

Basin Analysis and Subsurface Characterization for Hydrocarbon Prospect of the Indo-Gangetic Basin, India



Thesis submitted in partial fulfillment

for the Award of Degree

Doctor of Philosophy

By

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विद्यारम्भं करिष्यामि सिद्धिर्भवतु मे सदा ॥

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Jitendra Argal...

Dedication

This thesis is dedicated to my beloved nation, my parents

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Abbreviations

AI/Z	: Acoustic Impedance
BH	: Bahraich Formation
BSFR	: Basal Surface of Forced Regression
BA	: Bouguer Anomaly
BGC	: Bundelkhand Granite Complex
CWT	: Continuous Wavelet Transform
DD	: Drilled Depth
EGM	: Earth Gravitational Model
FSST	: Falling-Stage Systems Tract
FFT	: Fast Fourier Transform
Fm	: Formation
GR	: Gamma-Ray
GB	: Ganga Basin
GH	: Gravity High
GL	: Gravity Lows
HST	: Highstand Systems Tracts
IGP	: Indo-Gangetic Plain
BGI	: International Gravimetric Bureau
KB	: Kelly Bushing
LS	: Lower Siwalik
LST	: Lowstand Systems Tracts
MPD	: Matching Pursuit Decomposition
MFS	: Maximum Flooding Surfaces
MS	: Middle Siwalik
mGal	: Miligal
Ma	: Million Years
NSP	: National Seismic Programme
OBNs	: Ocean-Bottom Nodes
PP	: Punjab Plain
RAPS	: Radial Averaged Power Spectrum
RU	: Regional Unconformity

SB	: Sequence Boundary
STFT	: Short-Term Fourier Transform
TD	: Targate Depth
TLR	: Tilhar Formation
TFCWT	: Time–Frequency Continuous Wavelet Transform
TOC	: Total Organic Carbon
TS	: Transgressive Surfaces
TST	: Transgressive Systems Tract
TWT	: Two-Way Travel Time
UJH	: Ujhani Formation
UC-1	: Unconformity Surface 1
UC-2	: Unconformity Surface 2
US	: Upper Siwalik
WT	: Wavelet Transform

Preface

Sedimentary basins are geological regions characterized by long-term, tectonically induced subsidence of the Earth's crust, within which sediments accumulate to substantial thicknesses and are preserved over extended geological timescales. These basins are of significant scientific and economic importance, as they host critical resources such as hydrocarbons, minerals, and metals, and therefore have been the subject of intensive research.

A sedimentary basin can be fully understood only by considering all factors that influence its evolution. Basin analysis is the discipline that investigates basin formation and development, with basin architecture primarily resulting from the interplay between sediment supply and accommodation space.

This thesis focuses on the Ganga Basin, a Category-III sedimentary basin, a classification that indicates the presence of hydrocarbon potential despite the basin remaining underexplored. Although hydrocarbon indications have been reported from some exploratory wells, no commercial production has yet been established. Geological studies, however, have revealed well-developed structural and stratigraphic traps and good-quality fractured rocks, making the basin a promising exploration target.

The Ganga Basin is a peripheral, east–west trending foreland basin that developed in response to the ongoing India–Eurasia continental collision since the Cenozoic. Despite its thick sedimentary cover and favorable tectono-stratigraphic architecture for hydrocarbon accumulation, the basin has not been extensively explored. This thesis adopts a multidisciplinary approach to subsurface characterization and basin modelling by integrating seismic reflection data with gravity data and well log interpretation to evaluate hydrocarbon prospectivity.

Earlier investigations of the basin were constrained by sparse seismic coverage, limited well control, and reliance on surface geological data, resulting in an oversimplified stratigraphic framework, particularly for the deeply buried Proterozoic successions. Consequently, the tectono-stratigraphic evolution of the basin prior to Tertiary sedimentation including early basin initiation, deformation history, and the role of unconformities remained poorly constrained.

The acquisition of high-resolution regional seismic data under the National Seismic Program (NSP) provided an opportunity to re-evaluate the deep structure and stratigraphy of the Ganga Basin. However, these datasets had not been systematically integrated with gravity data, well logs, and advanced seismic interpretation techniques such as gravity–seismic modelling, paleo-flattening, and Time–Frequency Continuous Wavelet Transform (TFCWT) based spectral decomposition combined with RGB blending. This gap motivated the present research, which aims to establish a unified and robust geological framework by integrating seismic interpretation, gravity modelling, depositional environment analysis, and stratigraphic reconstruction. The study seeks to identify previously unrecognized Proterozoic sequences, resolve the origin of gravity anomalies, reconstruct basin evolution through time, and assess implications for hydrocarbon prospectivity.

Seismic interpretation establishes a refined tectono-stratigraphic framework by identifying six previously unrecognized Proterozoic stratigraphic sequences (S1–S6). Integration with two-dimensional gravity modelling demonstrates that regional gravity highs are associated with dense Paleoproterozoic sedimentary successions rather than basement uplifts, fundamentally revising existing interpretations of basin architecture. The identification of major unconformities (UC-1, UC-2, and the Regional

Unconformity) provides critical constraints on deformation phases, uplift, erosion, and basin reactivation, which are essential for petroleum system analysis.

Application of paleo-flattening techniques reconstructs the depositional and tectonic evolution of the basin through four major geological stages, spanning from the Paleoproterozoic to the Cenozoic. Correlation of deep seismic sequences with the Gwalior and Bijawar formations of the northern Indian Shield strengthens regional stratigraphic linkages and improves understanding of early basin development.

The analysis reveals good reservoir potential associated with well-developed fluvial–deltaic sand bodies capped by thick shale and claystone seals. Gravity and structural anomalies support the presence of multiple trap configurations. Although commercial hydrocarbon production has not yet been established, hydrocarbon shows in exploratory wells, combined with favorable source reservoir seal assemblages, indicate promising prospects.

Overall, this thesis provides a comprehensive geological framework for the Ganga Basin and contributes significantly to understanding its tectono-stratigraphic evolution, thereby supporting future hydrocarbon exploration efforts.

The workflow of this thesis is summarized as follows:

Chapter 1. Introduction

This chapter describes the types of sedimentary basins and their critical role in hydrocarbon generation and accumulation. It introduces basin analysis as a fundamental tool in petroleum exploration and outlines the motivation and significance of the present study.

Chapter 2. Study Area

This chapter discusses the regional extent, tectonic setting, and general stratigraphy of the Ganga Basin, focusing on the eastern part encompassing the southern Gandak and Madhubani depressions.

Chapter 3. Basin Evolution History and Literature Review

This chapter reviews the geological evolution of the Ganga Basin from the Proterozoic to the Cenozoic, including rift initiation, passive margin sedimentation, pericratonic development, and foreland basin formation related to the Himalayan orogeny.

Chapters 4 & 5. Data and Methodology

These chapters describe the seismic, gravity, and well data used, along with the methodologies applied to interpret subsurface structure and stratigraphy. The seismic was acquired under National Seismic Program (NSP). Satellite gravity data and two exploratory wells drilled in the area have been used for this purpose.

Chapter 6. Evaluation of Proterozoic Sedimentary Sequences Using Seismic Data and Gravity Modelling

This chapter delineates Proterozoic sequences using NSP seismic data and gravity modelling, demonstrating that gravity highs correspond to dense Paleoproterozoic sedimentary successions rather than basement uplifts.

Chapter 7. Depositional Environment Analysis Using TFCWT Spectral Decomposition

This chapter applies Paul wavelet-based TFCWT spectral analysis with RGB blending to delineate depositional elements and interpret seismic stratigraphy across pre-Tertiary and Tertiary successions.

Chapter 8. Sequence Stratigraphic Evaluation of Proterozoic Depositional Architecture

This chapter reconstructs the cyclic depositional history of the basin, correlating deep seismic sequences with Gwalior and Bijawar Group equivalents and identifying major depositional hiatuses.

Chapter 9. Conclusions and Future Scope

This chapter summarizes the key findings and outlines future research directions, including higher-resolution seismic acquisition, integrated potential-field modelling, petroleum system analysis, and advanced seismic attribute studies to reduce exploration uncertainties.

Chapter 1 : Introduction

1.1 Background

Basin analysis is an essential technique in petroleum prospecting, involving a comprehensive evaluation of sedimentary basins to determine their potential for hydrocarbon generation, migration, accumulation, and preservation. It is the study of sedimentary basins that are depressed or lowland areas in the Earth's crust formed due to tectonically induced long-term subsidence, in which sediments accumulate into successions to considerable thickness during a particular period at a significantly greater rate, over hundreds of millions of years, by the combined action of deposition of eroded material, precipitation of chemicals, and organic debris within water environments in large-scale areas (Einsele, 2000; Allen and Allen, 2013; Lee et al., 2019; Selley and Sonnenberg, 2023) (Figure 1.1). Geoscientists classify sedimentary basins based on their tectonic settings.

Rift basins develop when the lithosphere undergoes horizontal extension, leading to crustal thinning, fault-bounded subsidence, and the accumulation of syn-rift sediments. Passive-margin basins form along continental margins that have become tectonically quiescent following rifting, where thick successions of clastic sediments and carbonates are deposited over a thermally subsiding, extended lithosphere.

Intracontinental basins occur within stable continental interiors, commonly associated with reactivated ancient rift systems or lithospheric sagging, and experience long-term subsidence that allows the accumulation of thick sedimentary sequences.

Foreland basins develop adjacent to orogenic belts as a result of lithospheric flexure under the load of advancing thrust sheets, and are progressively filled with sediments

eroded from the uplifting mountains (Allen and Allen, 2013; Marshak, 2021; Ju et al., 2022; Selley and Sonnenberg, 2023) (Figure 1.2).

Sedimentary basins constitute the primary geological settings for the generation, migration, and accumulation of hydrocarbons, as they provide the necessary conditions for the development of complete petroleum systems. These basins commonly host organic-rich source rocks, porous and permeable reservoir units, effective sealing lithologies, and favourable thermal and burial histories that collectively govern hydrocarbon prospectivity. Understanding the evolution of sedimentary basins is therefore a fundamental objective in petroleum exploration, as it enables the identification of hydrocarbon-bearing formations and the evaluation of their spatial extent and economic viability.

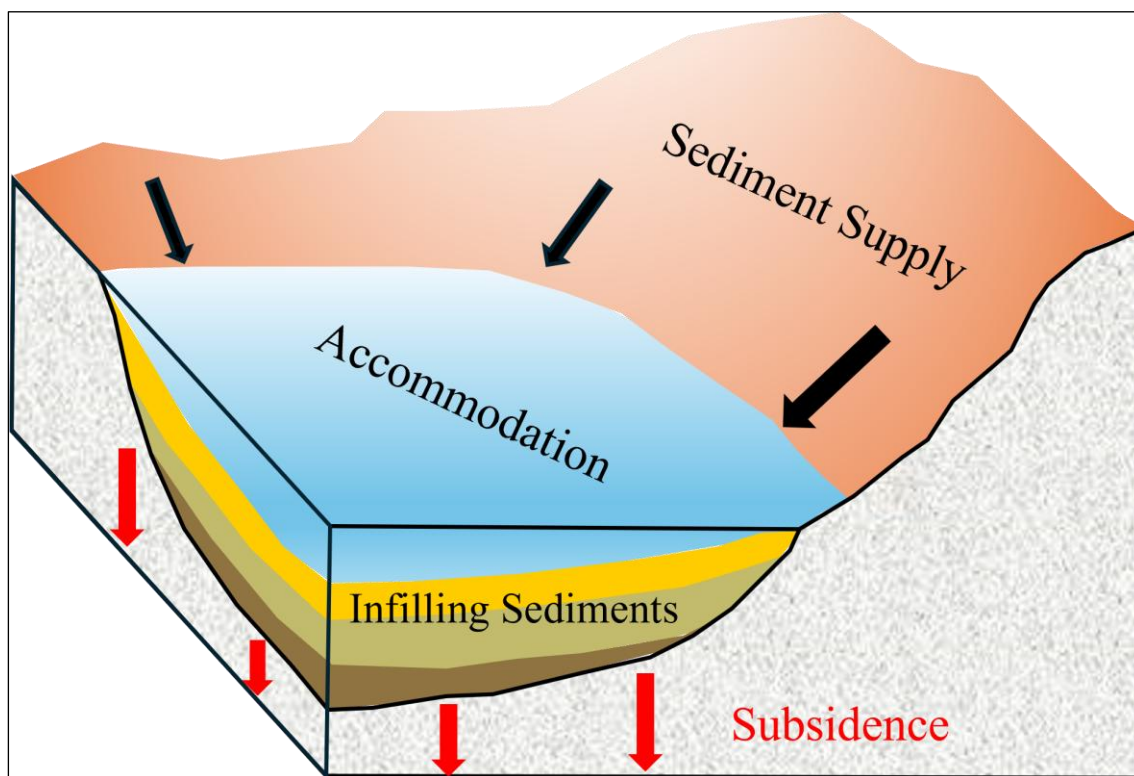


Figure 1.1: Mechanism of Basin Development (after Lee et al. (2019)).

The ultimate goal of hydrocarbon exploration is to identify structural and stratigraphic traps capable of accumulating hydrocarbons and to assess their potential through reliable

subsurface characterization. This objective is achieved through the application of advanced geophysical techniques, including seismic reflection surveys, gravity and magnetic studies, electrical and electromagnetic methods, and well-log analysis. These techniques provide critical constraints on subsurface geometry, lithological variations, and fluid distributions, thereby reducing geological uncertainty prior to drilling. This multidisciplinary approach integrates geological, geophysical, geochemical, and geomechanical data to reconstruct the basinal tectonic evolution, depositional history, and petroleum system elements.

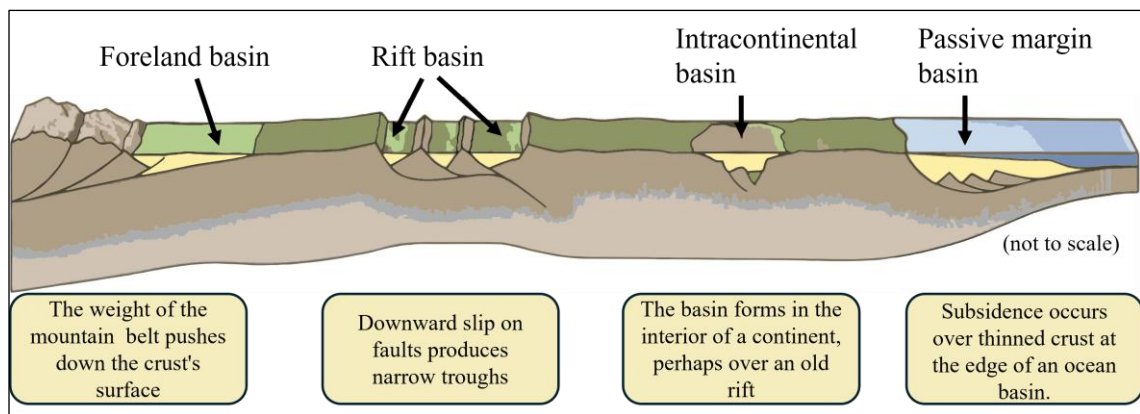


Figure 1.2: The geologic setting of sedimentary basins (after Marshak (2021)).

