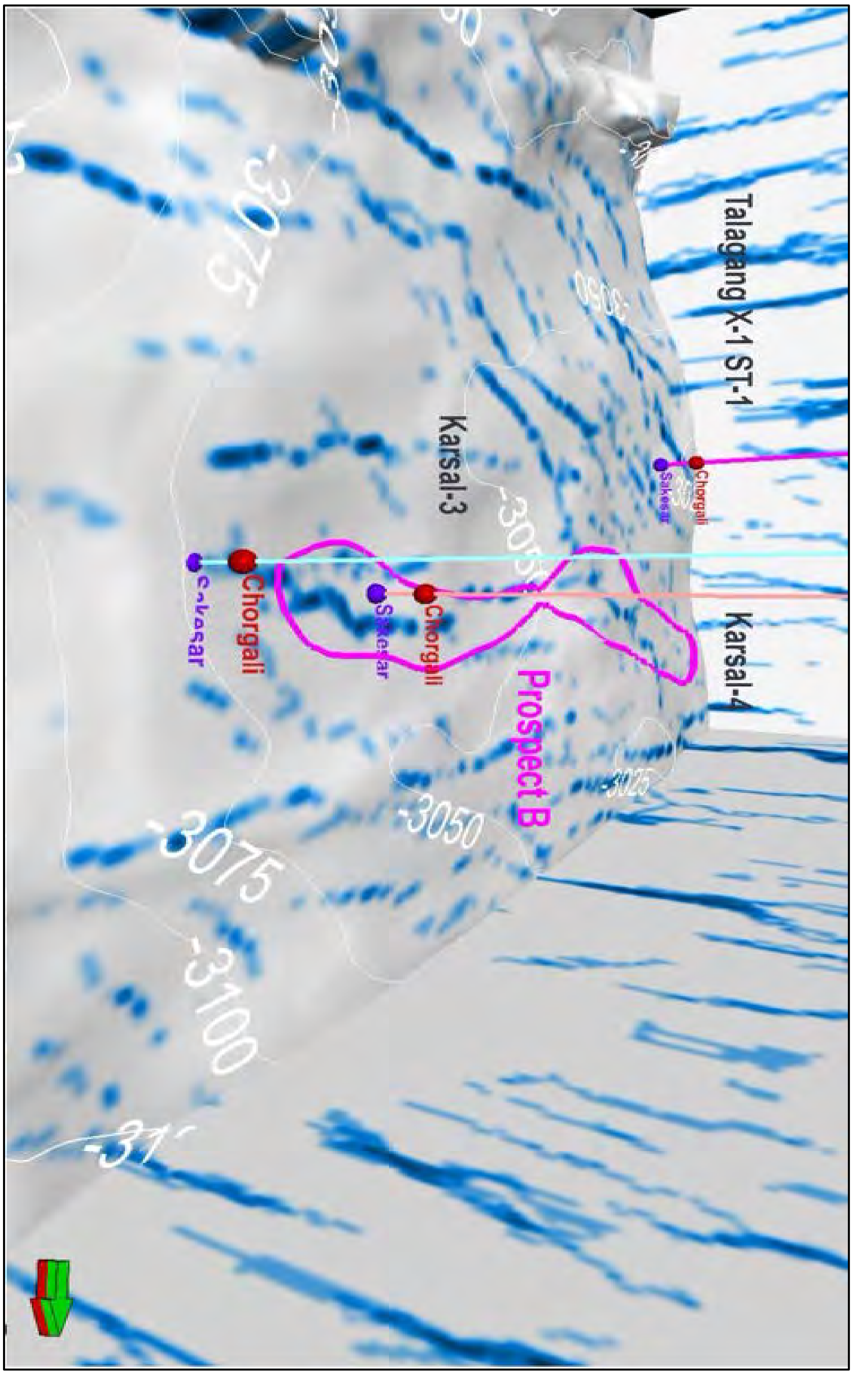

Figure 5.20: 3D view of the prospect area B based on ant-track and the anisotropic integration proposed well location with prognosis.

In the figure 5.20, the blue color lines represent the fracture corridors aligned in the maximum stress direction as per the integration of the anisotropic and post stack attribute at the sakaesar level surface with Inline, Xline in the triangle view 3D Orange color polygon represent the prospect area **B** with respect to the anisotropic and Api behavior of the hydrocarbons just stabled and shown above.

