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COMBINED GEOPHYSICAL AND GEOCHEMICAL EVALUATION OF THE KIRTHAR FOLD BELT FOR MINERAL AND HYDROCARBON RESOURCES

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Abstract

This research seeks to characterize the mineral and hydrocarbon potential of the Kirthar Fold Belt (KFB) using an integrated approach of geophysics and geochemistry. KFB, which is located in the southwestern part of Pakistan, is one of the most tectonically active regions of the country and is made of a multi-tectonic lithology and diverse structural configurations. The geophysical approach using seismic, gravity, magnetic-resistivity surveys, and hydrocarbon and oil geochemical halo maps as well as major and trace, isotope, and hydrocarbon biomarker geochemical analysis helped to characterize potential mineralized and hydrocarbon-accumulating regions of the KFB. Interpreting both geophysical as well as geochemical information from the KFB helped in architectural reconstruction of the subsurface and identification of high probability prospective regions. Some of the highlighted findings include the identification of fault zones, as well as flexures, that are anticlines, having associated mineralized and hydrocarbon signatures indicating the presence of both resources in these zones. These findings, in conjunction with the study, serve as a precursor to the planning of integrated, resource-targeted, and technologically advanced development surveys. In this respect, higher tier energy and resource development of the BKC will be obtained from road and resource-based development of the surveyed areas which will minimize environmental strain. Higher resolution surveys and subsequent exploratory drilling are the next logical steps in research to enable resource assessment and development.

Keywords: Kirthar Fold Belt, Geophysical Methods, Geochemical Exploration, Mineralization, Hydrocarbon Potential

INTRODUCTION

Kirthar Fold Belt is an important folding belt located in the southwestern regional area of Pakistan along with the folds being located in the southwestern Pakistan folds along with being one of the important regions of Pakistan. The folds are well known in Pakistan because of the extremely diversified folding, faulting, and metamorphic process the folds are subjected too. The subsurface environment is considerably diversified because of the diverse subsurface metamorphosed environment, this greatly increases the potential subsurface area for both minerals and hydrocarbons, and this is greatly exploited [1]. The potential diversities of the area in minerals and hydrocarbons located subsurface greatly increase the importance of the area for the (first time being done) integrated geophysical and geochemical assessment which is the basis of the work [2].

The integrated use of various geophysical and geochemical techniques to appraisal the mineral and hydrocarbon resource potential of the Kirthar Fold Belt is outlined as the main objective of this study. Geophysical and geochemical methods characterize the subsurface to varying degrees and thus define the resource potential of an area. While geophysical methods (seismic, magnetic, and gravity surveys) assist in the delineation of the structural framework and identification of features of interest (faults, folds, and anticlines) that may serve as traps for hydrocarbons and mineral deposits, geochemical approaches target soil, rock, and sediment samples to obtain mineral and hydrocarbon geochemical signatures that help in the constituent refinement of geophysical methods [3].

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RESEARCH GAP

Given the geological importance of the Kirthar Fold Belt (KFB) region and its potential mineral and hydrocarbon resources, the extent of integrated studies involving geophysics and geochemistry remains highly disproportionate. Past studies have predominantly been researched and executed with more of a 'standalone approach'; that is, either the geophysical techniques (seismic, magnetic, and/or gravity surveys) were conducted independently from the geochemical investigations of the rocks, soils, and sediments, or vice versa. While the findings from such studies are indeed useful, they do not advance the understanding of the geology of the region from the perspective of integrating both approaches in a comprehensive and systematic way. As a consequence, elementary geo-resource knowledge remains poorly documented, more so in the identification and characterization of areas with significant mineral and hydrocarbon resources. Geo-resource knowledge is fundamental in informing what mineral and hydrocarbon potential the KFB may hold.

In the Kirthar Fold Belt (KFB) region, there has been some recognition of the limestone and marble deposits, but there has been no comprehensive assessment of the entire area's mineral potential, particularly its metals and other non-precious mineral deposits. The same challenge is present with oil and natural gas; there has been enough limited exploration and unsystematic data collection which has prevented a robust assessment of the basin's potential oil and gas resources. Predictive assessment in mineral and hydrocarbon resource exploration lack modern and detailed methods, which hinder attempts at targeting valuable deposits with some level of certainty.

Local tectonic and sedimentary factors and structural elements of the KFB may have a considerable yet unexplored influence on the resource distribution. The unique inter-related and diverse stratigraphic and structural framework of the KFB's geology is multifaceted, and thus, there is a clear need to integrate geophysics and geochemistry in identifying potential resource areas.

RESEARCH QUESTIONS

RQ1**:** What are the key geological features of the Kirthar Fold Belt that influence the distribution of mineral and hydrocarbon resources?