Basin analysis is inherently multidisciplinary, integrating geological, geophysical, geochemical, and geomechanical data to reconstruct the tectonic evolution, depositional history, and petroleum system elements of a basin. A comprehensive understanding of the tectonic and structural framework is particularly crucial, as the tectonic setting such as rift, passive margin, foreland, or intracratonic basin exerts a primary control on subsidence patterns, sediment thickness, heat flow, and accommodation space. Structural features, including faults, folds, fractures, and basement uplifts not only influence sediment dispersal and basin architecture but also play a critical role in hydrocarbon migration, trapping, and preservation.

Stratigraphic and sedimentological analyses provide insights into the temporal and spatial distribution of sedimentary sequences, enabling the interpretation of depositional environments such as fluvial, deltaic, shallow marine, and deep marine systems. These

depositional settings directly control reservoir quality, continuity, and heterogeneity, as well as the effectiveness of seals. Sequence stratigraphy further enhances basin interpretation by identifying systems tracts, depositional sequences, and unconformities that govern reservoir compartmentalization and influence hydrocarbon migration pathways. Paleogeographic reconstructions of basin evolution, including shoreline migration and sediment supply patterns, aid in predicting reservoir facies distribution and identifying favourable source rock development zones.

Geochemical analysis focuses on evaluating the presence, richness, kerogen type, and thermal maturity of source rocks, which are critical for assessing hydrocarbon generation potential. Thermal history reconstruction, maturity modelling, and basin modelling techniques are employed to determine whether source rocks have entered the oil or gas generation windows and to estimate the timing of hydrocarbon expulsion relative to trap formation. Petroleum system modelling integrates structural, stratigraphic, thermal, and geochemical parameters to simulate hydrocarbon generation, migration, accumulation, and preservation over geological time (Ombati et al., 2023).

In summary, basin analysis provides a holistic framework for understanding the complex interactions between tectonics, sedimentation, thermal evolution, and fluid flow within sedimentary basins. This integrated approach enables exploration geologists and geophysicists to rank prospects, reduce exploration risk, and optimize exploration strategies by identifying regions with the highest probability of economically viable hydrocarbon accumulations.

India is endowed with a large and geologically diverse assemblage of sedimentary basins, collectively covering an area of approximately 3.36 million sq. km. These basins extend across both onshore and offshore regions and include shallow-water domains up to about

400 m water depth, as well as deep-water areas extending to the limits of the Exclusive Economic Zone (EEZ). The onshore sedimentary basins occupy nearly 1.63 million sq. km, while offshore basins within the shallow-water zone (up to the 400 m isobath) cover approximately 0.41 million sq. km. In addition, the deep-water sedimentary basins beyond the 400 m isobath are estimated to encompass about 1.32 million sq. km (DGH, 2024) (Figure 1.3 and Table 1.1). Besides their importance for hydrocarbon exploration, these sedimentary basins also host significant resources of coal, lignite, groundwater, and various minerals.

Based on the current level of hydrocarbon exploration maturity and resource assessment, 26 sedimentary basins of India (Figure 1.4) have been grouped into 3 categories (Figure 1.5 and Table 1.2). **Category-I** basins comprise those with proven hydrocarbon reserves that are already under commercial production. **Category-II** basins include those with contingent resources that are yet to achieve commercial viability, while **Category-III** basins represent prospective basins where hydrocarbon resources are anticipated but remain largely undiscovered.

The present study is focused on the Ganga Valley Basin, which falls under Category-III, indicating that although the basin exhibits favourable geological conditions, it remains underexplored and its hydrocarbon potential is yet to be fully established. The Ganga Valley Basin is a classic example of a peripheral foreland basin formed due to flexural subsidence of the Indian lithosphere in response to the tectonic loading imposed by the Himalayan orogeny. Structurally, the basin is characterized by broad, gently dipping synclines and deeper troughs, infilled with thick successions of Cenozoic alluvial sediments derived predominantly from Himalayan erosion (Sinha et al., 2005; Sinha, 2008).

Geologically, the Ganga Basin constitutes an extensive intermontane depression extending across Uttar Pradesh, Bihar, and West Bengal, bounded by the Himalayan fold-thrust belt to the north and the Bundelkhand Craton of the Indian shield to the south. The basin contains several kilometers of sedimentary fill, dominated by unconsolidated alluvium that conceals deeper Mesozoic and Paleozoic successions. These older strata may host viable source rocks, reservoir sandstones, and effective sealing units. However, the considerable thickness of alluvial cover poses significant challenges for subsurface imaging, thereby limiting exploration activities in the basin.

From a petroleum system perspective, the Ganga Basin is theoretically promising. Potential source rocks are expected in the deeper stratigraphic levels, while fluvial channel sands and point-bar deposits within the younger alluvial succession may serve as reservoir units. Interbedded clay and shale horizons could act as effective seals. Additionally, foreland basin tectonics may give rise to subtle structural traps and stratigraphic pinch-outs, particularly in proximity to basement highs and faulted zones (Raiverman et al., 1984; Prasad et al., 2002). Despite its vast areal extent and substantial sedimentary thickness, hydrocarbon discoveries in the basin have so far been limited, primarily due to sparse exploration, poor seismic resolution through thick alluvium, and limited deep drilling. Nevertheless, recent advancements in seismic imaging, gravity–magnetic methods, and basin modelling techniques provide renewed opportunities to reassess the hydrocarbon prospectivity of the Ganga Valley Basin.

Table 1.1: Categories of Indian sedimentary basins with an areal coverage (<https://mopng.gov.in/en/exp-and-prod/conventional-hydrocarbon>).

Type of Basins	Area (Sq. Km.)	Hydrocarbons Prospectivity	Basins/Region
Category-I (7 Basins)	9,98,325	Established commercial production	Cambay, Assam Shelf, Mumbai Offshore, Krishna Godavari, Cauvery, Assam Arakan Fold Belt, Rajasthan
Category-II (5 Basins)	7,80,974	Known accumulation of hydrocarbons but no commercial production yet	Kutch, Mahanadi & Andaman-Nicobar, Vindhyan, Saurashtra
Category-III (14 Basins)	15,86,150	Indicated hydrocarbons show that are considered geologically prospective.	Himalayan Foreland, Ganga-Punjab, Kerala-Konkan-Lakshadweep, Bengal, Karewa, Spiti-Zaskar, Satpura-South Rewa Damodar, Narmada, Decan Syncline, Bhima-Kaladgi, Cuddapah, Pranhita-Godavari, Bastar, Chhattisgarh
Total Area	3,365,449		
Geographical Area			
Type of Basins	Area (million sq. km.)	Percentage (%)	
Onland	1.63	49	
Shallow water	0.41	12	
Deepwater	1.32	39	
Total Area	3.36		

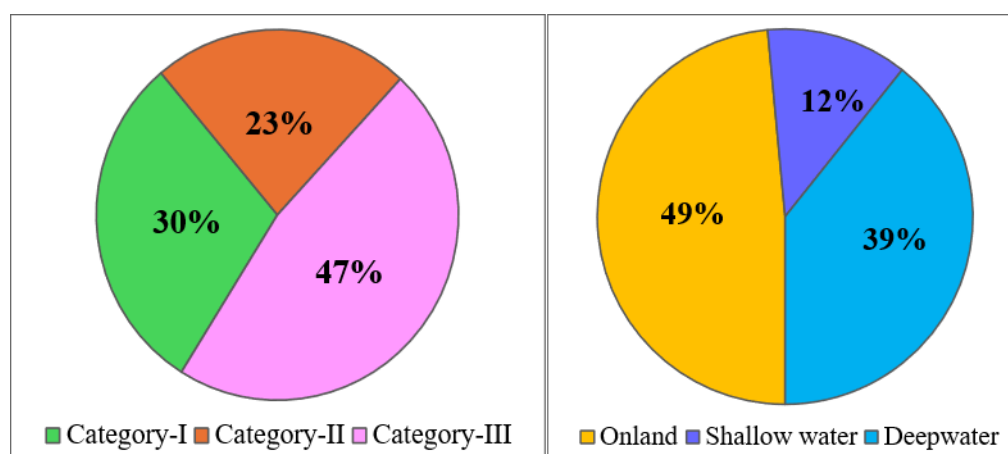


Figure 1.3: Aerial proportionality of the sedimentary basin included category and geographical distribution in a total area of 3.36 million sq. km.

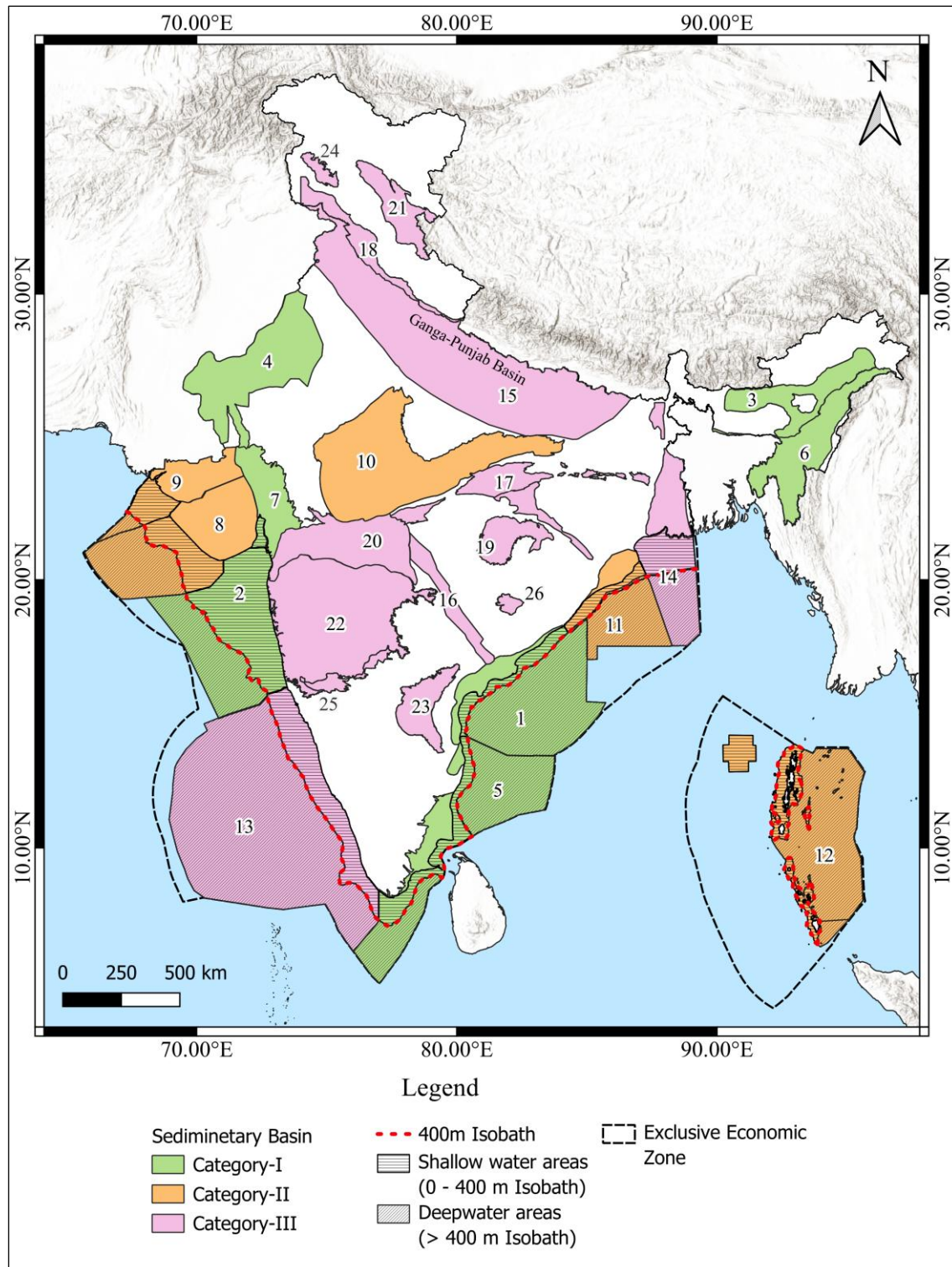


Figure 1.4: Petroliferous sedimentary basins of India (modified from <https://dghindia.gov.in>).

Table 1.2: Categorical classification of petroliferous sedimentary basins of India (<https://dghindia.gov.in>).

Category-I		Category-II		Category-III	
1	Krishna-Godavari	8	Saurashtra	13	Kerala Konkan
2	Mumbai Offshore	9	Kutch	14	Bengal Purnea
3	Assam Shelf	10	Vindhyan	15	Ganga Punjab
4	Rajasthan	11	Mahanadi	16	Pranhita Godavari
5	Cauvery	12	Andaman	17	Satpura-South Rewa-Damodar
6	Assam Arakan Fold Belt			18	Himalayan Foreland
7	Cambay			19	Chhattisgarh
				20	Narmada
				21	Spiti Zanskar
				22	Deccan
				23	Cuddapah
				24	Karewa
				25	Bhima Kaladgi

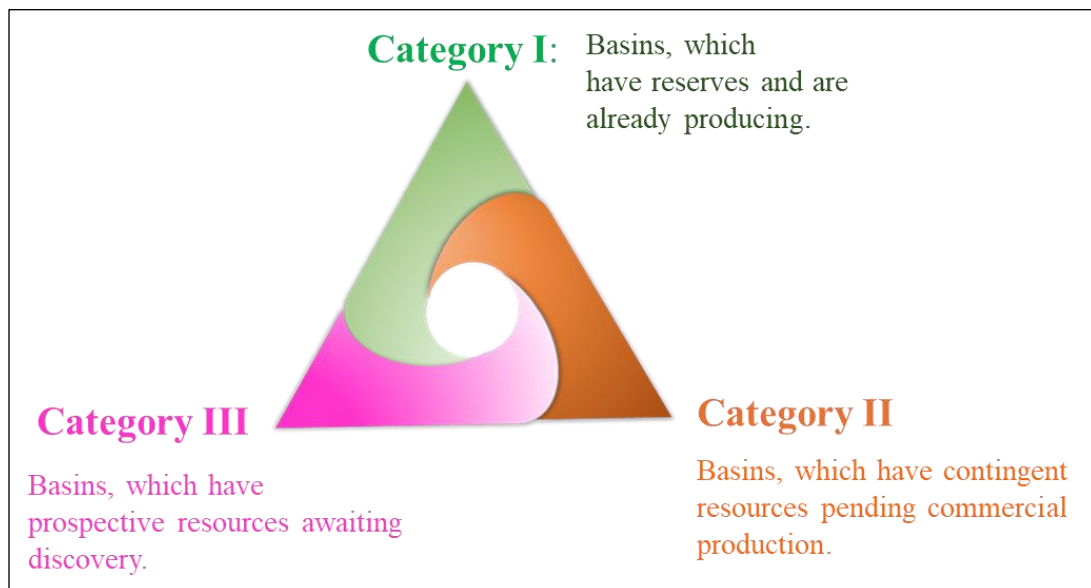


Figure 1.5: Classification of the Indian sedimentary basin (<https://dghindia.gov.in>).