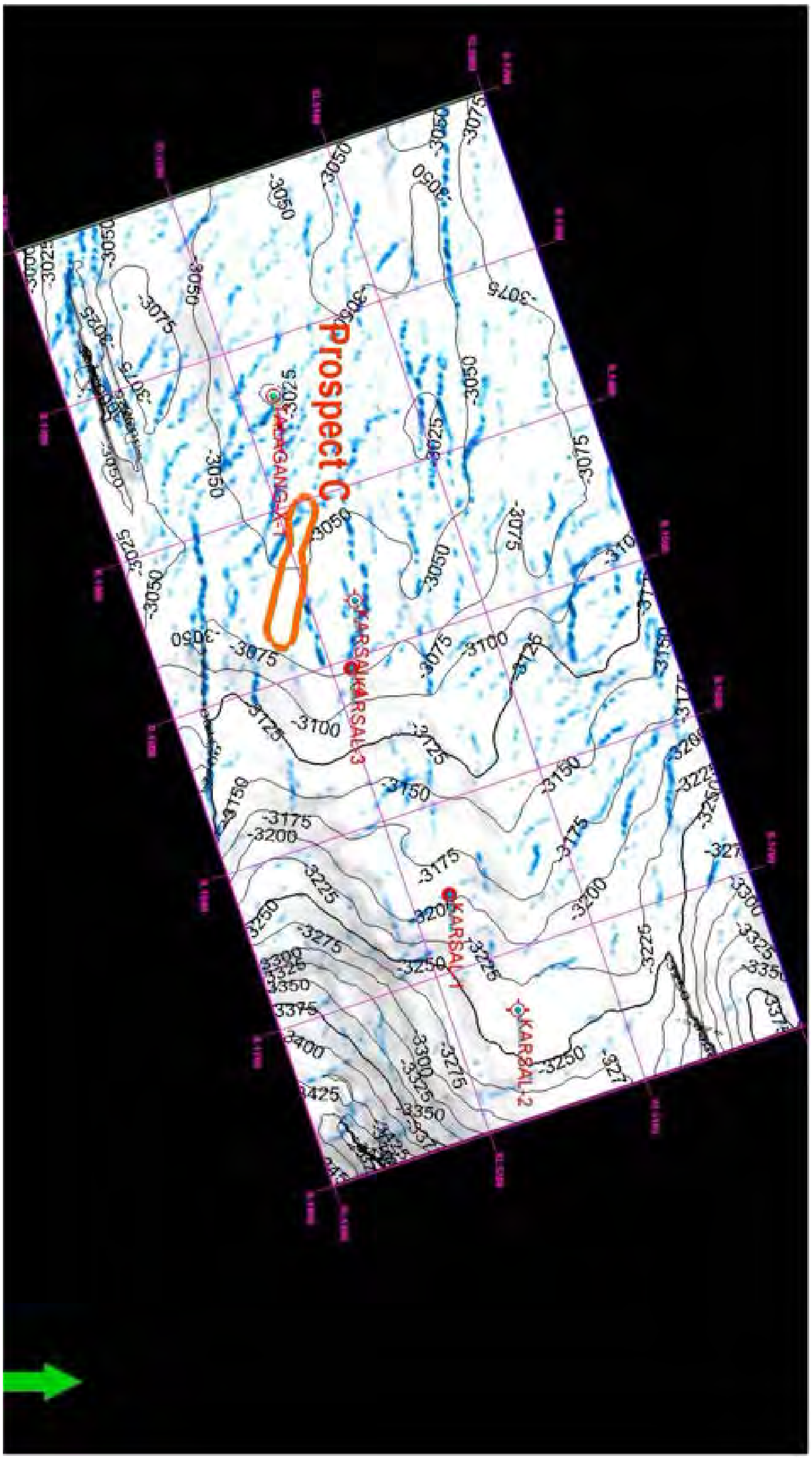

Figure 5.21: Map view of the prospect area C based on ant- track and the anisotropic integration well location with prognosis.2D contours overlaid on the sakaesar surface ant-track results and monocline trend is reflection the data nature at sakaesar level with highlighting orange color polygon with anisotropic based data integration marked at the PSDM a level.