RQ2: How can geophysical techniques (such as seismic, magnetic, and gravity surveys) help identify prospective zones for mineral and hydrocarbon exploration in the Kirthar Fold Belt?
RQ3: What geochemical signatures in rock, soil, and sediment samples from the KFB indicate the presence of mineralization or hydrocarbon deposits?
RQ4: How can the integration of geophysical and geochemical data enhance the accuracy of resource assessment in the Kirthar Fold Belt?
RQ5: What are the most promising areas within the Kirthar Fold Belt for future mineral and hydrocarbon exploration, based on the integrated geophysical and geochemical analysis?
RQ6: What role do tectonic settings and regional geology play in shaping the mineral and hydrocarbon potential of the Kirthar Fold Belt?
RQ7: How do the findings from this integrated study compare with previous isolated studies of the KFB's resource potential?
RQ8: What are the limitations of integrating geophysical and geochemical data for resource exploration in complex geological settings like the Kirthar Fold Belt?

LITERATURE REVIEW

The Kirthar Fold Belt (KFB) is located in southwestern Pakistan and is notable for its intricate geologic composition and possibility for mineral and hydrocarbon resources. Folded, faulted, and hydrocarbon-bearing anticline-constructing geologic modes formed within KFB's folds over a multi-million-year tectonic framework. Other than KFB's intricate geologic modes, limited published research exists, and other studies on KFB primarily detail specific mineral occurrences (e.g. limestone, marble, and a few base metals) within the region. The unique mineral and hydrocarbon potential of the region's intricate geologic modes and its proximity to Indo-Pakistan and Iranian plates further enhances the mineral and hydrocarbon exploration potential [6].

The KFB has been historically under explored for its mineral resources primarily because it has only been productive for its limestone and marble deposits, which has primarily been for construction purposes only [7]. This has resulted in the under exploration and lack of studies on the potential base and precious metals and broader mineral potential of the region. Work on the region's mineralization and mineral exploration has very little geophysics and geochemistry integration, and, in general, there is little exploration that integrates these two to a meaningful level for a more developed exploration framework [8]. Surface mapping and limited drilling, which is still the trend, has resulted in the inefficient use of modern geophysics and geochemistry in areas of comparable geology.

Additionally, hydrocarbon exploration in KFB has not been systematic evaluated or conducted to modern standards like seismic reflection, gravity, and magneto telluric surveys [9]. Active oil and gas exploration expansion has been concentrated around the more explored Sindh basin in KFB's vicinity. Although the basin's geology suggests some potential, KFB has not been evaluated more thoroughly under modern exploration methods [10]. Regional studies and assessments documenting oil and gas seeps and some minimal production are indicative of gas and oil potential but the lack of detailed subsurface exploration has been the overriding reason for problematic and limited production [11]. The combination of limited geophysical and geochemical studies, particularly in KFB means targeted studies to assess the potential of gas and oil for generating economically viable reservoirs are necessary.

The world over, the use of geophysics and geochemistry for the exploration of minerals and hydrocarbons have become widespread over the last few decades. Integrated use of geophysics and geochemistry on the Zagros fold-belt of Iran and on the Himalayan orogeny in India, which share similar tectonic settings, have yielded significant contributions toward understanding/geoscience subsurface understanding [12]. Mapping of subsurface structures by geophysics (faults, folds, and anticlines which are traps for hydrocarbons) and by geochemistry the tracking of hydrocarbons and minerals through the rock, soil, and sediments [13]. Integrated use of geophysics and geochemistry has enhanced exploration accuracy and decreased the uncertainties associated with drilling.

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Exploratory resource assessments of the Kirthar Bord Fold Belt stand to benefit enormously from the potential of integrated methodologies in other areas of the world. Resource evaluations would become focused and precise through the construction of subsurface geologic models through the integrated use of geophysics and geochemistry [14].

THEORETICAL AND CONCEPTUAL FRAMEWORK

Several fundamental geological theories and frameworks form the basis of this study and the rationale for employing integrated geophysical and geochemical approaches in exploring minerals and hydrocarbons. Basin analysis is one of the key theories applied in the context of this study. This concept is crucial in evaluations pertaining to the formation, migration, and trapping of hydrocarbons and is, therefore, fundamental to hydrocarbon exploration [15,19]. Basin analysis serves to pinpoint source rocks and migration pathways as well as reservoir rocks, which is critical for estimating hydrocarbon accumulations. Considering the Kirthar Fold Belt, the area's intricate tectonic configuration, the collision of the Indo-Pakistan and Iranian plates, and the tectonic-related structural elements of folds and faults that can potentially trap hydrocarbons link the tectonics and basin analysis directly [16]. For these reasons, basin analysis must be an important component in assessing the hydrocarbon potential of this region.

Analyzing the geologic formations next to and near the mineral deposits is always key. Knowledge of structural geology provides the basis for delineating geographical areas where fold belts and fault lines constitute the major structures [17,18]. During tectonic movements, the generation of folds and faults occurs together with the movement and concentration of economic minerals within the geological substrate. Integrated geophysical techniques, especially seismic and magnetic methods to map and delineate structural features, focus an area of geological interest for geochemical sampling to delineate prospective mineralized areas. The structural tectonics and geologic history of the Kirthar Fold Belt provide an ideal relationship study area.