1.2 Motivation and significance of the study

The Ganga Basin has attracted sustained interest for hydrocarbon exploration over several decades owing to its vast sedimentary thickness and complex tectono-stratigraphic evolution. Although exploration activities began in the 1960s, the basin

remains underexplored, particularly with respect to its deeply buried Proterozoic sequences. Earlier investigations were largely constrained by sparse well control and limited-resolution geophysical data, resulting in a simplified understanding of basin architecture that extended only up to the Bahraich Formation. The absence of detailed subsurface imaging has hindered robust evaluation of deeper stratigraphic units and their hydrocarbon potential.

Recent commercial gas discoveries in Proterozoic reservoirs of the adjoining Vindhyan Basin have renewed interest in analogous plays beneath the Ganga Basin. These discoveries highlight the possibility that deeply buried Paleoproterozoic–Mesoproterozoic sequences, concealed beneath thick Vindhyan and Tertiary successions, may host viable petroleum systems. However, the tectono-stratigraphic framework, depositional history, and structural configuration of these older sequences remain poorly constrained, underscoring the need for a comprehensive re-evaluation using modern datasets and integrated analytical approaches.

The availability of newly acquired high-resolution regional 2D seismic data under the National Seismic Programme (NSP) provides a unique opportunity to address these knowledge gaps. When integrated with gravity data and well-log constraints, these datasets allow improved imaging of basement configuration, identification of previously unrecognized stratigraphic sequences, and assessment of density variations within deep crustal units. Application of advanced interpretation techniques, such as paleo-flattening and integrated gravity-seismic modelling, further enables reconstruction of basin evolution across multiple tectonic phases.

The significance of this study lies in its contribution to refining the geological and stratigraphic framework of the Ganga Basin from the Paleoproterozoic to the Cenozoic.

By identifying six previously unrecognized Proterozoic sequences and delineating major unconformities, this research provides new insights into early basin development, tectonic reactivation, and sedimentary processes. The study also establishes subsurface correlations with exposed Proterozoic successions of the northern Indian shield, thereby strengthening regional geological models.

The outcomes of this study advance understanding of hydrocarbon prospectivity in the Ganga Basin by defining structurally complex Proterozoic sequences, potential reservoir facies, and major unconformities. These insights refine exploration concepts and reduce subsurface uncertainty, offering a robust basis for future basin analysis and exploration initiatives. The findings of this study may also have broader implications. In particular, the methodologies and interpretations developed herein can be applied to other underexplored Proterozoic sedimentary basins in India and analogous basins worldwide, thereby contributing to a wider understanding of basin evolution and hydrocarbon prospectivity.

1.3 Research Questions

Despite several decades of hydrocarbon exploration, the tectono-stratigraphic framework and petroleum potential of the Ganga Basin remain poorly understood because of limited deep drilling and the lack of integrated interpretation of modern geophysical datasets. Earlier studies were largely restricted to the upper sedimentary succession and did not adequately constrain the deeper Proterozoic sequences, basement configuration, or the origin of regional gravity anomalies. Consequently, this research addresses the following key scientific questions:

1. Recent commercial gas discoveries in Proterozoic reservoirs of the adjoining Vindhyan Basin have demonstrated the hydrocarbon potential of deeply buried

Proterozoic successions. Do analogous Paleoproterozoic–Mesoproterozoic sequences exist beneath the Ganga Basin, and what are their tectono-stratigraphic characteristics and implications for petroleum system development?

2. What is the tectono-stratigraphic architecture of the eastern Ganga Basin, and how can newly acquired NSP seismic data, integrated with gravity and well-log information, improve the understanding of its subsurface geological framework?
3. Are the regional gravity highs within the Ganga Basin associated with crystalline basement uplifts or with dense Paleoproterozoic sedimentary successions?
4. How have tectonic deformation, major unconformities, and depositional processes controlled the evolution of the basin, structural development, and hydrocarbon prospectivity?
5. Can spectral decomposition improve the interpretation of depositional environments and seismic stratigraphy within the pre-Tertiary and Tertiary successions of the Ganga Basin?
6. Do the deeper seismic reflections represent previously unrecognized Proterozoic sedimentary successions, and how do these correlate with the exposed Gwalior and Bijawar successions of the northern Indian Shield?

1.4 Objectives of the study

The Ganga Basin is an east–west-trending peripheral foreland basin that developed in response to the ongoing India–Eurasia continental collision during the Cenozoic. This tectonic interaction caused flexural downwarping of the Indian lithosphere and led to the accumulation of a thick succession of Tertiary and Quaternary sediments, derived largely from erosion of the rising Himalayan orogeny (Khanolkar et al., 2020). Although the basin has long been recognized as prospective for hydrocarbons, its deeper tectono-stratigraphic framework remains poorly constrained because of sparse deep drilling and

limited subsurface imaging. The availability of newly acquired high-resolution regional 2D seismic data under the National Seismic Programme (NSP) provides an opportunity to re-evaluate the deep geological framework of the Ganga Basin. Integration of seismic reflection data with gravity measurements and well-log information reduces the uncertainty associated with basement geometry, density distribution, and stratigraphic interpretation. This integrated approach enables the identification of previously unrecognized Proterozoic sequences, improves constraints on deep basin architecture, and provides a more robust basis for reconstructing basin evolution and evaluating hydrocarbon prospectivity.

The principal objective of this thesis is to develop a refined tectono-stratigraphic and petroleum exploration model of the Ganga Basin through the integrated interpretation of 2D/3D seismic reflection, gravity, well-log, and spectral analysis. The study aims to improve the understanding of basin evolution, basement configuration, depositional history, and hydrocarbon prospectivity, while providing new geological evidence for the deeper Proterozoic succession beneath the basin.

The specific objectives of the present research are as follows:

- To establish a refined tectono-stratigraphic framework of the Ganga Basin using newly acquired high-resolution National Seismic Programme (NSP) seismic data integrated with gravity measurements and well-log information.
- To identify and characterize the deep Proterozoic sedimentary sequences, major unconformities, and basement architecture, and evaluate their significance in the tectonic evolution of the basin.
- To delineate subsurface lithological and structural features, including faults, folds, basement highs, and stratigraphic traps, in order to identify prospective stratigraphic intervals and structural zones within the Proterozoic and pre-Tertiary successions.

- To reconstruct the depositional and structural evolution of the basin by integrating seismic stratigraphy, structural interpretation, and gravity modelling, with particular emphasis on the influence of tectonic deformation, uplift, erosion, and unconformities on basin architecture.
- To establish regional tectono-stratigraphic correlations between the deep subsurface successions of the Ganga Basin and the exposed Proterozoic successions of the northern Indian Shield, particularly the Gwalior and Bijawar Groups, in order to improve the understanding of regional geological continuity.
- To resolve the origin of regional gravity anomalies through the integrated interpretation of seismic reflection data, gravity modelling, and well-log-derived density information, thereby distinguishing basement uplifts from dense Paleoproterozoic sedimentary successions.
- To evaluate the implications of the interpreted tectono-stratigraphic framework for hydrocarbon prospectivity by identifying potential structural and stratigraphic traps, assessing the role of major unconformities in reservoir development and hydrocarbon preservation, and delineating favourable exploration targets within the Proterozoic and pre-Tertiary successions.
- To evaluate the role of spectral decomposition in reconstructing depositional environments and relative sea-level changes across the pre-Tertiary–Tertiary transition, including the northeastward thickening of fluvial sediments from the Regional Unconformity to the Lower Siwalik succession.

Chapter 2 : Study Area

2.1 Introduction

The Ganga Basin represents one of the least explored foreland basins in India despite its thick sedimentary succession and favourable tectonic setting for hydrocarbon accumulation. Understanding its tectonic framework, stratigraphic architecture, and basin evolution is fundamental for interpreting deep seismic reflections, constraining gravity models, and evaluating the petroleum potential of the concealed Proterozoic succession investigated in this study. The Ganga Basin, also referred to as the Indo-Gangetic Foreland Basin, evolved in response to the collision between the Indian and Eurasian plates during the early Cenozoic. This continental convergence led to the uplift of the Himalayan orogen and the development of a flexural foredeep south of the mountain belt, forming a classic peripheral foreland basin (Khanolkar et al., 2020). Progressive subsidence of the Indian plate resulted in the accumulation of thick fluvial, deltaic, and alluvial sediments derived predominantly from erosion of the rising Himalayas.

Stratigraphically, the basin is dominated by Cenozoic deposits, particularly Neogene and Quaternary sediments. However, geophysical and drilling evidence suggests the presence of older Paleogene, Mesozoic, and Proterozoic successions at depth (Chakraborty et al., 2020). These sedimentary sequences record a wide range of depositional environments, from floodplain clays to channel and point-bar sands, which collectively provide favorable conditions for hydrocarbon generation, migration, and entrapment. Consequently, understanding the tectono-stratigraphic evolution of the Ganga Basin is critical for evaluating its petroleum system elements and exploration potential.

The Indian subcontinent exhibits remarkable physiographic and geological diversity shaped by prolonged tectonic activity, sedimentation, erosion, and magmatism. It is broadly divided into three major physiographic regions: the Peninsular Plateau, the Extra-Peninsular region (Himalayas), and the Indo-Gangetic Plain (IGP) (Figure 2.1).

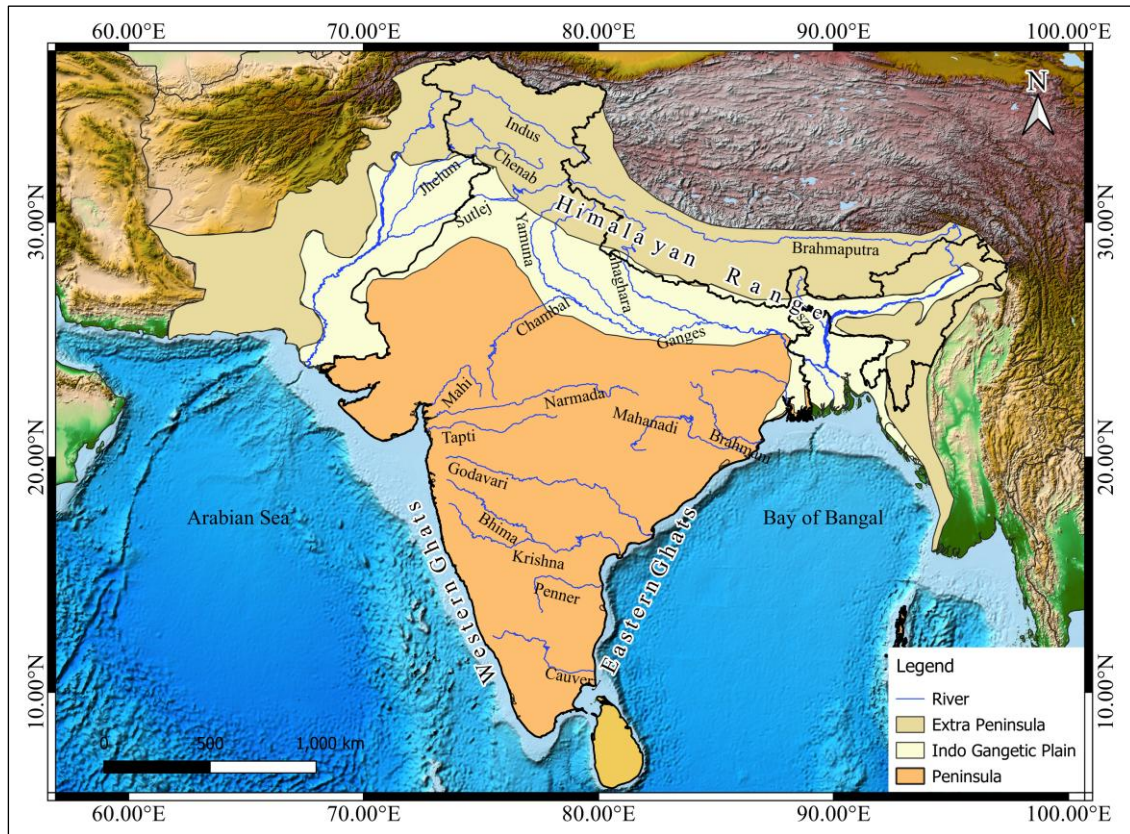


Figure 2.1 Physiographic classification of the Indian subcontinent (after Valdiya, 2016). The Peninsular Plateau represents the stable cratonic core of India, known as the Indian Shield. It consists primarily of Precambrian rocks, gneisses, schists, and granites, and includes the Archean Dharwar craton, the Vindhyan and Cuddapah sedimentary basins, and extensive Deccan Traps formed by massive Late Cretaceous to early Paleogene basaltic lava flows. This region is tectonically stable but is dissected by faults and rift zones, contributing to its rugged topography. Surrounding the plateau are the Coastal Plains, formed through marine transgressions and regressions, deltaic deposits, and erosional features (Meert et al., 2010). The Western Coastal Plain, narrow and steep, is

bounded by the Western Ghats and features laterites and marine sediments, while the Eastern Coastal Plain is broader, with deltaic formations from major rivers like the Mahanadi, Godavari, Krishna, and Cauvery (Kale, 2014).

The Northern Mountains, primarily the Himalayas, are the result of the ongoing collision between the Indian and Eurasian tectonic plates. Geologically young and seismically active, these ranges consist of sedimentary and metamorphic rocks and include three subdivisions: the Greater Himalayas with high-grade metamorphics, the Lesser Himalayas with low-grade metamorphics and fossil-rich sediments, and the Siwalik Hills composed of unconsolidated fluvial deposits from the Neogene-Quaternary periods (Adlakha and Sain, 2022).

Situated between these two major tectonic domains, the Indo-Gangetic Plain represents a vast foredeep basin formed as a consequence of Himalayan uplift during the late Cenozoic (Tandon et al., 2008). This region is characterized by thick alluvial deposits transported by the Indus, Ganga, and Brahmaputra river systems, resulting in limited surface rock exposure. The Indo-Gangetic Plain is subdivided into the Indus, Punjab, Ganga, Brahmaputra, and Bengal basins, among which the Ganga Basin constitutes a major component.

The Indo-Gangetic Plain, encompassing the Ganga Basin (GB) and Punjab Plain (PP), spans an area of 304,000 sq. km, and stretches over 1,000 km in an east-west direction with an average width of about 300 km in width, situated between longitudes $77^{\circ} - 86^{\circ}$ E and latitudes $25^{\circ} - 30^{\circ}$ N (Figure 2.2). The Ganga Basin extends over approximately 242,444 sq. km, accounting for more than half of the Indo-Gangetic Plain.

The basin represents the most extensive Quaternary alluvial sedimentary province in northern India and serves as a modern example of an active peripheral foreland basin (Sastri et al., 1971). It consists of alternate beds of sand and clay with intermittent

calcareous, poorly consolidated interbeds down to the bedrock. The course of the river in the Ganga basin is controlled by Himalayan tectonics (Kumar et al., 2004; Sahu and Saha, 2014; Aas and Sinha, 2023a). The sediment thickness of the Ganga basin is estimated to be between 4.5 and 7 km, increasing northward along the Himalayan foothills (Hetényi et al., 2006; Adilakshmi et al., 2021). This is also confirmed by Sastri et al. (1971), who suggested that the sediment thickness in the Ganga basin reaches 6 km along the northern boundary, decreasing gradually towards the south with localized occurrences of Vindhyan sediments at depths exceeding 4.5 km.