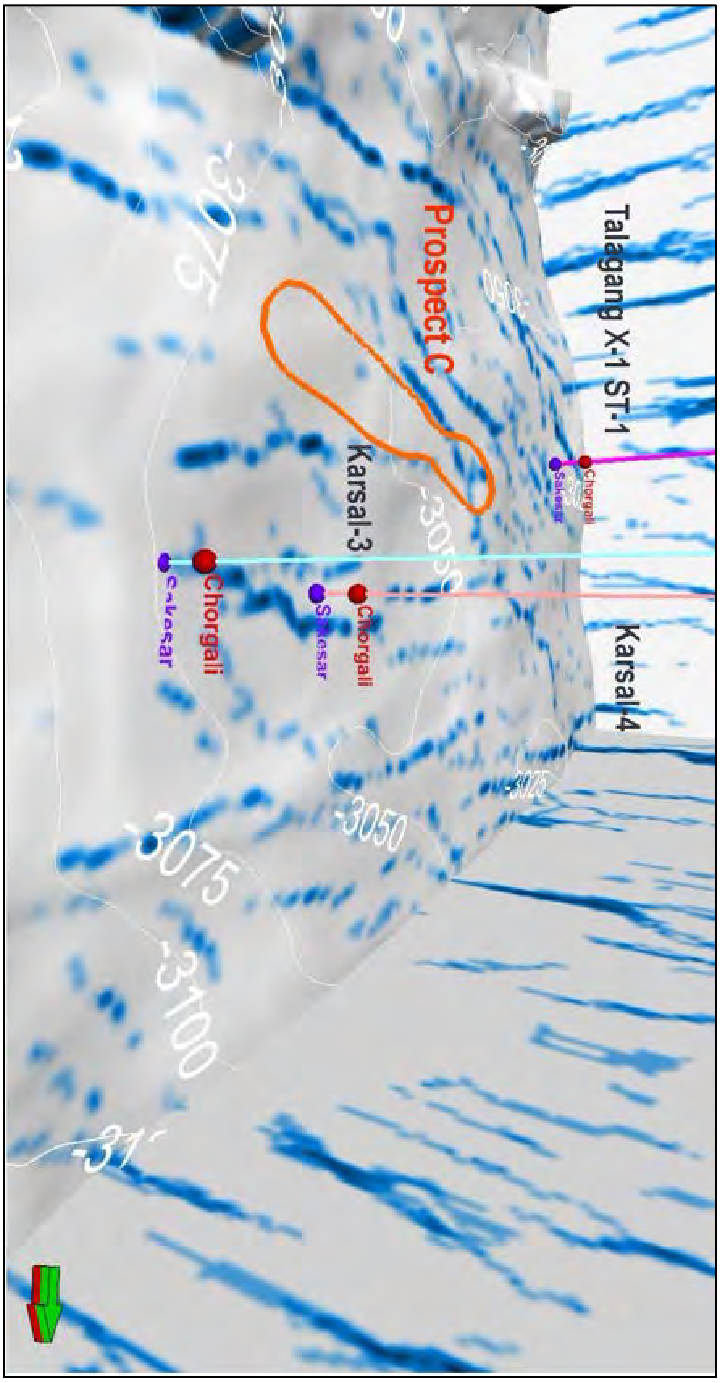

Figure 5.22: 3D view of the prospect area C based on ant-track and the anisotropic integration proposed well location with prognosis. In figure 5.22, the blue color lines represent the fracture corridors aligned in the maximum stress direction as per the integration of the anisotropic and post stack attribute at the sakaesar level surface with INLINE, XlINE in the triangle view 3D Orange color polygon represent the prospect area C with respect to the anisotropic and Api behavior of the hydrocarbons just stabled and shown above.

Chapter -06

Discussion and Conclusions

Discussion

In the early 1950s and late 1960s, it was believed that Karsal was a surface anticline, based on preliminary concepts and assumptions. Consequently, four wells were drilled in accordance with this understanding. However, after the acquisition of 3D seismic data in 2014, it was revealed that Karsal was a monocline without structural entrapment. This discovery shed light on the inadequacies of surface-based drilling methods, which were based on faulty assumptions about the subsurface geology.