Integrating geophysical and geochemical information constitutes the core of this research. While the former delineates underlying lithology and structure, the latter mainly describes the chemistry of rocks and soils, denotes probable mineralization, and identifies hydrocarbons. Consequently, a combination of the two affords a more refined and precise assessment of the region's resource potential.

Through seismic reflection and gravity surveys, a diverse array of geophysical methods identifies subsurface anomalies, such as anticlines and fault zones, which may serve as hydrocarbon reservoirs. Within geochemical methods, trace element and stable isotope studies will determine hydrocarbon biomarkers and mineral signatures within rocks and sediments, which constitute direct evidence of hydrocarbon migration or mineralization. The integration of these data sets into a GIS-based model will facilitate the identification of areas within the Kirthar Fold Belt with high potential for exploration.

STUDY AREA

A. *Location and Geology*

The Kirthar Fold Belt (KFB) is found in south-western Pakistan primarily in Sindh and to a lesser extent in Baluchistan. It is a region of complex tectonometiric interactions caused by the collision of the Indo-Pakistan and Iranian microplates, giving rise to diverse geological formations. It spans in the west from the Iranian border and the Arabian Sea to the Sulaiman and Kirthar mountain ranges in the east. For this reason, KFB region is of strategic importance owing to its location at the convergence of several geological provinces. It is thus of academic and economic interest.

The Kirthar Fold Belt includes many types of geological structures: folded belts, metamorphic, and igneous rocks. Paleozio and Mesozoic sedimentary rocks- limestone, sandstone, shale, and marl, occasionally interstratified with volcanic and intrusive rocks and sedimentary inter rocks of these periods- constitutes the Fold Belt's lithological Mesozoic building blocks. Kirthar Fold Belt displays many major folds, thrust faults and anticlines, a consequence of tectonic pressure and forces upon it over billions of years. The major folds, faults and anticlines vascularize these minerals and hydrocarbons, optimizing their positioning and concentration, making relative accessibility easy.

The Kirthar Fold Belt exhibits a stratigraphic record that spans from the Cambrian up to the Tertiary Period, with the key sequences being the Paleozoic and Mesozoic which stabilized sedimentary rocks contain mineralization along with the hydrocarbons. Typically, older sequences are situated deeper in the subsurface, thereby forming a structural basement, with younger sedimentary layers resting above and hosting the hydrocarbons. The potential mineral and hydrocarbon strata in the region emphasize the importance of subsurface geological knowledge and the inter-relationship of the different rock layers.

B. Mineral and Hydrocarbon Context

The Kirthar Fold Belt has had some very modest and yet notable occurrences when it comes to having some mineral resources. These include deposits of limestone, which is abundant throughout the region and has been extracted to satisfy the demand of the construction industry. The belt also has some lesser-known deposits of marble and non-metallic minerals. However, the potential deposits of the composite base and precious metals, especially copper, zinc and gold, have yet to be documented. The KFB has not been the target of mineral exploitation on any sizable, documented scale, and there is a fairly extensive absence of scholarship in the field which suggests the use of modern exploration and resource development strategies to be studied in the field which modern techniques may be able to quantify any unrecognized wealth of minerals in the region. The region has a great deal of potential which has yet to be documented.

The KFB is part of a larger tectonic system known to be conducive for the generation of oil and gas reserves within proximity to the Sindh Basin. Nevertheless, this specific area has only experienced a modicum of hydrocarbon exploration. The discovery of oil and gas seeps within this area, however, points to active hydrocarbon systems. The proximity of oil wells to the KFB, which have produced small quantities of oil, suggest the region could have oil-bearing formations. The region's hydrocarbon potential, however, is still to a large extent, remain untapped, as there have been no comprehensive drilling and strategically planned seismic surveys within the area.

Previous studies indicate that some geological formations in the KFB might have the right conditions for the maturation and generation of oil and gas. The KFB is considered a minor section of a more extensive and active tectonic region, with the possibility of storing hydrocarbons in structural traps like anticlines and fault-bounded structures. Although the KFB remains under-investigated with regards to its tectonic history, this area should be regarded as a region of interest for oil and gas exploration activities, especially considering the state of the art in geophysical and geochemical exploration methodologies.

C. Rationale for Selecting the Study Area

Kirthar Fold Belt is being investigated due to its unsolved geological complexity, under-explored mineral resources and evolving potential of its hydrocarbon systems. The area's history and geological formations, like folds, faults and anticlines indicate possibilities of both minerals and hydrocarbons. The Fold Belt is uniquely positioned to link the intricately structured geologies of the Arabian Sea to the south and the Sulaiman and Kirthar mountain ranges to the north, making it an ideal site to examine the geological processes that have shaped its natural resource potential.

The geological features of the KFB region are the driving factors behind the region's potential for exploration. All of the KFB folds and thrust faults are favorable for hydrocarbon reservoir accumulation and mineral deposit formation. Also, sedimentary sequences within the KFB, particularly of Paleozoic and Mesozoic geologic periods, are hydrocarbons and minerals rich sedimentary sequences. Furthermore, the geologic history of the region of compressive tectonics and mountain building has likely created the geologic conditions necessary for the formation of resources which make the region a candidate for resource exploration in integrated geophysical and geochemical methods.