The subsurface architecture of the Ganga Basin is structurally complex, with an uneven basement surface characterized by buried ridges and fault systems. Major basement highs include the Delhi–Haridwar Ridge, interpreted as a northerly extension of the Aravalli Range, as well as the Faizabad and Munger–Saharsa ridges, which represent extensions of the Bundelkhand and Satpura massifs, respectively. These structural elements are interconnected by deep-seated faults inherited from the Indian Shield and play a significant role in controlling sedimentation patterns, basin geometry, and hydrocarbon prospectivity (Sinha et al., 2010).

The present study focuses on the eastern part of the Ganga Basin and aims to delineate depositional environments, structural configurations, and sequence stratigraphy through the integrated analysis of gravity data, 2D/3D seismic reflection profiles, and well-log information. This integrated approach provides critical insights into basin evolution and supports the reassessment of hydrocarbon potential in this underexplored foreland basin.

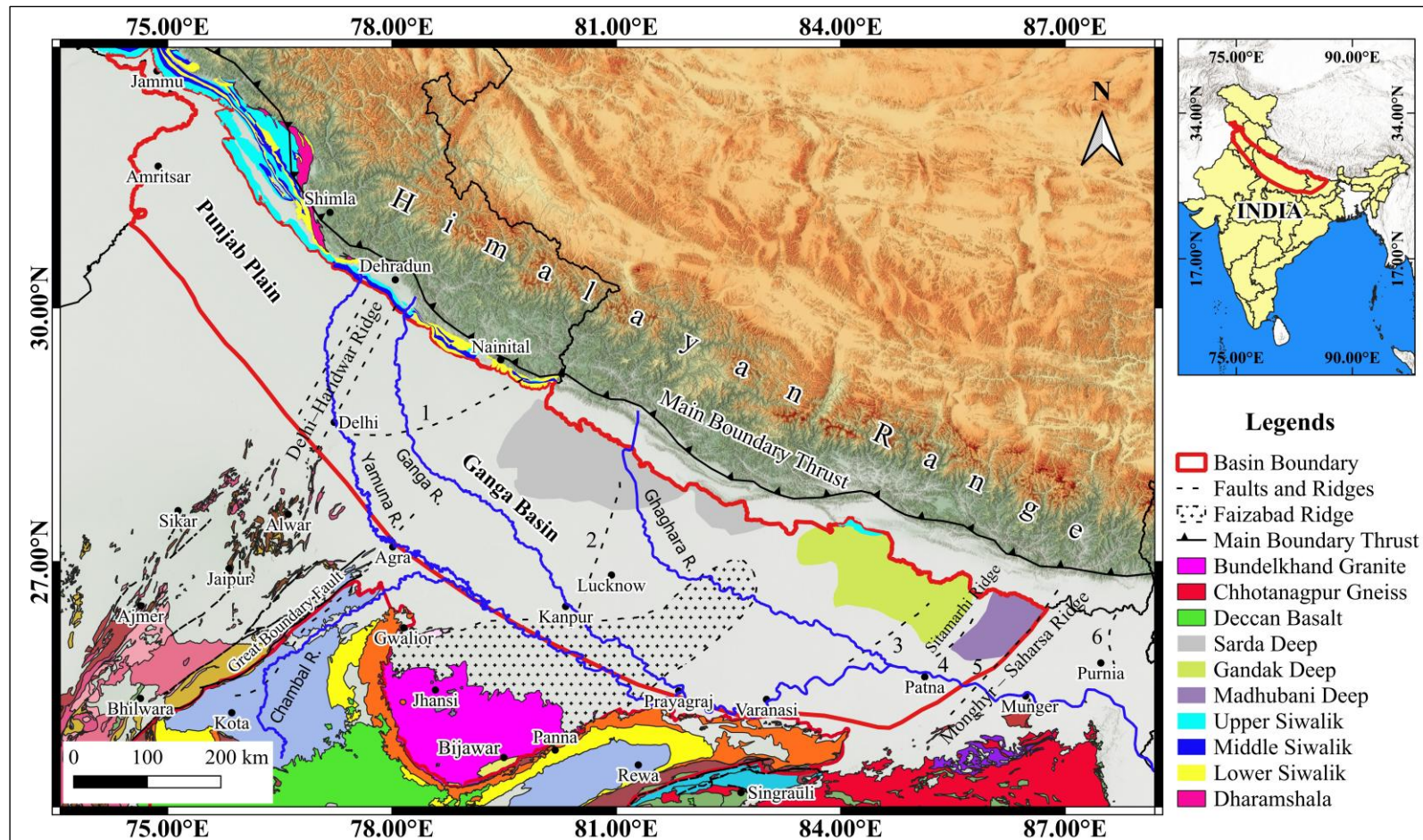


Figure 2.2: The regional map depicts the lithology and tectonic structures of the Ganga Valley Basin and Punjab Plain. Numbers represent the major subsurface faults identified using geophysical methods. 1. Delhi-Moradabad Fault, 2. Lucknow Fault, 3. West Patna Fault, 4. East Patna Fault, 5. Monghyr-Saharsa Ridge Fault, 6. Malda-Kishanganj Fault; R. River. [after (Sastri et al., 1971; Rao, 1973; R. Sinha et al., 2005; Srinivas et al., 2014)] (modified from GSI map available at <https://bhukosh.gsi.gov.in/Bhukosh/Public>).

2.2 Geological Settings of the Ganga Basin

The Ganga basin is one of the major sedimentary basins in the Indian subcontinent, located in the northern margin of the Indian platform. The basin is limited by the subsurface Monghyr–Saharsa ridge in the east and the Delhi–Sargodha ridge in the west, with middle Proterozoic rocks. In the north, it is bounded by the outermost Siwalik foothills of the Himalayas by the Himalayan Frontal Fault (a series of reverse faults), which runs parallel to the Himalayas from west to east along the southern fringe of the basin. The exposed Purana sediments (Vindhyan group) and Bundelkhand granites/gneiss massif limit the basin in the south (Figure 2.2).

Sastri et al. (1971) and later on Pramanik et al. (1996) provided a comprehensive tectonic and geological classification of the Ganga Basin from west to east: (1) Delhi–Hardwar ridge (2) Sarda Depression, (3) West Uttar Pradesh Shelf, (4) Faizabad Ridge, (5) Gandak Depression, (6) East Uttar Pradesh Shelf, (7) Madhubani Depression and (8) Monghyr–Saharsa Ridge. These subdivisions are based on variations in basement configuration, sediment thickness, fault patterns, and tectonic history, and they significantly influence the basinal geomorphology, fluvial behaviour, and seismicity.

2.2.1 Delhi–Hardwar Ridge

The Delhi–Haridwar ridge is considered the northern extension of the Delhi–Aravali Fold Belt, of metasedimentary formation of Middle Proterozoic age, trending in a SW to NE direction towards the Himalayan foothills (Rawat et al., 2023). It plays a significant role in the regional tectonic framework and seismic activity. This ridge forms the western limit of the Ganga Basin.

2.2.2 Sarda Depression

The Sarda depression, located in the northern part of the West Uttar Pradesh shelf, is a structurally synclinal feature distinguished by the inferred alluvial sediment thickness of more than 6 km and by NW-SE trending structures. The large thickness of sediments in this area may include the Mesozoic and Paleogene besides the Vindhya and the Neogene. The depression is bounded by faults and interpreted to have formed due to foredeep subsidence along the Himalayan front (Sastri et al., 1971).

2.2.3 West Uttar Pradesh Shelf

The West Uttar Pradesh Shelf, west of the Faizabad Ridge, is underlain by similar Proterozoic basement rocks and shows less structural complexity. However, it is influenced by tectonic elements such as the Delhi-Haridwar Ridge and associated faults, which create minor flexures and local seismicity (Sastri et al., 1971).

2.2.4 Faizabad Ridge

The Faizabad ridge, the most important tectonic element differentiating the Ganga basin, is a northeastward subsurface projection of the Bundelkhand massif (Sastri et al., 1971) uplift that acts as a tectonic hinge line. Geologically, the ridge is believed to be composed of Archean-Proterozoic crystalline rocks. This ridge not only separates the East and West Uttar Pradesh Shelves but also divides the basin into zones of differing sediment thickness and tectonic activity.

2.2.5 Gandak Depression

The Gandak Depression is a large depression located east of the Sarda Depression (Rao, 1973). The Gandak depression is distinguished from the East Uttar Pradesh shelf based on the sedimentary thickness of more than 6 km. Rocks of the Satpura folded belt

probably form the basement of this depression, successively overlain by the Vindhyan, Paleogene, and Neogene sequences (Ojha, 2012).

2.2.6 East Uttar Pradesh Shelf

The East Uttar Pradesh shelf is delineated by the Monghyr-Saharsa ridge to the east and the Faizabad ridge to its west. The outcropping Vindhyan of the Son Valley and the basement form the southern border of this zone. This shelf merges to the north into the Gandak depression. The basement here is assumed to be the continuation of the Satpura folded belt, overlain successively by the Vindhyan and Neogene sequences.

2.2.7 Madhubani Depression

The Madhubani Depression originated as a narrow graben during the Middle Mesoproterozoic (~1400 Ma) as a result of transtensional rifting. It hosts a sedimentary succession exceeding 7000 meters in thickness. Notably, the deepest well in the Ganga Valley, Madhubani-1, was drilled in this depression, reaching a depth of 5957 meters (Ojha, 2012). The depression is limited by the Sitamarthi Ridge in the west and the Monghyr-Saharsa Ridge in the east. The Patna fault defines the southern margin of this basin. The Madhubani Depression contains massive shales within the Lower Vindhyan, which are considered reliable regional seals.

2.2.8 Monghyr-Saharsa Ridge

Monghyr-Saharsa Ridge, sometimes referred to as the Munger-Saharsa Ridge (MSR), is the northeast extension of the Satpura folded belt of Chhota-Nagpur Plateau, forming the eastern boundary of the Ganga Basin (Dutta et al., 2023). It extends in a NNE–SSW direction beneath the Ganga Basin, primarily within Bihar, and serves as a prominent basement ridge influencing the regional tectonics, seismicity, and geothermal activity. It

is bounded by the Son-Narmada geofracture to the south and the Main Boundary Thrust to the north (Gahalaut and Kundu, 2012).

Figure 2.3 delineates a cross-section through these ridges and depressions from SW to NE. These depressions collectively contribute to the complex tectonic and sedimentary framework of the Ganga Basin. Their significant sedimentary thicknesses and structural settings make them important targets for hydrocarbon exploration and studies related to seismic hazard assessment.

2.3 Stratigraphy of the Ganga Basin

The stratigraphy of the Ganga Basin has been documented by numerous researchers, each providing distinct interpretations based on available geological, geophysical, and paleontological evidence. This section presents an integrated overview of the comparative and generalized stratigraphic framework across the basin, summarized in Table 2.1.

One of the earliest systematic stratigraphic classifications was proposed by Shukla et al. (1994), who identified five major formations within the pre-Tertiary sedimentary record, distinguished primarily by their lithological variations. According to their interpretation, the Bahraich Group dated to the Palaeoproterozoic–Mesoproterozoic, forms the lowermost sedimentary package and directly overlies the granitic basement. Above this lies the Madhubani Formation of the Lower Vindhyan Group, followed by three formations of the Upper Vindhyan sequence: the Ujhani, Tilhar, and Karnapur formations. Collectively, these units comprise the Vindhyan Supergroup within the subsurface of the Ganga Basin. A major regional unconformity of approximately 454 million years separates the Vindhyan successions from the overlying Tertiary deposits, beginning with the Matera Formation. The younger stratigraphy continues with the

deposition of the Lower Siwalik during the Early to Middle Miocene, the Upper Siwalik during the Pleistocene, and finally the extensive Holocene alluvium.

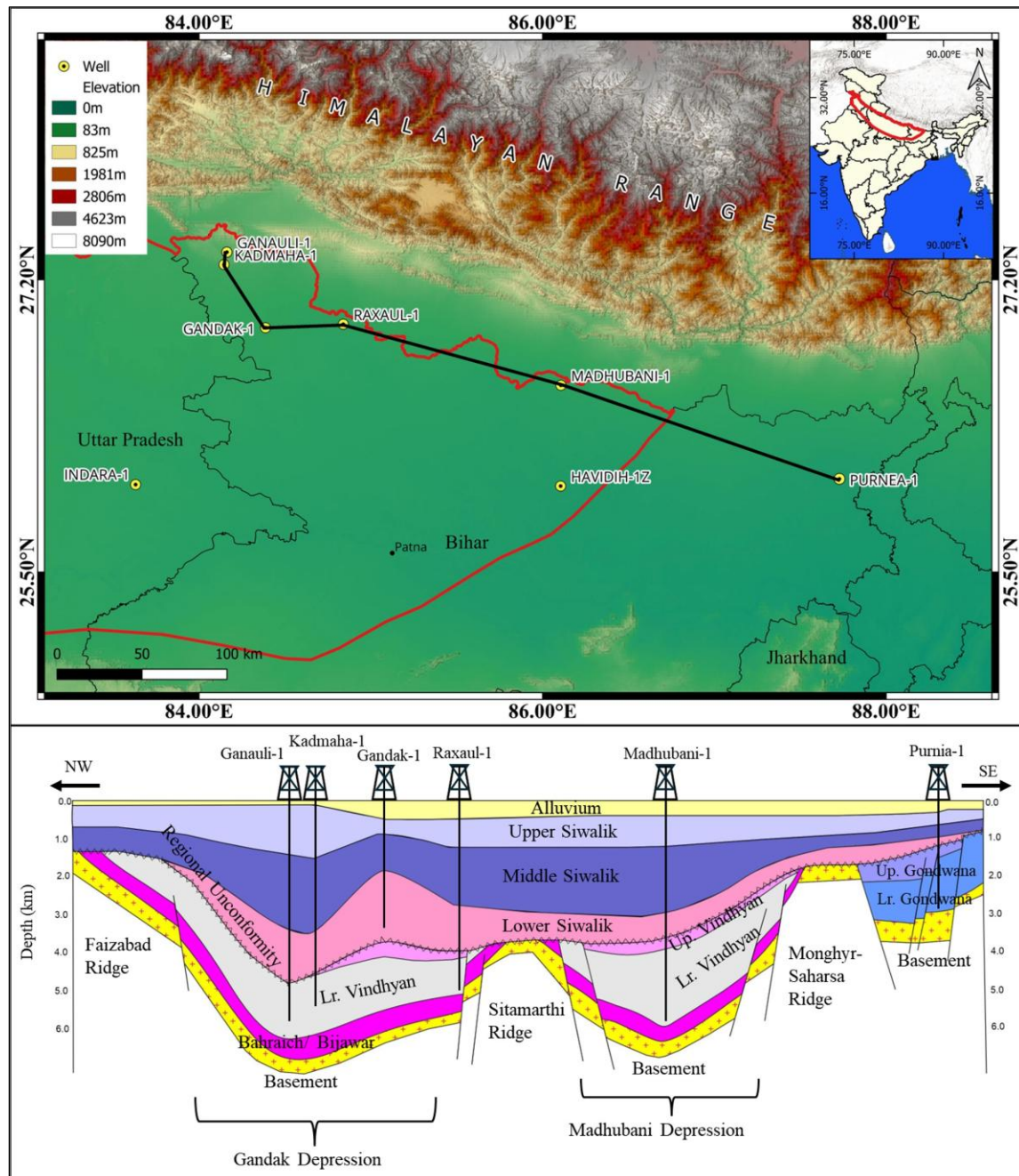


Figure 2.3: A schematic diagram represents the NW-SE elongated geological profile across the Gandak and Madhubani depression along the Himalayan Frontal Thrust (Sinha, 2005).