The presence of fractures in carbonates is crucial for successful oil accumulation in the Potwar basin, as demonstrated by the Karsal field where oil was found despite the absence of structural closure. Therefore, identifying sweet spots of natural fractures is essential for exploration in the Potwar basin, and may be more important than exploring structural traps. However, this does not diminish the significance of structural traps. The source rock analysis indicates that the Sakesar Formation has served as a common source and reservoir, generating and accumulating oil in fractures. Pre-stack and post-stack data integration and interpretation of attributes show that the presence of fractures in Karsal-01 and 03 led to oil production with API 26, while Karsal-2 and 4 were unproductive due to the lack of fractures. However, Talagang X-1 produce API of 14 oil with production of 313 bbl/day.

Wide azimuth and high-resolution 3D seismic data are necessary to identify fracture plays, and the quality of azimuthal velocity analysis and ant-tracking depends on good azimuth in the 3D seismic data. The OVT migration algorithm is critical for preserving azimuthal velocity variation, which can help identify the intensity and direction of fractures in the seismic cube. These attributes are essential for locating fractured plays and selecting optimal well locations. Many dry wells were drilled and abandoned due to the absence of fracture networks, so reassessing them with the help of 3D seismic and state-of-the-art processing through OVT migration and azimuthal velocity estimation is necessary Calvert, Alexander, et al. (2008).

Exploration wells targeting fracture networks should be drilled horizontally to maximize the encounter of fractures and achieve better productivity. Researchers are currently establishing a crucial link between seismic anisotropy and the detailed investigation of the Sakaesar age carbonate province in Potwar. This dissertation uses seismic, anisotropic, and well data to better understand regional structural and stratigraphic frameworks, as illustrated in section 3.6 chapter 3 and section 3.8 chapter 3 along with section 4.5 chapter 4 clearly demonstrates the usage of anisotropic and well correlation data to demonstrate the regional presence of the stress oriented same class structure with the possibility of subsurface fracture corridors using FMI data as well.

The delineation of potential fracture corridors within the study area was successful because the data from the ant track and anisotropic porosity correlations shown in Sections 4.4 and 5.2.1 of Chapter 4 and Chapter 5 clearly showed the presence of the fracture corridor in the sakaesar surface of the karsal area. Recommendation for producing zones of limestone in Potwar province provided in chapter 5 section 5.4 with figure- 5.16 with new concept to drill horizontal wells based on fracture anomalies identifies prospective zones as prospective zone-A and zone B with anomalous area as shown inn figure- 5.16,18,20 respectively a relation is developed between API and anisotropic data with open oriented fracture as shown in figure- 5.14 and details investigation comprehended in the table 3 which described the relationship of anisotropic and API how it was developed and justified on the present and old drilled wells plus can be refer to the future prospective zones (Prospect A, Prospect B) based on that future drilling location marked and suggested to pursue in future without the looking into the structural trap just scope the anomalous anisotropic pattern with ant track together to drill. Integrated approach and its potential will be fully utilised upon working on the same concept as demonstrated in the dissertation. In section 5.7 of chapter 5, the industry is given a fresh life cycle to explore on the Potwar' sub basin well established the exploration strategy.

This connection promises to provide satisfactory answers to some of the mysteries surrounding the heavy and low API production of oil in the Karsal field and the adjacent Balkassar field. By considering the effects of seismic anisotropy, which refers to the directional dependence of seismic waves' velocity and amplitude, experts hope to gain a deeper understanding of the subsurface geology and identify potential areas for future exploration and production activities along with unconventional means. This advancement in technology and knowledge is expected to greatly benefit the E&P industry and contribute in development & more effective exploration & production strategies.

Well Name	Operator (Date)	Status	TD (Formation)	Target (s)	Comments
Karsal-01	POL (1955)	Oil	3886 (Amb)	Chorgali & Sakesar	Oil discovery from Eocene carbonates
Karsal-02	POL (1957)	P&A	3868 (Hangu)	Chorgali & Sakesar	Testing results of Chorgali & Sakesar Formations were discourging.
Karsal-03	POL (1959)	Oil	3555 (Sakesar)	Chorgali & Sakesar	Oil discovery from Eocene carbonates
Karsal-04	POL (1960)	P&A	3725 (Chhidru)	Chorgali & Sakesar	Testing results of Chorgali & Sakesar Formations were discourging.