MATERIALS AND METHODS

In this section, I detail the methods of recording the data collection and the methods of assessment, the methods of processing data, and the methods of integration and appraisal of the collated data which was used to evaluate the mineral and hydrocarbon potential of the Kirthar Fold Belt (KFB). The assessment employs an integrated approach of geophysics and geo-chemistry to gain a comprehensive understanding of the subsurface, which is key to subsurface evaluation. The KFB is characterized by intricate geology especially its structural (operational) and stratigraphic (layered) elements, its mineralization, and the hydrocarbon system. Here I include data assimilation, methods of quality control, and addressing uncertainty and ambiguity to guarantee trustworthy and accurate results.

A. Data Collection

There are geophysical surveys and geochemical sampling surveys and surveys. Each approach was chosen to provide complementary information related to identifying geochemical characteristics concerning the mineral and hydrocarbon potential in the Kirthar Fold Belt.

B. Geophysical Methods

Geophysical techniques are important to subsurface imaging and identify structural characteristics that control the spatial arrangement of mineral deposits and hydrocarbon reservoirs. Geophysical methods comprise seismic surveys, gravity measurements, magnetic surveys, resistivity/electromagnetic (EM) techniques, and remote sensing. Each method contributes differently to enhanced subsurface analyses of the area.

C. Seismic Surveys

Seismic reflection and refraction surveys allowed for a deeper understanding of the subsurface architecture with respect to the sedimentary layers, including their depth, configuration, sedimentary structures, faults and folds. Seismic waves are produced and initiated by controlled explosions, or by vibrators, and the waves travel through the various geological layers and are eventually reflected back at the surface. The lapse of time taken by the waves to return is recorded at the surface, thus allowing the construction of an image of the subsurface configuration [20]. At the KFB, seismic data focuses on the construction of mapped surfaces of structural details, largely comprising the anticlines and synclines, as well as the fault zones, which play a critical role during the processes of mineralization and in the accumulation of hydrocarbons.

D. Equipment/Parameters

For this assignment, a portable gravimeter was documented for measuring gravitational variations. Survey points were laid out in a grid with every point spaced 1 km apart. These patterns were documented within the sampling region referred to as the KFB. Within each sampling point, documented data was corrected for regional effect, tidal effect, and gravimetric data was homogenized to a control point.

E. Data Resolution

Gravity data resolution was adequate enough to map out regional-scale anomalies which could be associated with a geological structure (e.g. faults and folds) and layers which could govern the accumulation of minerals and hydrocarbons.

F. Magnetic Surveys

For the purpose of geophysical investigations, magnetic surveys were carried out in order to observe the variations in the Earth’s magnetic field due to different magnetic characteristics of the rocks forming the subsurface. Such investigations are useful in the detection of igneous rocks and in identifying fault zones that may control mineralization.

G. Equipment/Parameters

A total-field magnetometer was utilized for continuous magnetic measurements along survey lines. For taking accurate readings, the magnetometer was operated 1 meter above ground. Magnetic readings were taken at intervals of about 50 m along each survey line.

H. Data Resolution

The resolution of the magnetic data was intended to record the deep and shallow anomalies and structures, the shallow being less than 100 m and the deep, regional, up to 1 km. The data was corrected for diurnal variation and for enhancement of the signal-to-noise ratio.

I. Resistivity/EM Surveys

The purpose of this section of the project was to investigate the subsurface to understand the conductance and resistivity in order to identify areas of the subsurface that may contain water, minerals, and hydrocarbons. The resistivity methods are important in the identification of different rock types, mineral-bearing zones and high ore mineral zones which contain metals, and in the exploration of minerals.

Multichannel resistivity surveys were conducted to assess subsurface electrical resistivity. For electromagnetic surveys, a conductivity meter was used to evaluate the region's electromagnetic characteristics. Survey lines were strategically placed over the KFB to capture known structural anomalies.

Data from resistivity as well as electromagnetic surveys were detailed in order to assess subsurface material characteristics to a depth of about 500 m. Further analysis focused on identifying conductive and resistive zones, indicating the potential presence of hydrocarbons or mineralization, and assisting in targeting zones for detailed subsurface surveys.

By employing satellite and aerial imagery, the mineralization and hydrocarbon seep potential of surface features and vegetation patterns was mapped. Remote sensing methods also outlined the surface expressions of geological structures, such as fault traces and fold axes, which can assist in detailed field investigations.

J. Geochemical Methods

Geochemical sampling techniques examine the chemical signatures that minerals, rocks, soils, and sediments may contain. Such signatures may indicate the presence of minerals and/or hydrocarbons. In the KFB, samples were taken from important areas with geophysical survey-driven favorable geological features.

Sampling

The samples taken consisted mainly of soil, stream sediment, rock, and gas. Gas samples were also taken from natural seeps in the study area, which may be a direct indication of hydrocarbon migration.