Fuloria (1996) proposed a more detailed subdivision, classifying the entire basin succession into nine formations. In this scheme, the granitic basement constitutes Formation IX, overlain by the Proterozoic Bijawar Formation (Formation VIII). The

Ujhani Formation equivalent to the Lower Vindhyan and assigned an Upper Proterozoic to Lower Cambrian age is designated as Formation VII. This is unconformably overlain by the Badaun Formation (Formation VI), considered equivalent to the Upper Vindhyan and assigned a Cambrian age. Overlying these is the Raxaul Formation (Formation V), dated to the Upper Jurassic-Lower Cretaceous. The Tilhar Formation is placed stratigraphically higher and categorized as Formation IV of Cretaceous age. Formations III, II, and I represent the Puranpur, Siwalik, and Alluvium units, respectively, collectively spanning the Early Eocene to Holocene.

A major contribution to understanding the Pre-Tertiary successions comes from Prasad and Asher (2001), who reported an extensive assemblage of acritarch microfossils from various subsurface intervals. Their work distinguished two major groups within the Ganga Basin Supergroup: the Bahraich Group of Paleoproterozoic age and the younger Madhubani Group, ranging into the Paleozoic. They also recognized the Matera Formation as part of the Cenozoic stratigraphy, although the Siwalik and younger deposits were not incorporated into their formal stratigraphic scheme.

For the present study, a refined stratigraphic framework has been adopted from Ojha (2012) and Srinivas et al. (2014), further modified to develop a generalized stratigraphic model (Table 2.1). The oldest recognized sedimentary sequence is the Bahraich Group of Mesoproterozoic age, subdivided into the Avadh and Sarda formations, which rest directly upon the Bundelkhand Granite Complex (BGC). A significant hiatus of nearly 550 million years (1350-800 Ma) separates these Mesoproterozoic deposits from the overlying Neoproterozoic to Early Paleozoic platformal sediments.

These younger sequences, largely confined to the Sarda, Gandak, and Madhubani depressions, consist predominantly of siliciclastic units with intermittent carbonate

horizons, indicative of deposition within a passive-margin environment. They appear in drill cores as the Ujhani, Tilhar, and Karnapur formations. Their accumulation reflects sustained platformal sedimentation, though locally influenced by pre-existing basement ridges and fault-controlled subsidence.

A prolonged depositional break spanning from ~540 to 35 Ma precedes the deposition of the Matera Formation (Eocene-Oligocene), which is restricted to the Sarda Depression. In contrast, the Siwalik sediments of Tertiary age are widespread across the basin, forming one of its most extensive stratigraphic components and transitioning upward into the basin-wide Holocene alluvium.

Table 2.1: Comparative chrono-stratigraphy of the Indo-Gangetic Basin by various authors [after (Prasad et al., 2002; Ram, 2005; Ojha, 2012; Srinivas et al., 2014)].

Age			Ma	Comparative Stratigraphy					Generalized Stratigraphy								
				(Shukla et al., 1994)		(Fuloria, 1996)		(Prasad and Asher, 2001)									
Cenozoic	Quaternary	Holocene	0.011	Alluvium		Formation-I (Alluvium)				Alluvium							
		Pleistocene	2.4	Siwalik Group	Upper Siwalik (Badaun fm.)					Upper Siwalik							
	Neogene	Pliocene	5.3		Formation-II (Siwalik fm.)		Middle Siwalik										
		Miocene	Late		23	Lower Siwalik	Lower Siwalik										
			Middle														
	Paleogene	Early	23	Matera fm.		Formation-III (Puranpur fm.)		Matera fm.		Matera							
		Oligocene	34					Regional Unconformity (Major Upliftment)		Regional Unconformity (Major Upliftment)							
		Eocene	55.8														
	Palaeocene	65.5															
	Mesozoic	Cretaceous	145	Regional Unconformity (Major Upliftment)		Formation-IV (Tilhar fm)											
Jurassic		199	Formation-V (Raxaul fm)														
Triassic	251	Regional Unconformity (Major Upliftment)				Regional Unconformity (Major Upliftment)						Ganga Supergroup		Madhubani Group		Karnapur fm.	
Paleozoic	Permian			299				Tilhar fm.									
	Carboniferous			359													
	Devonian			416													
	Silurian			443													
Cambrian	Ordovician	488	Upper Vindhyan		Upper Vindhyan		Formation-VI (Badaun fm.)		Ujhani fm.								
	Late	1000									Vindhyan Super Group		Lower Vindhyan		Formation-VII (Ujhani fm.)		
	Middle																
Early	542			Lower Vindhyan		Madhubani fm.											
Neo-Proterozoic	Vendian	1000						Vindhyan Super Group		Upper Vindhyan		Karnapur					
	Late													Tilhar			
Riparian	Middle			1600		Lower Vindhyan										Madhubani fm.	
	Early	Bahraich Group						Sarda fm.									
										Bahraich		Sarda fm.					
Paleo-Proterozoic	2500			Bahraich group (Metamorphics)		Formation-VIII (Bijawar fm.)										Archean Basement (Bundelkhand Granite/Gneiss)	
Archean			Granitic Basement		Formation-IX (Basement)		Bundelkhand Granitic Gneiss				Archean Basement (Bundelkhand Granite/Gneiss)						

Chapter 3 : Exploration History, and Literature Review

3.1 Basin origin and evolution

The Ganga Basin, commonly referred to as the Indo-Gangetic Foreland Basin, represents one of the largest Quaternary alluvial sedimentary basins globally, extending over approximately 1,000 km in length and nearly 300 km in width along the northern margin of the Indian subcontinent. The origin and evolution of this basin are fundamentally linked to the continental collision between the Indian and Eurasian plates, which commenced during the early Cenozoic, around 45-50 Ma (Sinha, 2008). This tectonic convergence resulted in the uplift of the Himalayan orogenic belt and the concomitant development of a foreland basin along its southern margin (Gibling et al., 2005).

Progressive growth of the Himalayan mountain chain imposed a substantial tectonic load on the Indian lithosphere, inducing flexural subsidence and generating a long, narrow peripheral foreland depression. This subsiding basin acted as an efficient sediment sink, accommodating vast volumes of detritus eroded from the rising Himalayas. Sedimentation initiated during the late Paleogene and intensified markedly through the Neogene and Quaternary periods. Consequently, the Ganga Basin accumulated thick successions of fluvial, deltaic, and floodplain deposits dominated by sand, silt, clay, and gravel. These sediments were transported primarily by major Himalayan river systems, including the Ganga, Yamuna, Ghaghara, and Gandak, leading to the development of an extensive alluvial plain (Gibling et al., 2005).

Structurally, the basin is bounded to the north by the Himalayan Frontal Thrust (HFT), which marks the active deformation front of the Himalayan orogen, and to the south by the relatively stable Vindhyan and Bundelkhand cratonic blocks (Valdiya, 2016). The

basin is characterized by a very thick accumulation of unconsolidated Quaternary alluvium, beneath which older sedimentary successions-possibly of Cretaceous to Tertiary age-are deeply buried. These deeper sequences remain poorly imaged due to the attenuating effects of the overlying alluvial cover and limited subsurface data (R. Sinha et al., 2005).

Earlier studies by Dewey and Bird (1970) and later by Sinha et al. (2005) emphasized that the formation of the Ganga Basin was a direct response to Himalayan uplift following the Indian–Asian plate collision initiated in the Paleogene. A linear crustal sag developed contemporaneously with the orogeny, forming the fundamental structural framework of the basin. This foreland depression was progressively infilled by molasse sediments derived from the eroding Himalayas to the north, as well as clastic sediments sourced from the Vindhyan proto-continent to the south. Together, these processes shaped the present-day architecture and sedimentary fill of the Ganga Basin.

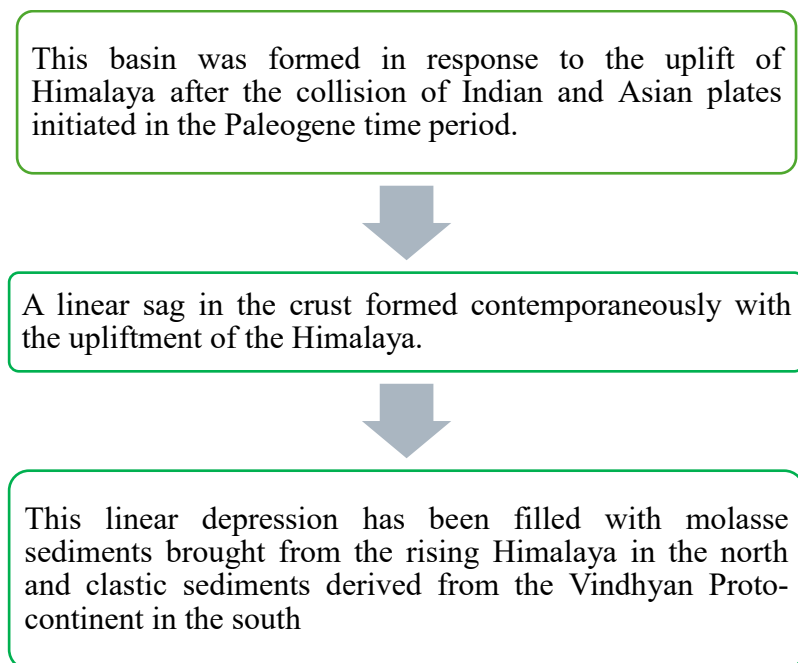


Figure 3.1: General stages of formation of the Ganga Valley basin in the Indo-Gangetic Plain (Dewey and Bird, 1970; R. Sinha et al., 2005).

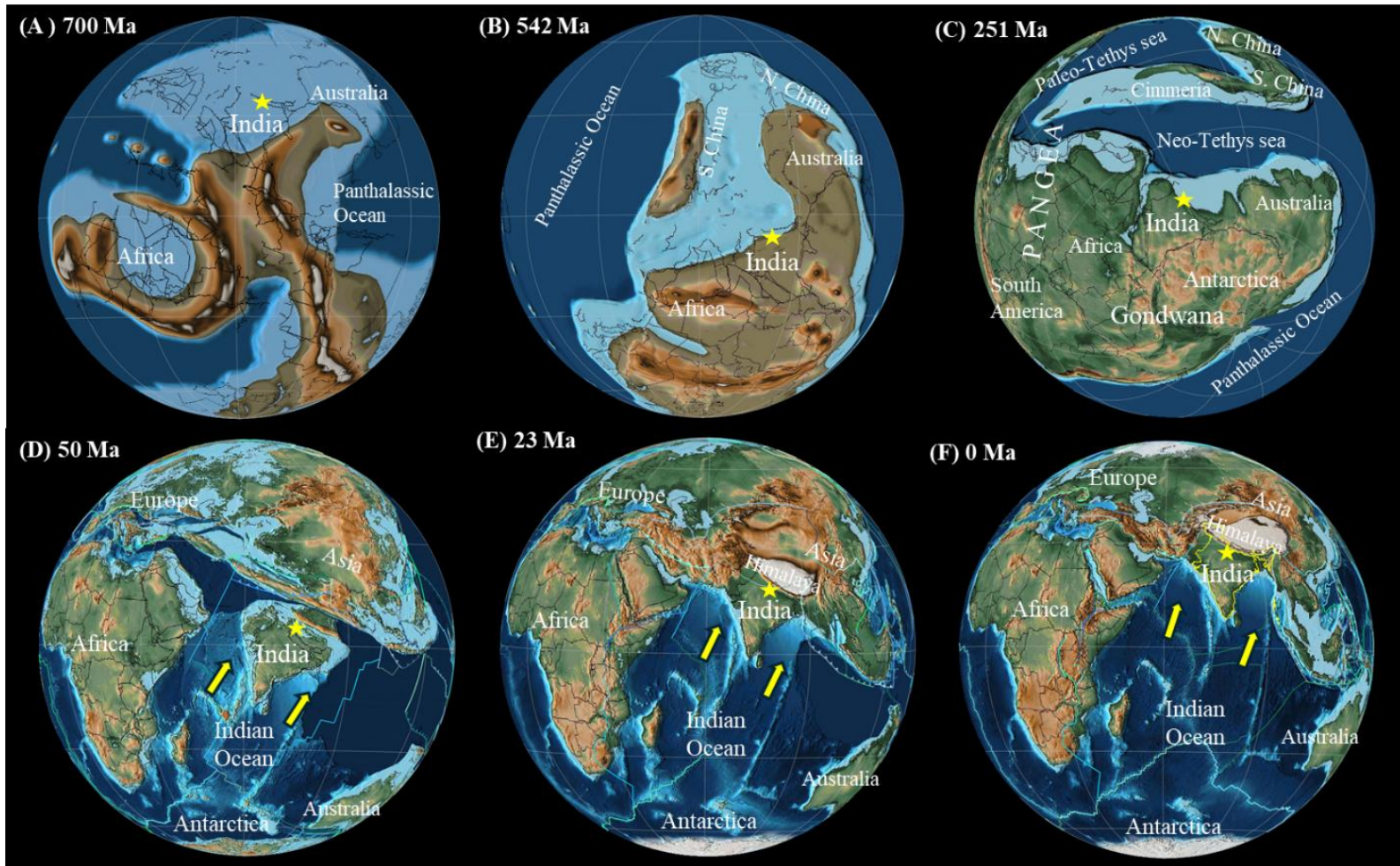


Figure 3.2: Schematic map of the supercontinents from A to F represents tectonic and paleogeographic reconstructions for the Ganga basin throughout its journey, located in the northern part of the Indian plate (marked in yellow colour star) for the period from 700 to 0 Ma. (A)(Middle Neoproterozoic), B(Cambrian/Precambrian boundary), C(Permian-Triassic Boundary), E(Early Eocene), F(Present-day) after Scotese (2016).

The Ganga Basin represents a composite, multi-phase sedimentary basin with a prolonged and complex geological history spanning from the Mesoproterozoic to the Pleistocene (Figure 3.2). Its evolution reflects successive tectonic regimes, beginning with intracratonic rifting and culminating in the development of a peripheral foreland basin associated with Himalayan orogeny.

The basin was initiated as an intracratonic rift during the early Proterozoic under extensional tectonic conditions and subsequently evolved into a pericratonic basin. The earliest phase of rifting occurred during the Mesoproterozoic, when passive-margin sedimentation commenced with the deposition of the Bahraich Group. These platform sediments overlie the crystalline basement of the Bundelkhand Granite Complex and represent the first sedimentary fill of the Ganga Basin following the suturing of the Bundelkhand Cratonic Block with the Dharwarian Block. Sedimentation during this phase continued until approximately 1350 Ma and is widely attributed to lithospheric extension associated with the fragmentation of the Columbia supercontinent (Rogers and Santosh, 2002; Li et al., 2008; Santosh, 2012; Meert and Pandit, 2015).