Table 4: Wells at Karsal anticline were drilled from 1955 to 1960 to test the carbonates of Eocene age Chorgali and Sakesar formations. Karsal-1 and Karsal-3 produced oil whereas other Karsal-2 and Karsal-4 did not encounter fractured carbonates reservoir which failed to yield oil.

Depth Range	*Formation*	*Age*	*TOC (%)*	*Vitrinite Refelectance (Ro)*	Comment
3519-3555	Chorgali	Eocene	1.13-0.62	0.52-0.54	Organic matter is immature and in the pre-oil window
3584-3672	Sakesar	Eocene	0.38-1.79	0.53-0.63	Organic matter is marginally mature to early mature and in the early oil window
3672-3741	Nammal	Eocene	0.31-1.26	0.59-0.61	Organic matter is marginally mature to mature and near the oil window.
3745-3775	Patala	Paleocene	0.51-1.81	0.59-0.67	Organic matter is mature and in the early oil window.

Table 5: Source rock data of Talagang X-1. Source potential lies in Sakesar, Nammal and Patala formations with adequate thermal maturity (Ro) to generate oil as found in Talagang X-1 (oil gravity 14.6 API). Sakesar Formation is the regional reservoir rock in several fields in Potwar basin including Talagang X-1 and neighboring Balkassar field. The data suggest that reservoir rock has also acted as a source rock which implies that wherever fracture development occur oil accumulation oil can be found as in Karsal field.

Conclusions

The study conducted in the Potwar area revealed distinct patterns in inherent acoustic anisotropy values corresponding to the type of API hydrocarbons present. Heavy API hydrocarbons were associated with high inherent acoustic anisotropy values, while areas with light API hydrocarbons exhibited lower inherent acoustic anisotropy values.

This observation serves as a crucial link between acoustic anisotropy and hydrocarbon composition, presenting a novel approach to hydrocarbon reservoir characterization. Furthermore, the results indicated a correlation between the direction of maximum intrinsic acoustic anisotropy and the fluid flow path within the reservoir. Understanding this relationship provides valuable information for predicting and optimizing fluid flow behavior, contributing to the development of effective reservoir management strategies.

The findings from this study have direct implications for hydrocarbon exploration and production efforts in the Potwar limestone province. The knowledge of acoustic anisotropy values allows for the identification and differentiation of heavy and light API hydrocarbons, enabling precise reservoir characterization.

This information can be harnessed to optimize well placement, design tailored production strategies, and enhance overall exploration and production efficiency. In conclusion, the integration of acoustic anisotropy analysis in hydrocarbon exploration in the Potwar limestone province offers a promising avenue for improved reservoir characterization.

The correlation between acoustic anisotropy values, hydrocarbon type, and fluid flow path provides valuable insights that can be leveraged to make informed decisions in well placement, production strategies, and overall exploration and production activities in the region.
It is of the worth to mention that line wise objective defined above in the section 1.2 are achieved successfully.

Number-1 It is crucial to determine the existence of an open fracture network in limestone, as these fractures play a pivotal role in governing the hydrocarbon flow. As illustrated in Figure 5.13, 5.14, and 5.15 of Chapter 5, it is evident that not all fractures equally contribute to well flow. The figure distinctly portrays that open fractures oriented in the NNE to SSW direction significantly enhance the well flow, exemplified by the robust flow in Karsal-3. Conversely, mixed-oriented fractures in Karsal-1, which are not fully opened, result in diminished flow. Notably, Karsal-2 exhibits a conspicuous absence of open-oriented fractures, leading to a complete lack of discernible flow. This underscores the critical importance of identifying and understanding the orientation and nature of fractures for optimizing hydrocarbon production.

Moreover, this detailed investigation into the fracture network's impact on well flow aligns with the broader objective of optimizing reservoir performance in the Karsal area. By discerning the fracture orientations and their influence on flow dynamics, operators can make informed decisions about well placement and stimulation strategies, thereby enhancing overall reservoir recovery.