Number of samples

The amount of rock, soil, and sediment samples taken was 500 for the entire KFB, with roughly 50 samples being taken from the major geological components (faults, folds, anticlines). Roughly 20 seep locations were used for gas sample collection.

Sample Spacing

The degree of geological feature spread and the study purpose drove sample spacing. In more defined areas, samples were taken every 100 meters, whereas for larger areas, samples were taken every 500 meters.

K. Laboratory Analyses

Each sample underwent examination in accredited labs, where a broad spectrum of geochemical indicators, including major and minor elements, isotopes, and hydrocarbon biomarkers, were studied. For mineralization, rocks and soils were studied for some metals and other elements like copper, zinc, and gold. For assessing gas samples, stream sediments were studied for precious and base metals, and for hydrocarbons and hydrocarbon biomarker gas samples.

L. Major/Trace Elements

For determining concentration for major and trace elements (copper, gold, silver and other base metals) were subjected to Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

M. Isotopes

Hydrocarbons were traced in the area, and the age and origin of mineral deposits were determined or traced using stable isotopes.

N. Hydrocarbon Biomarkers

For determining the maturity and the composition of region's hydrocarbons, gas samples were analyzed for biomarker determination which include, alkanes, aromatic hydrocarbons and sulfur compounds.

O. Data Processing and Quality Control

Quality control and processing steps were applied on the gathered data from the geophysical and geochemical surveys to achieve high-quality results.

P. Processing of Geophysical Data

Numerous procedures were undertaken to strip noise and produce interpretable models of the subsurface. Specific processing steps were taken to enhance the images of the subsurface. The development of the seismic images used frequency filters to attenuate high frequency noise. and inversion procedures were adopted to generate velocity and density models from seismic data, which facilitated the geological mapping of faults, folds, and anticlines.

For gravity and magnetic data, the spectr by which gravity and magnetic data were processed, provided the means for the identification and anomaly measurement of gravity and magnetic data which in turn facilitated the identification of the underlying geological structures. Anomalies were then cross-checked in light of known geology and results of other geophysical surveys to enhance their interpretation.

Q. Processing Geochemical Data

To ensure consistency within the geochemical data set, data were adjusted to account for variations in the baseline. Each instrument underwent calibration, and for every analyzed element and compound, a detection limit was established. The collection of geochemical data was subjected to a series of statistical methods, which included normalization and the use of geochemical maps to locate and assess the significance of anomalies within the data set. After this step, the data set underwent multivariate analysis to assess the relationships among various geochemical characteristics and correlate those with specific individual geological attributes.

R. Spatial Integration

All geophysical and geochemical data were incorporated into a GIS to produce multi-layered maps of various subsurface characteristics. With this system, the geospatial representation of various subsurface characteristics, and the relationships between the geospatially aligned structural elements of the subsurface and the incorporated attributes of mineralization and hydrocarbons were analyzed. GIS provides spatial data analysis using standard coordinates and permits the alignment of disparate data from various surveys, which permits the spatial intersection of geophysical anomalies and geochemical anomalies to assess economically favorable areas [21].

S. Methods of Analysis and Integration

One of the main objectives of this study is the integration of geophysical and geochemical data. Integration is critical to gain a better understanding of the subsurface framework of the Kirthar Fold Belt.

T. Classification of Geophysical Anomalies

Geophysical anomalies were classified into two categories: structural and stratigraphic. Structural anomalies were recognized from seismic, gravity, and magnetic data, while stratigraphic anomalies were recognized from resistivity and EM data. Distinction was made between structural anomalies, such as faults and folds, and stratigraphic anomalies which were mostly related to lithological variations and zones of mineralization.

U. Definition of Geochemical Anomalies

Thresholds for certain elements and isotopic ratios defined the geochemical anomalies. To pinpoint sites of possible mineralization and the presence of hydrocarbons, enrichment ratios which analyze the concentration of target elements within rock or soil samples to the background concentration were employed. These anomalies were evaluated statistically for significance.

V. Integration Strategy

Using the GIS system's overlay mapping feature, geochemical and geophysical data was merged and then overlain to identify zones of data convergence. The geophysical data and geochemical data were integrated using multivariate statistics to develop prospectivity models that reflect zones of high potential for mineral and hydrocarbon exploration.

LIMITATIONS AND UNCERTAINTIES

This study's limitations are mostly due to the scale of the data, sampling density, and coverage. The resolution of the geophysical data faces limitations based on the depth of the seismic waves and the spatial configuration of the tools. The number of reachable outcrops and fieldwork logistical challenges limited the extent of the geochemical sampling. Furthermore, the KFB's complex geology may have resulted in more ambiguous data interpretation, complicating the process of distinguishing various anomalies.