This initial depositional phase was followed by a prolonged period of non-deposition and erosion. Subsequently, Neoproterozoic to Paleozoic sedimentation resumed in a pericratonic rift setting, leading to the accumulation of the Madhubani, Tilhar, Ujhani, and Kanapur formations. This phase is tentatively linked to tectonic events related to the breakup of the Rodinia supercontinent between ~750 and 633 Ma (Figure 3.2A). During the Pan-African orogeny, uplift of Peninsular India, including the Trans-Aravalli region, resulted in northward regression of the sea. Consequently, sedimentation was localized within the Ganga Basin, whereas much of the Indian subcontinent experienced erosion. This depositional cycle was terminated by regional uplift associated with the Hercynian

(Tanzanian) orogenic movements, marking the end of Paleozoic platform sedimentation (Figure 3.2B).

Paleozoic deposition within the basin was strongly influenced by basement-controlled structural highs and faults, such as the Faizabad Ridge, Monghyr–Saharsa Ridge, Gandak Fault, and Patna Fault, which constrained sediment dispersal and thickness variations (Valdiya, 1976). During the late Paleozoic, rifting associated with the Gondwana basins elsewhere in the Indian shield induced a compressional regime within parts of the Ganga Basin. This resulted in tectonic deformation, uplift, and partial erosion of Paleozoic sediments (Figure 3.2C) (Cawood et al., 2007).

The Mesozoic and early Paleogene represent a second major phase of non-deposition and regional peneplanation, during which widespread erosion removed sediments from structural highs, preserving them only within a few linear depressions. This extensive erosional surface is recognized as the Regional Unconformity (RU), representing a basin-wide hiatus of approximately 384 Ma.

A fundamental shift in the tectonic regime occurred during the Paleogene with the collision of the Indian and Eurasian plates at ~45–50 Ma. This event transformed the regional setting from divergence to convergence, leading to the uplift of the Himalayas and the simultaneous development of a peripheral foreland basin along its southern margin. Neogene molasse sediments, collectively referred to as the Siwalik Group, were deposited over pre-orogenic Paleogene shelf sequences (Figure 3.2D). Several workers suggest that the present-day depression of the Ganga Basin was accentuated during the Middle Pliocene, coinciding with the most intense phase of Himalayan folding and thrusting (Biswas, 1987; Goswami et al., 2009; Acharyya and Saha, 2018).

This foreland depression was rapidly infilled by enormous volumes of terrigenous sediments supplied by rivers draining the rising Himalayas and the northern margin of

the Indian peninsula, ultimately giving rise to the modern Ganga Basin configuration. During the Tertiary, following a long hiatus, the basin evolved into a frontal foredeep trough (Figure 3.2E) (Sinha et al., 2010).

Dewey and Bird (1970) similarly attributed the formation of the Ganga Basin to flexural subsidence of the Indian lithosphere in response to Himalayan uplift following the India–Asia collision. The resulting linear crustal sag was progressively filled with molasse sediments derived from the Himalayas to the north and clastic sediments sourced from the Vindhyan proto-continent to the south. This evolutionary history confirms that the Ganga Basin is a classic example of a peripheral foreland sedimentary basin formed during Pliocene-Pleistocene orogenic intensification. Ongoing sediment supply through an extensive fluvial network continues to shape its stratigraphy, making the basin a region of sustained interest for hydrocarbon exploration (Summons et al., 1988; Sinha et al., 2010; Demudu Babu et al., 2020).

Accordingly, the present study focuses on the Ganga Basin, a dominant and tectonically significant component of the Indo-Gangetic Plain.

3.2 Depositional Environment

Tectonic regime and depositional environment are the two principal controls governing sediment characteristics and stratigraphic architecture within a sedimentary basin. In the Ganga Basin, sedimentation was initiated during the Mesoproterozoic in an extensional tectonic setting, when the Bahraich Group was deposited unconformably over the Archean granitic basement. This initial sedimentary succession represents the foundation of the basin fill and marks the onset of long-term sediment accumulation within the Ganga Basin.

The Bahraich Group has been subdivided into two lithostratigraphic units, namely the Sarda (lower) and Avadh (upper) formations. The Sarda Formation is composed

predominantly of basic volcanic rocks, phyllites, and schists, whereas the overlying Avadh Formation consists mainly of orthoquartzite sandstones with subordinate limestone and minor shale intercalations (Shukla et al., 1994; Prasad and Asher, 2001). These sediments were deposited in a shallow marine, inner-shelf to tidal-flat environment under relatively low-energy conditions. The orthoquartzite-dominated Avadh Formation records a regressive depositional phase, as evidenced by the commonly observed coarsening-upward stratigraphic motif. Subsequent tectonothermal events resulted in low-grade metamorphism of the Bahraich Group sediments (Ojha, 2012).

The Neoproterozoic to Paleozoic succession of the Ganga Basin comprises the Ujhani, Tilhar, and Karnapur formations, which were deposited along a passive continental margin under shallow marine conditions. Collectively, these units represent a prolonged phase of platform sedimentation during Paleozoic time, although marked lithological variations occur among individual formations.

The Ujhani Formation consists of alternating shale, sandstone, and limestone units forming a thick, unmetamorphosed sedimentary succession. In seismic sections, this formation is characterized by weak to moderate reflectivity, consistent with fine-grained lithologies. The depositional environment of the Ujhani Formation reflects a progressive marine transgression, evolving from intertidal to shallow inner-shelf settings.

The Tilhar Formation is dominated by carbonate sediments, indicating the development of a restricted, semi-arid carbonate platform. This unit represents middle- to outer-shelf depositional conditions, with limited tectonic activity and reduced clastic influx. Continued marine transgression led to the eventual retreat of the carbonate shelf and the establishment of fine-grained, clastic-dominated outer-shelf environments (Tandon et al., 2008; Khanolkar et al., 2020).

The Karnapur Formation comprises thick alternations of shale and sandstone deposited in a shallow marine environment. Taken together, the Lower Paleozoic succession of the Ujhani, Tilhar, and Karnapur formations records sedimentation across a range of depositional facies, from littoral and marginal-marine to middle-shelf environments (Cawood et al., 2007).

Following deposition of the Karnapur Formation, the basin experienced widespread regression and uplift. Much of the Mesozoic and early Paleogene was characterized by erosion and regional peneplanation, resulting in the removal of sediments from structural highs and their preservation only within a few linear depressions. This extensive erosional surface is identified as the Regional Unconformity (RU).

Renewed sedimentation commenced during the Tertiary, following the India–Asia collision at ~45-50 Ma, which transformed the regional tectonic regime from extensional to compressional. This event led to the uplift of the Himalayas and the development of a peripheral foreland basin, into which thick Neogene molasse deposits, collectively referred to as the Siwalik Group, were deposited over pre-orogenic Paleogene shelf sequences. The Siwalik succession is subdivided into Lower, Middle, and Upper Siwalik subgroups. The Lower Siwalik sediments were deposited primarily in lacustrine environments with intermittent marine influence, whereas the Middle and Upper Siwalik units record a transition to braided and meandering fluvial systems.

Overall, the Tertiary and Quaternary sedimentary succession of the Ganga Basin represents a foreland basin fill dominated by fluvial–lacustrine depositional systems. The Tertiary fluvial deposits commonly exhibit upward-fining sequences, indicating evolving sediment supply and accommodation conditions. Energy conditions generally increase upward through the stratigraphic succession. The Siwalik sediments are overlain by

unconsolidated Gangetic alluvium, consisting of loose sand, gravel, pebbles, kankar, and sandy clay, which form the present-day alluvial cover of the basin (Table 3.1).

Table 3.1: Generalized stratigraphic sequence of the Ganga basin [modified after (Ojha, 2012; Srinivas et al., 2014)].

Era	Period		Age (Ma)	Group / Formation	Thickness (m)	Lithology	Depositional Environment	Tectonics	
Cenozoic	Quaternary		1.5 - Recent	Alluvium	200-426	Loose sand, Kankar, Gravel, and Pebbles	Widespread braided fluvial system	Himalayan Orogeny	
	Tertiary	Neogene	6.5-1.5	Upper Siwalik	200-1300	Interbedded Sandstone, Silty Claystone			
			10.8-6.5	Middle Siwalik	250-1970	Sandstone, Claystone, and Siltstone			
			18.3-10.8	Lower Siwalik	130-1540	Sticky clay, Sandy claystone, and hard siltstone			
	Paleogene	35-28	Matera	400	Grey to black silt shale alternation, occasional sandstone	Marine Incursion in Basal Part			
Regional Unconformity									
Neoproterozoic-Lower Paleozoic			635-540	Karnapur	50-450	Dominantly arenaceous with fissile shales and claystone	Outer Shelf	Tianshanian Orogeny	
			670-635	Tilhar	210-380	Argillaceous Limestone, Dolomitic at base with Shale	Carbonate Shelf	Extensional Tectonics around Gondwana	
			Unconformity						
			700-800	Ujhani	130-850	Quartzitic Sandstone with Shale and Claystone	Shallow Marine	Gondwana Stabilization, Rodinia Breakup	
Unconformity									
Mesoproterozoic			1450-1350	Bahraich	Avadh	527+	Quartzitic Sandstone, Limestone	Marginal Marine, Synrift Sediments	Tectonic Subsidence
			1550-1450		Sarda				
Archean Basement (Bundelkhand Granite/Gneiss)									

3.3 Petroleum system

3.3.1 Source rocks

In the Ganga basin source rocks are discontinuous, very lean, and immature. But at some places, source rock studies indicate the presence of potential source rocks for hydrocarbon generation in the Tertiary succession, particularly within the Lower Siwalik Formation, as well as the existence of effective source rocks in Neoproterozoic strata encountered in wells drilled in the Sarda Depression. Bilaspur well in the Sarda Depression gave total organic carbon (TOC) values in the range 1.62–2.24%. Madhubani Formation from the interval 4670–5144 m, also has a fair to good organic carbon content. Tisua -1, indicates potential source rocks in two sequences at 2715–2740 m and 2770–2790 m in Neoproterozoic Ujhani Formation (Chand et al., 2012; Ojha, 2012).

The Neoproterozoic–Paleozoic succession has also been studied in the Gandak-1 well over the depth interval of 3620–5250 m, encompassing the Ujhani, Tilhar, and Karnapur formations. Within this section, residual Total Organic Carbon (TOC) values range from 0.02% to 1.28%, with the presence of Type II kerogen, which is typically associated with oil-prone source rocks. In the Ganauli-1 well, TOC values between 0.06% and 0.34% have been recorded over the 4810–5422 m interval, indicating lower but still relevant organic richness. Notably, in the Kadmaha-1 well, the Karnapur Formation at a depth of 4724–4727 m has yielded higher TOC values ranging from 0.27% to 3.49%, suggesting better source rock potential in localized zones. The Tertiary sequence, specifically the Lower Siwalik Formation in the Ganauli-1 well between 4417–4457 m, exhibits Type III kerogen with TOC values ranging from 1.01% to 2.19%, indicating a potential for gas-prone source rocks. Overall, the geochemical analysis suggests that the basin hosts fair to good quality source rocks with both Type II and Type III kerogen (T. Dutta et al.,

2023), capable of generating liquid and gaseous hydrocarbons under suitable thermal conditions (DGH, 2012).

A general classification of source rock richness based on Total Organic Carbon (TOC) is as follows:

Table 3.2: Assessing the richness of source rock intervals (Peters, 1986; Jarvie, 1991).

Generation potential	Wt% TOC, Shales	Wt% TOC, Carbonates	Significance
Poor	0.0-0.5	0.0-0.2	Typically considered a poor source rock with limited hydrocarbon generation potential.
Fair	0.5-1.0	0.2-0.5	A fair source rock, with some potential for hydrocarbon generation
Good	1.0-2.0	0.5-1.0	A good source rock, with good potential for hydrocarbon generation
Very Good	2.0-4.0	1.0-2.0	A very good source rock, with high potential for hydrocarbon generation
Excellent	> 4.0	> 2.0	Excellent hydrocarbon generation potential

3.3.2 Reservoir rocks

The petroleum geology of the Ganga Basin indicates that potential reservoir rocks include limestones, dolomites, and sandstones within the Lower to Upper Vindhyan formations (Precambrian to Cambrian), as well as sandstones in the Lower Siwalik Formation (Middle Miocene). Lithological data from the Bilaspur-1 and Madhubani-1 wells reveal predominantly calcareous sequences comprising dolomites, limestones, and marls, interbedded with shale and minor sandstone. These sandstone and limestone units, deposited in marginal to shallow marine environments, are expected to exhibit moderate porosity and are considered prospective reservoir rocks. In the Tilhar Formation, which is dominantly carbonate, good secondary porosity is expected in these intervals. The Ujhani Formation, ranging in age from Neoproterozoic to Lower Ordovician, consists of

carbonates, shales, and sandstones and is considered more promising in terms of reservoir potential. Mineralogical and sedimentological analyses suggest deposition in a marginal to shallow marine setting, with tidal flat and intertidal sandstones in the Ujhani Formation offering favorable conditions for the development of quality reservoir facies (Ojha, 2012).

3.3.3 Cap rocks

In the Ganga basin, the intraformational shales are believed to be the expected cap rocks. Thick shale units within the Lower Vindhyan, particularly in the Rampur Low and Madhubani Depression, serve as reliable regional seals. In the Neoproterozoic- Paleozoic succession, several argillaceous intervals ranging from 10 to 50 meters in thickness, typically found at the top of fining-upward cycles, are considered effective cap rocks for hydrocarbon entrapment. Shales within the Ujhani and Tilhar formations, along with clay-rich layers in the Karnapur Formation, also exhibit good sealing potential. Marine transgressive phases recorded in the basin have led to the deposition of widespread shales, further enhancing regional seal capacity. In the Tertiary Siwalik succession, floodplain and overbank shales associated with fluvial systems may function as effective local cap rocks. The regional unconformity surface between the Tertiary and pre-Tertiary age could act as a good seal for hydrocarbons (Ojha, 2012).

3.3.4 Traps

The Ganga Basin exhibits a variety of trap types, including structural, stratigraphic, and combined structural–stratigraphic traps across its extent. In the central Gandak Depression, structural traps are more favorable within the Upper Vindhyan sequence. Within the Gandak Depression, structural traps occur in the northwest, and both structural and stratigraphic traps are identified in the northeast. The Madhubani Depression in the

east hosts stratigraphic traps primarily within the Lower Vindhyan. In the Sarda Depression, structural traps dominate the northern region, while the southern margin features combined structural–stratigraphic traps (Ojha, 2012; Argal et al., 2024).

3.4 Exploratory drilling

Several exploration wells have been drilled in the Indian and Nepalese portions of the Ganga basin. Most of the drilled wells intersecting the Siwalik Group (Upper, Middle, and Lower Siwalik) indicate poor source rock potential. Organically-rich Subathu Formation samples in the form of coal show total organic content levels up to 80%, suggesting the Subathu Formation (and correlative units) may have source rock potential. Ganauli-1 and Shajahanpur-1 wells showed minor combustible gas that flowed from the Karanapur Formation. Similarly, minor gas was reported from the Madhubani Formation in the Madhubani-1 well. Tisua-1 has exhibited good golden yellow fluorescence (GYF) and a moderate cut, with nearly 0.73% total gas during drilling at 2061 m. The well indicated the presence of residual oil at depths of 1593 m (Tilhar) and 2061 m (Bahraich) (Ojha, 2012).