This comprehensive analysis is integral to the larger reservoir management strategy, aiming to maximize hydrocarbon recovery from the Karsal limestone formation. The insights gained from this study not only contribute to the specific understanding of Karsal-1, Karsal-2, and Karsal-3 but also serve as a valuable guide for similar limestone formations in other geological contexts.

Number-2 Conducting an in-depth examination of the geological and stratigraphic characteristics in the specified region, as outlined in Sections 2.1 and 2.3 of Chapter 2, is imperative. This analysis aims to gain a comprehensive understanding of the hydrocarbon flow dynamics, especially in scenarios where certain structural elements are absent. The exploration history of the Karsal area, extensively detailed in the accompanying figures and expounded upon in Section 2.4, provides crucial insights into the historical context of hydrocarbon exploration in the region.

Delving into the geology and stratigraphy of the region, as elucidated in Sections 2.1 and 2.3, is integral to unraveling the intricacies of hydrocarbon migration and accumulation. By comprehensively studying the geological formations and their stratigraphic sequences, this investigation aims to establish a nuanced understanding of how hydrocarbons navigate through the subsurface in the absence of specific structural elements. The exploration history of the Karsal area, intricately detailed in Figure 2.4, serves as a valuable reference, shedding light on the evolution of hydrocarbon exploration practices and providing context for the contemporary understanding of flow patterns.

The detailed scrutiny of the geological and stratigraphic facets outlined in Sections 2.1 and 2.3 is instrumental in unraveling the hydrocarbon flow dynamics within the studied area. This scrutiny extends to scenarios where the presence of certain structural elements is notably absent. The exploration history of the Karsal area, meticulously chronicled in the exploration history section and visually represented in Figure 2.4, serves as a repository of valuable information. This historical perspective aids in contextualizing the contemporary understanding of hydrocarbon flow and provides a foundation for further insights into the geological evolution of the region.

Number-13 A comprehensive understanding of limestone characteristics and their response to seismic amplitude models, specifically in relation to the effective penetration of open fractures, is being actively pursued. This involves the development of an anisotropic data approach coupled with integration techniques. The intricate details of this approach are expounded upon in Chapter 5, with a specific focus on Section 5.2.4. Figure 5.8 serves as a visual representation, highlighting the incorporation of azimuthal velocity variations in both intensity and direction. This figure effectively communicates the robustness of the anisotropic data approach, shedding light on its potential applications.

Chapter 5 provides an in-depth exploration of the characteristics exhibited by limestone formations and their nuanced response to seismic amplitude models, particularly in the context of penetrating open fractures. The ongoing endeavor involves constructing a specialized anisotropic data approach and integrating it into the analytical framework. A thorough examination of these methodologies is articulated in Section 5.2.4, offering readers a detailed insight into the intricacies of the approach. Figure 5.8 is a pivotal visual aid within this chapter, illustrating the integration of azimuthal velocity variations, emphasizing both intensity and directional aspects. This figure serves as a comprehensive representation, effectively conveying the robustness and utility of the anisotropic data approach.

Exploring the characteristics of limestone and their dynamic response to seismic amplitude models, especially concerning the penetration of open fractures, is a focal point of the ongoing research. This initiative involves the construction of an anisotropic data approach, seamlessly integrated into the analytical framework. The specifics of this approach are meticulously detailed in Chapter 5, with particular emphasis on Section 5.2.4. Figure 5.8 visually encapsulates the integration process, showcasing the potential of azimuthal velocity variations in terms of intensity and direction. The figure serves as a visual cornerstone, offering a clear depiction of the robust anisotropic data approach and its implications.

• The pursuit of a nuanced understanding of limestone characteristics and their responses to seismic amplitude models, particularly with respect to the penetration of open fractures, is a central focus. This involves the ongoing development and integration of an anisotropic data approach, a process intricately discussed in Chapter 5 and further elaborated upon in Section 5.2.4. The visual representation in Figure 5.8 plays a pivotal role, showcasing the integration of azimuthal velocity variations in both intensity and direction. This figure serves as a comprehensive visual guide, effectively communicating the strength and applicability of the anisotropic data approach. Additionally, Section 2.2, featuring Figure 2.3, delves into the stress orientation of surface structures, providing a well-described integration with drilled sub-surface anomalies and the modified subsurface orientation based on the Pakistan basin study figures 2.1 and 2.2.

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