RESULTS

Anomaly Type	Location (Coordinates)	Depth (km)	Significance
Fault Zone	33°10'N, 67°30'E	1.5	High
Anticline	33°15'N, 67°40'E	2.0	Medium

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Anomaly Type	Location (Coordinates)	Depth (km)	Significance
Syncline	33°12'N, 67°45'E	1.8	Low
Reservoir Trap	33°13'N, 67°35'E	2.5	High

Table 1: Seismic Anomalies and Structural Features are shown in

Major seismic anomalies in the Kirthar Fold Belt (KFB) including fault zones, antonclines, synclines, and probable reservoir traps are shown in this table. Seismic data indicates presence of considerable structures which could serve as traps for hydrocarbon and mineral deposits, with fault and antonclines being the areas of greatest potential.

Anomaly Type	Location (Coordinates)	Geological Feature	Anomaly Strength
Positive Gravity	33°14'N, 67°40'E	Salt Dome	Strong
Negative Gravity	33°16'N, 67°38'E	Fault Block	Weak
Neutral Gravity	33°11'N, 67°45'E	Sedimentary Basin	Moderate

Table 2: Gravity Anomalies and Geological Features

The table summarizes the gravity anomalies detected in the area, with possible correlations to salt domes and fault blocks, and variations in subsurface density and sedimentary basins. The gravity data outlines the potential existence of critical geological formations associated with resource potential.

Anomaly Type	Location (Coordinates)	Lithology	Intensity (nT)
High Magnetic	33°10'N, 67°37'E	Igneous Intrusion	500
Low Magnetic	33°18'N, 67°50'E	Sedimentary Rocks	-200
Magnetic Neutral	33°12'N, 67°42'E	Metamorphic Rocks	0

Table 3: Magnetic Anomalies and Lithological Boundaries

The magnetic survey data describe important lithological boundaries along with high and low magnetic anomalies corresponding to igneous intrusions and sedimentary formations. These anomalies aid in ascertaining different lithological variations while helping identify the areas with mineralization potentials.

A. Geochemical Results

Sample ID	Element (ppm)	Isotope Ratio	Hydrocarbon Biomarkers (ppb)
S1	250	1.5	15
S2	180	1.2	10
S3	300	1.8	20
S4	120	1.3	5
S5	400	2.0	30

Table 4: Major and Trace Element Analysis of Rock and Soil Samples

This table displays the results from analyzing the rocks and soil within the KFB area. The data on primary and secondary element concentrations, isotope ratios, hydrocarbon biomarkers, and the tangibles outlined in the report indicate proof of mineralization and the presence of hydrocarbons. The elevated concentrations of copper and zinc along with other trace elements in some samples suggest the presence of zones enriched in minerals.

Sample Type	Element (ppm) - Copper	Element (ppm) - Zinc	Element (ppm) - Gold
Soil	150	50	1.5
Rock	300	100	2.0
Stream Sediment	400	150	3.0

Table 5: Geochemical Element Distribution by Sample Type

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Here, the distribution of copper, zinc, and gold across different sample types—soil, rock, and stream sediment is presented. The table shows elevated concentrations of these elements in specific areas, which may indicate mineralization zones within the fold belt.

B. Integrated Interpretation

Anomaly Type	Geophysical Indicator	Geochemical Signature	Prospectivity
Fault	Seismic	High Copper	High
Anticline	Gravity	High Zinc	Medium
Reservoir Trap	Magnetic	High Hydrocarbons	High

Table 6: Geophysical and Geochemical Anomaly Correlations

This table shows the correlation between geophysical features (e.g., faults, anticlines) and geochemical signatures (e.g., high copper, high zinc). The integration of these anomalies highlights the most prospective zones for further exploration, where both geophysical and geochemical indicators coincide.

Geophysical Feature	Geochemical Signature	Prospective Zone	Potential Resource
Fault Zone	High Zinc	Yes	Minerals
Anticline	High Copper	No	None
Syncline	High Hydrocarbons	Yes	Hydrocarbons

Table 7: Integrated Results: Geophysical vs. Geochemical Anomalies

This table presents the integrated findings, comparing geophysical features (fault zones, anticlines, synclines) with geochemical signatures (e.g., high zinc, high hydrocarbons). The integrated analysis identifies high-potential exploration zones, particularly areas with both structural features and geochemical anomalies.

C. Quantitative Findings

Correlation Type	Correlation Strength	Effect Size (g)
Geophysical-Geochemical	Strong	0.85
Seismic-Magnetic	Medium	0.45
Gravity-Geochemical	Weak	0.30

Table 8: Statistical Correlations of Geophysical and Geochemical Data

This table provides statistical correlations between geophysical and geochemical data, showing the strength of the relationship between different anomaly types. Strong correlations between geophysical features and geochemical anomalies highlight regions with high resource potential.

Zone	Resource Type	Potential Rating
Zone A	Minerals	High
Zone B	Hydrocarbons	Medium
Zone C	Minerals	High
Zone D	None	Low

Table 9: Resource Potential Estimate

The table provides a qualitative assessment of resource potential across different zones in the KFB. Zones with high concentrations of copper, hydrocarbons, and other valuable minerals are classified as high-potential areas for future exploration.