Tilhar-1 well in the Vindhyan sediments of the Ganga basin showed the presence of dissolved gas at a depth of 2000 m from the Tilhar Formation (Prasad and Rao, 2006). Hydrocarbon shows in some of the drilled wells, and gas seeps in different parts of the basin are indications that hydrocarbon generation and migration have taken place. The source rock characteristics of the Proterozoic and the Lower Paleozoic sequences from some of the drilled wells support the petroliferous nature of the basin in geological history. Siliciclastic and carbonate reservoirs have been identified in drilled wells. Moreover, exploratory data generated in drilled wells indicate the presence of thin but organic-rich beds with good to fair hydrocarbon generation potential within the Ujhani Formation.

So far, 26 exploratory wells have been drilled in the Ganga-Punjab Basin, including 20 in the Ganga Basin and 6 in the Punjab Plain. Within the Ganga Basin, 2 wells were drilled in the Madhubani Depression, 5 in the Gandak Depression, and 13 in the Sarda Depression. The status of these drilled wells is provided in Table 3.3.

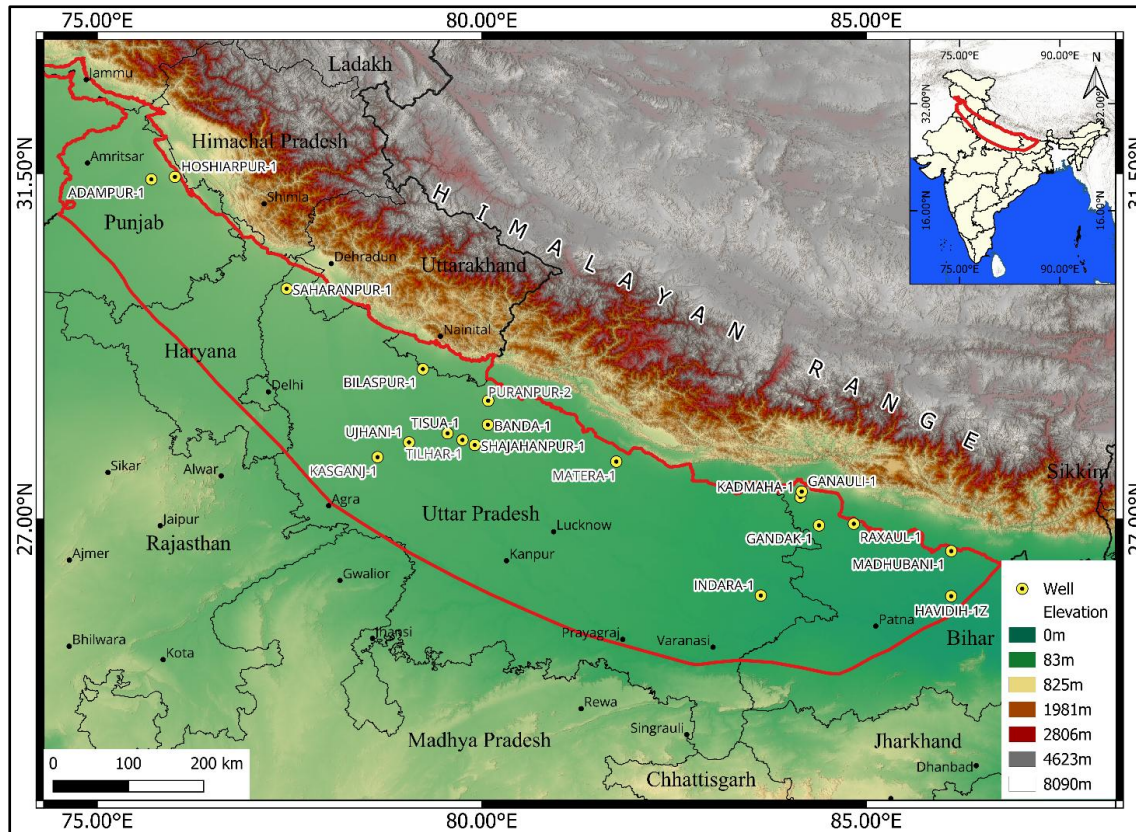


Figure 3.3: Schematic diagram showing the location of exploratory wells in the Ganga-Punjab basin.

Table 3.3: Status of exploratory drilled wells in Ganga-Punjab Basin.

SN	Well	Year	DD/TD (m)	KB (m)	Formation at DD	Results/Remark
PUNJAB PLAIN						
1	Zira-1	1960	742	312.64	Granitic Basement	Dry structural well
2	Adampur-1	1961	2538.6/3000	253.34	Basement Complex (Qtzite associated with mica schist)	Dry & Abandoned
3	Hoshiarpur-1	1960	3439.34	322.88	Lower Siwalik	Dry & Abandoned
4	Saharanpur-1	1990	2362/5500	287.2	Metasediments	Dry & Abandoned
5	Janauri-1	1960-61	4531.4/4500	583.98	Dharmshala?	Dry & Abandoned
6	Mohand-1	1964-65	5264.4/5500	513.01	Janauri Fm./Proterozoic	Dry & Abandoned

SARDA DEPRESSION						
7	Bilaspur-1	1998	4816/4250	208.2	Lower Vindhyan Equivalent sediments	Dry & abandoned
8	Kasganj St-1	1962-63	1250/1200	174.45	Ujhani Fm.	Dry & abandoned
9	Ujhani Deep-1	1961	2127.19/3000	5.69	Ujhani Fm.	Poor Hydrocarbon potential (Dry & abandoned)
10	Ujhani-STR-1	1961	1246/1200	170.17	Ujhani Fm.	Dry & abandoned
11	Ujhani-STR-2	1961	1065.04/1200	169.27	Metasediments; Sarda Fm. (Bahraich Group)	Dry & abandoned
12	Ujhani-STR-3	1961	1005.68/1200	171.6		Dry & abandoned
13	Tisua-1	2007	2819.5/3000	170.34	Ujhani Fm.	Dry & abandoned
14	Puranpur-2	1978-79	4234/6000	186.728	Metasediments; Sarda Fm. (Bahraich Group)	Dry & abandoned
15	Tilhar-1	1963-64	2225.3/3000	157.9	Ujhani Fm.	Dry & abandoned
16	Banda-1	2007-08	3507/3500	173.2	Ujhani Fm.	Dry & abandoned
17	Sahajanpur-1	1991-92	3351.85/3700	167.082	Sarda Fm. (Baharaich Group)	Dry & abandoned
18	Sahajanpur-1 (Dev)	1992-93	MD 2052; TVD 2042.01/2100	167.082	Karnapur Fm.	Dry & abandoned
19	Matera-1	1991	3927/5000	138.548	Metasediments; Sarda Fm. (Baharaich Group)	Dry & abandoned
GANDAK DEPRESSION						
20	Ganuli-1	1988-90	5422/6000	143.6	Tilhar Fm.	Dry & abandoned
21	Kadmah-1	1990-92	5371.95/5600	143.6	Ujhani Fm.	Dry & abandoned
22	Gandak-1	1983-85	5314/6000	89.69	Sarda Fm. (Baharaich Group)	Dry & abandoned
23	Indara-1	2013	1955/3500	80	Dolerite/ Basement	Dry & abandoned
24	Raxaul-1	1963	4901.3/5500	79.16	Pre-Tertiary sediments, (? Fm.)	Dry & abandoned
MADHUBANI DEPRESSION						
25	Madhubani-1	1987	5957/6000	71.5	Diabase	Dry & abandoned
26	Havidih-1z	2009	1700/2500	49.03	Tilhar (Metamorphic signatures are reported)	Dry & abandoned

3.5 Exploration history and hydrocarbon potential

Despite the occurrence of gas seeps along the Himalayan foothills and more than seven decades of hydrocarbon exploration, no commercially producible hydrocarbon accumulations have yet been discovered within the peripheral foreland basin succession of the Ganga–Punjab Basin. Exploration activities to date have resulted in the drilling of

26 exploratory wells across the combined Ganga–Punjab Basin, of which 20 wells are located within the Ganga Basin and the remaining six in the Punjab Plain (Figure 3.3).

Within the Ganga Basin, exploratory drilling has been unevenly distributed among its major structural depressions. Two wells were drilled in the Madhubani Depression, five in the Gandak Depression, and thirteen in the Sarda Depression. Most of these wells penetrated the Upper, Middle, and Lower Siwalik Group sediments, which generally exhibit poor source rock characteristics and limited hydrocarbon generative potential. Consequently, exploration efforts targeting the Siwalik succession have not yielded encouraging results.

In contrast, deeper stratigraphic intervals within the Ganga Valley, particularly the Vindhyan-equivalent Proterozoic to early Paleozoic successions, have been regarded as more prospective (Fuloria, 1996). Among these, the Ujhani Formation of Neoproterozoic to Lower Ordovician age has attracted significant exploration interest. This formation comprises alternating carbonate, shale, and sandstone lithologies and is interpreted to have been deposited in marginal-marine to shallow-marine environments based on mineralogical and sedimentological analyses.

Data from exploratory wells indicate the presence of thin but organic-rich intervals within the Ujhani Formation, exhibiting fair to good hydrocarbon generation potential. Both siliciclastic and carbonate reservoir facies have been encountered in several drilled wells, suggesting the presence of viable reservoir–source rock assemblages at depth.

Geochemical analyses further indicate that the most promising organic-rich source intervals occur within the Sarda Depression, particularly in wells such as Shahjahanpur-1, Banda-1, and Tisua-1. Additionally, the basal portion of the Ujhani Formation in the vicinity of the Tisua-1, Gandak-1, and Madhubani-1 wells, as well as deeper parts of the

basin, are considered attractive targets for future exploration. These observations underscore the need for focused exploration strategies aimed at deeper stratigraphic levels, supported by integrated geophysical and geochemical investigations.

In Tisua-1, the analysis reveals two mature source sequences located between 2715 – 2740 m and 2770 – 2790 m within the Ujhani formation. The shale samples obtained from these intervals indicate a remarkable organic richness with total organic carbon (TOC) ranging from 1.72 to 5.8%. Based on the findings of Tisua-1, it confidently asserts that these intervals have reached the late peak stage of maturity within the oil window, which has about 45 m of fair, mature source rock in the Lower Cambrian to Lower Ordovician Ujhani Formation (Chand et al., 2012).

In the Banda-1, the pyrolysis results indicate a 35 m thick, very good to excellent source rock at 2310 – 2345 m, having excellent hydrocarbon generation potential, and organic richness of TOC is about 2.73% with an early stage of maturation. Shahjahanpur-1 indicates a 3m thin shale layer from the Depth of 1809 to 1812m, which shows good hydrocarbon generation potential. Purnapur-2 at the 2810 – 2815m depth represents 2.11% TOC in the lower Siwalik and Karnapur formations. The Bilaspur-1 well in the Sarda Depression yielded total organic carbon (TOC) values ranging from 1.62% to 2.24%.

However, Indara-1 indicates poor organic richness and source rock with 0.01 – 0.31% TOC throughout the well Depth. Srinivas et al. (2014) observed 1.28 %, 0.28%, and 0.48% TOC in the Ujhani, Tilhar, and Karnapur formations near well Gandak-1. The large stratigraphic thickness and area of the Ujhani Formation, especially in the deeper northern part of the basin, offer the main source of rock potential for generating reasonable volumes of hydrocarbons (Padhy and Das, 2013). According to Ojha (2012),

minor combustible gas flow from the Karnapur formation was observed in wells Ganauli-1 and Shajahanpur-1. Likewise, there were reports of minor gas from the Madhubani formation in the well Madhubani-1. The presence of hydrocarbons in some drilled wells and gas seeps throughout the basin suggests the occurrence of hydrocarbon generation and migration. Analysis of source rock characteristics in the Proterozoic and Lower Palaeozoic sequences in certain drilled wells supports the idea that the basin has a history of petroleum accumulation. The well correlation in the east and west Ganga basin is shown in Figure 3.4A & B.

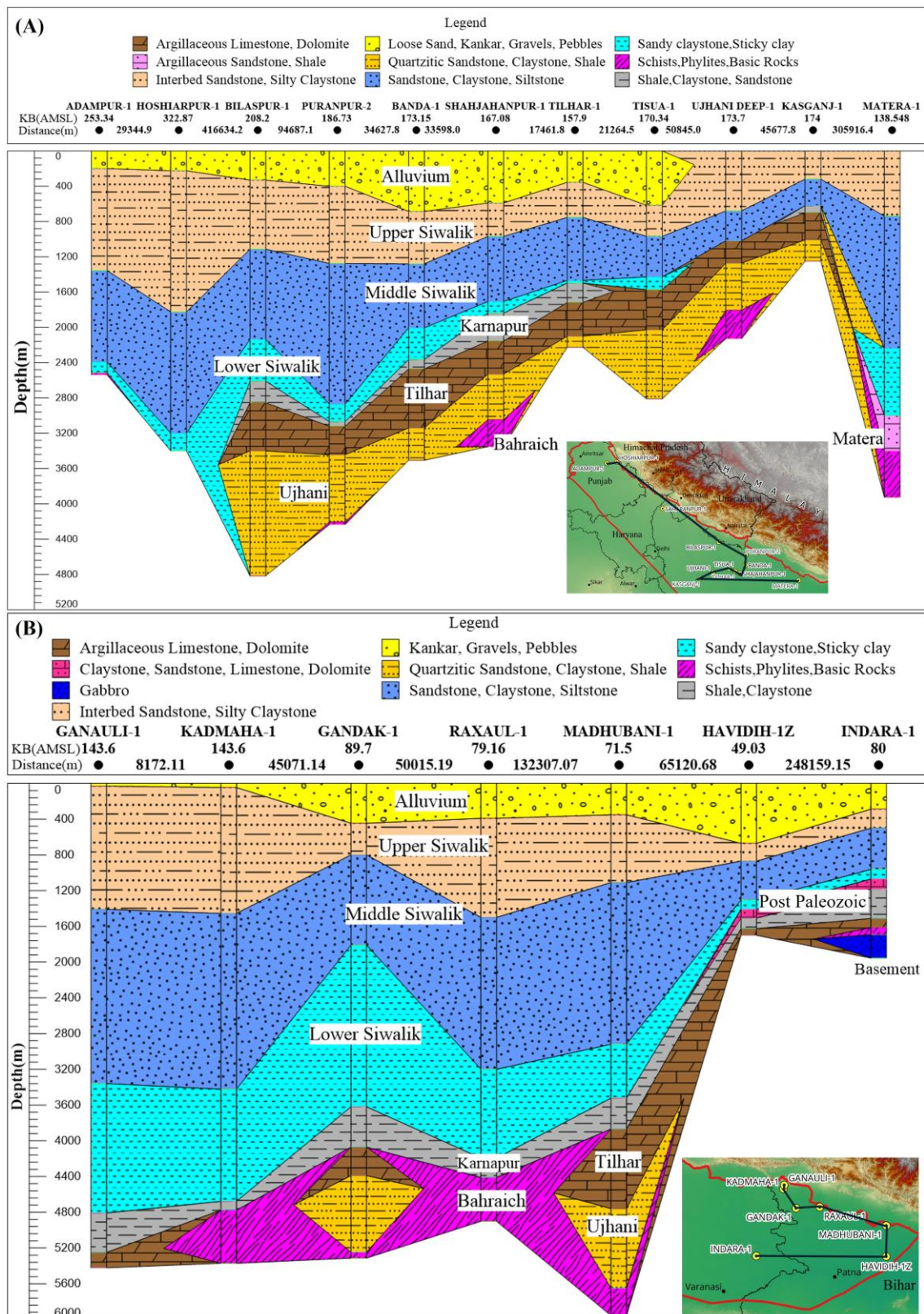


Figure 3.4: The schematic diagram illustrates subsurface lithological well correlations (A) in the East Ganga basin, specifically within the Gandak and Madhubani depressions, and (B) in the West Ganga basin, specifically within the Punjab Plain and Sarda depression. The well depths are measured from the Kelley Bushing (KB), which is positioned above mean sea level (AMSL).