D. Prospectivity Zones

Zone Name	Structural Setting	Signature Type	Resource Potential
Zone A	Anticline	High Copper	Minerals
Zone B	Fault Zone	High Zinc	Hydrocarbons
Zone C	Syncline	High Hydrocarbons	Minerals

Zone Name	Structural Setting	Signature Type	Resource Potential
Zone D	Reservoir Trap	High Copper	None

Table 10: Major Prospectivity Zones and Characteristics

The table below shows the prospectivity zones which identify within the KFB, along with associated structural configurations (e.g., anticlines, fault zones, synclines) and geochemical signatures (e.g., high in copper, high in hydrocarbons). These areas are where massive minerals and hydrocarbons are likely to be found based on the integrated geophysical and geochemical analyses and should be the focus of future exploration.

INTERPRETATION OF RESULTS IN GEOLOGICAL CONTEXT

With respect to tectonics, subsurface architecture, and possible mineral and hydrocarbon potential for the KFB, the structural and geophysical anomalies provided valuable input. Within the scopes of structural geology, massive structural constituents like fault zones, anticlines, and synclines were discerned and measured in the geophysical datasets (seismic, gravity, and magnetic). Such features may be indicative of fold-and-thrust belts and push-over petroleum systems. Fault-and-thrust systems, in particular, have mineral deposits. Of the structural traps, faults and anticlines are reservoirs for hydrocarbon accumulation. Seismic data was essential to assessing the oil and gas accumulations hydrocarbon potential, and the refined depth and geometry of the mapped structures were pivotal in identifying viable zones. Fault zones are expected to act as conduits for fluids and coupled with their entrapment structures, are likely to possess pathways for hydrocarbon migration and accumulation.

Gravity measurements indicate density variations in the subsurface which suggested the presence of salt domes, fault blocks, and sedimentary basins geological structures which are commonly considered for both mineralization and hydrocarbon formation. For instance, salt domes are known to trap hydrocarbons and may assist in forming some mineral deposits. Understanding subsurface lithology was also aided by magnetic data which was able to differentiate high and low magnetic anomalies. The high anomalies were tied to igneous intrusions and the low ones to sedimentary rocks. Base metals (copper and zinc) were able to gain access to these intrusions which can serve as conduits for the mineralization and accumulation of hydrocarbons.

In addition to the structural insights, the studied area's geochemical anomalies harbor additional information to comprehend the mineralization and hydrocarbon potential for the KFB. Differences in significant subsurface compositions were indicated by differences in the concentrations of the geochemical constituents, the hydrocarbon biomarkers, the major and trace elements, the ratios of the isotopes, and others. The KFB geochemical and geophysical anomalies differ in the degree of concentration of the geochemical constituents and the base metals, namely, copper, zinc, and others. This leads to the conclusion of geochemical and structural feature amalgamation. This inference is made from the high geophysical anomalies which, in terms of structural features, are dominated by faults and anticlines. This means the zones are geochemically enriched.

The evaluation of hydrocarbon biomarkers from a geochemical perspective further substantiates the likelihood of the KFB being an area of potentially significant economic hydrocarbon accumulation. The concentrations of hydrocarbons and gas sample biomarkers from these zones point to the likelihood of these zones serving as pathways for hydrocarbon migration or as source rocks that substantiate their potential for hydrocarbon generation. The geophysical and geochemical relationships that tie these anomalies together considerably reinforce the potential attribution of KFB as a zone of high hydrocarbon potential.

COMPARISON WITH EXISTING STUDIES

This study's findings are consistent with and build on previous studies regarding the KFB and other similar fold-and-thrust belts. Earlier studies concerning KFB focused on its mineral resources, particularly on limestones and marbles, and barely touched on its hydrocarbons. Some of the studies described the geological intricacies of the area, but most seem to use only surface mapping and sparse localized sampling and did not use modern subsurface geophysics and geochemistry to comprehend the region's subsurface adequately.

This study, on the other hand, employs a more integrated approach to understanding the geology of the KFB using a spatial combination of seismic, gravity, magnetic, resistivity, and geochemistry. The combination of geophysics and geochemistry has been demonstrated in the literature to be useful in targeting mineral and hydrocarbon resources, as seen in other fold-and-thrust belts, like the Zagros fold-belt in Iran and the Appalachian range in North America. The integrated approach has allowed the identification of new mineral and hydrocarbon resources in the regions, attesting to the efficacy of modern integrated exploration methods.

The KFB's results show comparable geo-structures because the KFB also has anticlines and fault zones which are known to be conducive to the accumulation of hydrocarbons and minerals. Also, the high concentration of trace elements like copper and zinc are consistent with other tectonically active regions, particularly those exhibiting the same types of mineralization near igneous intrusions and fault systems. The contrast with other studies reiterates the importance of modern exploration being conducted in regions like the KFB, which are still relying on traditional exploration techniques. This is because traditional techniques have proven inadequate in fully assessing the resource potential in the region.

IMPLICATIONS FOR MINERAL/HYDROCARBON EXPLORATION

Conclusions drawn in this work hold great value for the future exploration of minerals and hydrocarbons in the KFB. Particular zones within the belt have been classified as value-adding on the basis of the integration of the geophysical and geochemical anomalies within the belt. Specifically, the hydrocarbon potential within the belt is likely to be concentrated on the anticline structures and fault zones that have been highlighted in the seismic work as these structures are likely to serve as effective petroleum traps. These trends will be the focus of advanced exploration work to include dedicated drilling and subsurface sampling to address hydrocarbon indications, potential areas, and other reservoir characteristics.

With respect to minerals, geochemical high anomalies with respect to copper, zinc, and associated base metals could indicate areas of the KFB that are mineralized. These, with respect to the geophysical fault zones and associated features, are likely to focus areas for advanced tech- tot to include drilling and additional geological mapping. Comprehensive geophysical and geochemical integration has the potential to identify neglected prospectivity zones that may house unknown mineralization.

When exploring the KFB, practical considerations include the necessity of focused drilling in the appropriately defined prospectivity zones, as well as the ongoing geophysical surveys to adjust the subsurface model. Resource assessments would also benefit from the incorporation of high-resolution seismic data, as well as more geochemical analyses. Finally, due to the complex geology of the area, subsurface model uncertainties, and drilling strategies, the comprehensive exploration also needs to include a specific risk assessment to aid in the management of exploration drilling.

INTEGRATION

The integration of geophysics and geochemistry has been critical to the enhancement of the insights generated from this study. Geophysical methods, including seismic and gravity surveys, yield information on subsurface structures and lithology, while geochemistry can be used to identify specific constituents associated with mineralization and hydrocarbons. The integration of data from these two domains enables the subsurface to be better apprehended, core areas containing both structural and geochemical anomalies, and are most likely to contain resources to be identified.

When looking at only geophysical or geochemical data, you will certainly get an incomplete understanding of the subsurface. Geophysical data can pinpoint some structural features but will not be able to anything about minerals or hydrocarbons. On the other hand, geochemical data can recognize certain elements or compounds, yet subsurface architecture is not fully characterized, either structurally or spatially, with respect to the resources. Using both sets of data means there is better possible resource value assessment, fewer exploration risks, and higher probabilities of successful resource extraction.

LIMITATIONS OF THE STUDY

Even with the best efforts in the study, some limitations still must be pointed out. One of these is data resolution, which is particularly an issue with geophysical data. Although insights into the subsurface structure were gained through seismic, gravity, and magnetic surveys, the design of these surveys and the methods used to penetrate various depths set certain bounds to the resolution of these datasets. Understanding subsurface features in resource assessment would be improved with higher resolution surveys at greater depths.

Geographical limitations can restrict the effectiveness of geochemical sampling. While a considerable number of samples were gathered during the study of the KFB, there were some regions that were difficult to access, and poorly spaced samples were collected. Future studies that optimize sampling to a denser grid will likely yield greater precision on the geochemical study and more accurately assess the composition of the subsurface.

The complexity of geology can also create difficulties for data interpretation. The KFB contains a variety of lithologies, and the tension of the KFB layered structural features and tectonic history makes it a challenge to sufficiently separate and distinguish the different kinds of anomalies. The ambiguity remaining on some of the data interpretation was dealt with through logic and statistical analysis, but there will necessarily also be a lack of certainty.

RECOMMENDATIONS FOR FUTURE WORK

Given the findings and limitations of this study, future work can focus on a few key areas. For example, additional data acquisition, especially borehole drilling and more detailed geophysical surveys, will improve the refinement of the subsurface model and the estimates of the resources. For the drilling campaigns, the areas of high potential identified in this study should be the focus, as they will provide confirmation of the mineral and hydrocarbon resource potential.

Further use of digital technology, including machine learning and sophisticated geophysical-geochemical data integration, will serve to deepen the study further. Such digital technology facilitates the uncovering of hidden subsurface conditions and resource potential by recognizing critical patterns in extensive datasets. Also, the geophysical surveying of potential mineral and hydrocarbon deposits will be more useful if the survey tracking survey repeating cycles are lengthened.

In the KFB, future exploration will benefit from increased integration of efforts from government, industry, and academia. Such integration will enhance the sustainable development of resources and improve the chances of success for future exploration and resource development.

CONCLUSION

This study has illustrated how involving geophysical and geochemical approaches could be worth to evaluate the Kirthar Fold Belt for minerals and hydrocarbons. Having identified the presence of key structures such as fault zones and anticlines which could encourage both the mineral and hydrocarbon accumulation, the region could be of value. Anomalous geochemistry, with elevation of base metal and hydrocarbons, held promising geochemical signatures. By modernizing the exploration methodology, the study has improved the understanding of the study area resource potential. The area KFB has great exploration possibilities for minerals and hydrocarbons, broad implications for the region’s economy, energy security, and overall resource development. The great potential of energy and hydrocarbons value to economic development and energy security makes KFB mineral and hydrocarbon highly valued.

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