Chapter 4 : Methodology

4.1 Introduction

Seismic data interpretation is essential for basin analysis. It is a process of extracting meaningful geological and geophysical subsurface information from seismic reflection data in the basin. It is a key step in hydrocarbon exploration, reservoir characterization, and geohazard assessment. Over the years, seismic interpretation methods have evolved from basic structural mapping to sophisticated quantitative and attribute-based analyses, incorporating machine learning and rock physics (Chopra and Marfurt, 2012; Bruno, 2023).

The interpretation begins with structural analysis, where seismic horizons and faults are manually or semi-automatically picked to create time-structure or depth maps, aiding in the identification of traps, folds, and fault systems. This is followed by stratigraphic interpretation, which focuses on depositional environments, facies variations, and sequence boundaries. Techniques such as seismic facies analysis, sequence stratigraphy, and reflection termination patterns (e.g., onlaps and truncations) help reconstruct the stratigraphic architecture and sediment depositional history (Nanda, 2021). A more advanced and quantitative method is seismic attribute analysis, which extracts features such as amplitude, phase, frequency, coherence, curvature, and spectral components from the seismic signal (Chopra and Marfurt, 2005; Das et al., 2013; Ghoneimi et al., 2021). These attributes enhance the detection of hydrocarbons, thin beds, and structural discontinuities. Seismic inversion is another key method that transforms seismic reflection data into rock property models, such as acoustic impedance or elastic parameters, offering more direct links to lithology and fluid content (Maurya et al., 2020). Moreover, AVO (Amplitude Versus Offset) analysis interprets how seismic amplitude

varies with offset or angle to distinguish between gas, oil, and brine-filled reservoirs. The spectral decomposition and RGB blending of seismic data can be analysed in the time-frequency domain to detect thin beds and fluvial features (Wang, 2012). Together, these methods form a robust, multi-disciplinary toolkit for understanding the subsurface, reducing exploration risk, and optimizing reservoir development strategies.

4.2 Principles of Seismic Method

Seismic reflection data plays a critical role in the oil and gas industry as it allows detailed imaging and characterization of the subsurface of the Earth, which is key to hydrocarbon exploration and production. The interpretation of seismic data is the process of analysing seismic reflection signals to understand the subsurface geological structure, stratigraphy, and potential hydrocarbon zones. The seismic method relies on the generation and recording of acoustic waves that travel through the Earth, reflect, and refract off subsurface interfaces, and return to the surface (Mussett et al., 2000).

When seismic waves generated by an energy source travel through the Earth and encounter a boundary between two subsurface layers with different physical properties (such as density or seismic velocity), two main phenomena occur: reflection and refraction (Nanda, 2021).

In reflection, part of the seismic wave energy is reflected back toward the surface. This occurs because of the contrast in acoustic impedance (the product of velocity and density) between the two layers. The reflected wave travels back along a path that mirrors the angle at which it arrived, following the law of reflection. The intensity of the reflected wave depends on the magnitude of the contrast between seismic velocities and densities at the boundary (Kearey et al., 2002; Lowrie, 2007).

The remaining energy passes through the boundary but changes direction, a process called refraction. The amount of bending depends on the difference in seismic velocities of the two layers and is governed by Snell's Law. If the seismic wave enters a layer with a higher velocity, it bends away from the normal (an imaginary line perpendicular to the interface); if it enters a slower layer, it bends toward the normal (Figure 4.1).

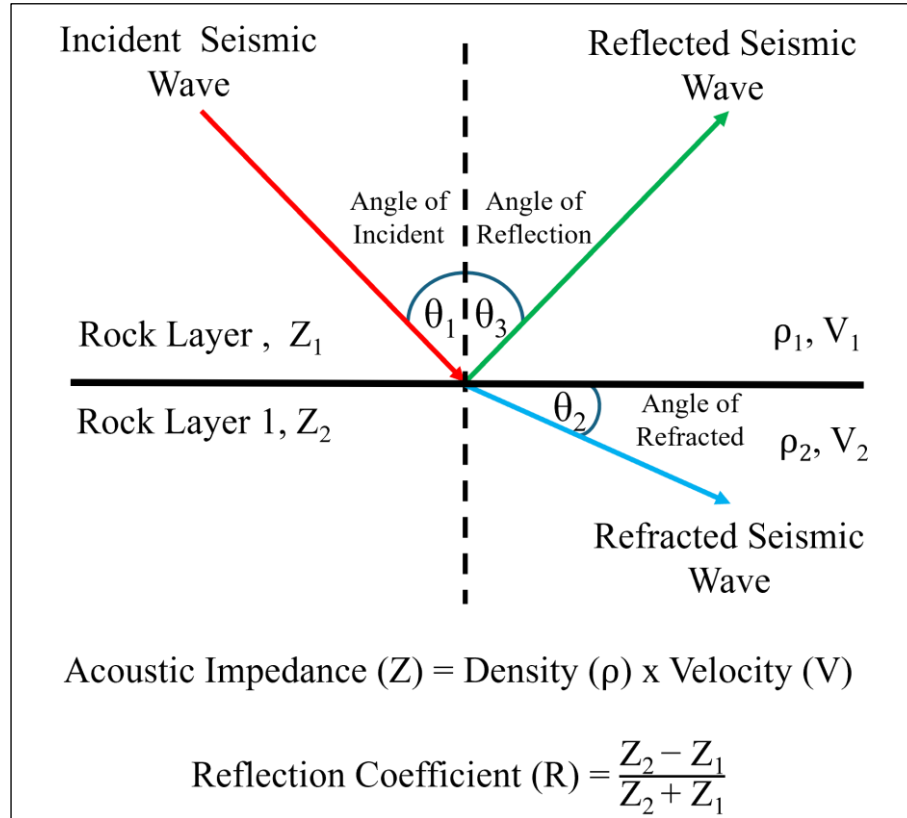


Figure 4.1: A Schematic diagram depicts the basic pathway of a seismic wave that is produced by the source, reflected or refracted at the geological interface, and subsequently recorded by the receiver at the surface. (Kearey et al., 2002; Bjorlykke, 2010; Cox et al., 2020).

The mathematical representation of Snell's law of refraction is as follows.

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{V_1}{V_2} \quad (4.1)$$

where θ_1 and θ_2 are the angles of incidence and refraction, V_1 and V_2 are the velocities of layer 1 and layer 2 (Onajite, 2014).

The product of velocity (V) and density (ρ) is the acoustic impedance $Z = V \rho$ of a medium. The strength of a reflection from an acoustic contrast interface is defined by the reflection coefficient (R)

$$\text{Reflection Coefficient (R)} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (4.2)$$

Where Z_1 = acoustic impedance of the first layer, and Z_2 = acoustic impedance of the second layer.

4.3 Types of seismic waves

Seismic waves are broadly classified as body waves and surface waves, each with unique characteristics and behaviours (Figure 4.2). Body waves propagate in three dimensions through the interior of the Earth and are characterized by higher frequencies and lower amplitudes, whereas surface waves travel along the near-surface of the Earth and typically show lower frequencies but higher amplitudes (Lowrie, 2007) (Figure 4.3 & Figure 4.4).

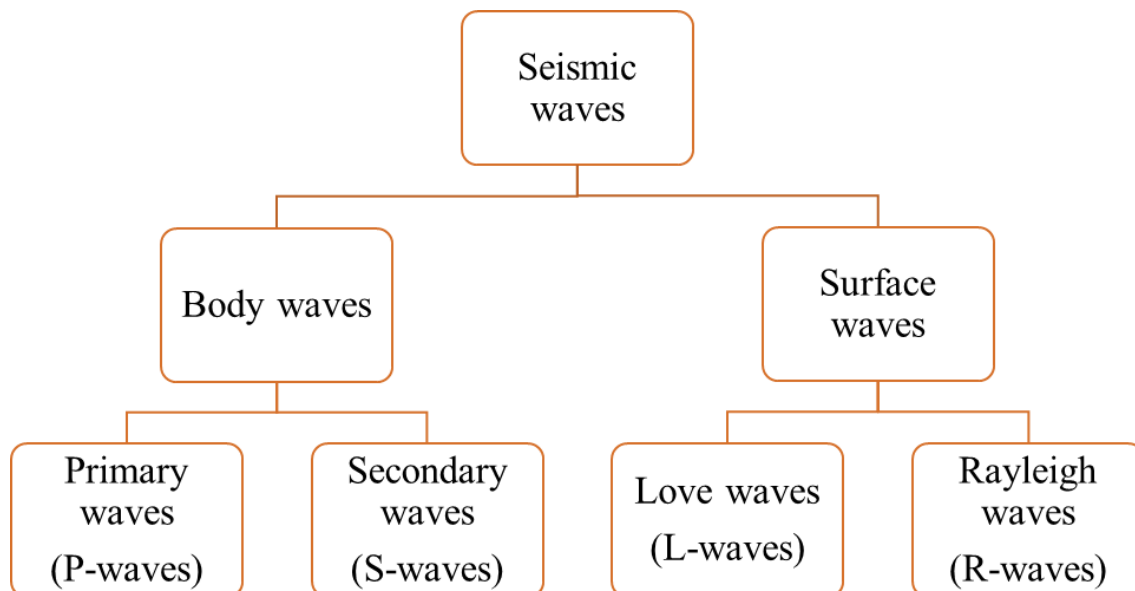


Figure 4.2: Seismic waves classification.

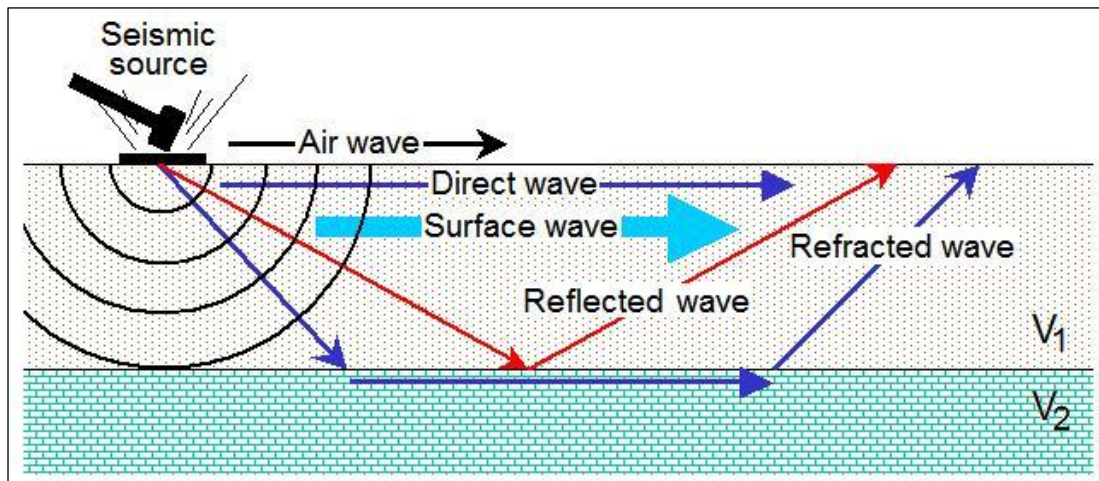


Figure 4.3: This schematic diagram represents types of seismic waves traveling through the subsurface (source: <http://masw.com>).

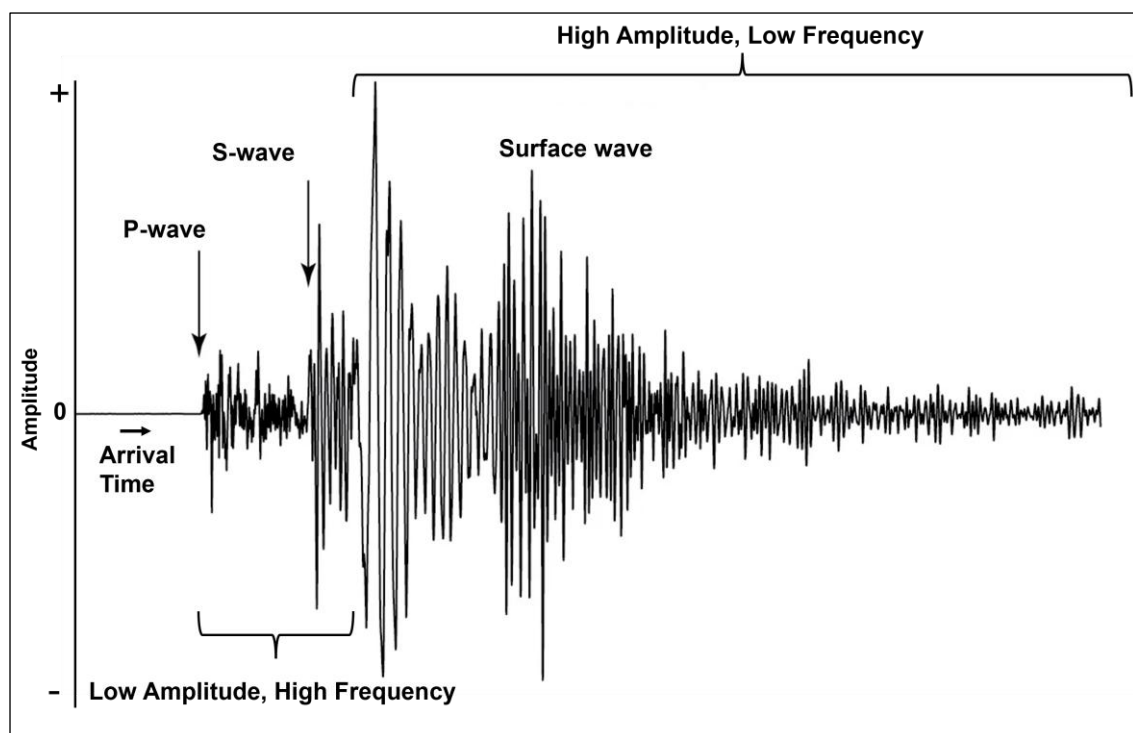


Figure 4.4: The diagram shows the arrival time of body waves (P and S) and surface waves (L and R), recorded by a seismometer. The P-wave is the first signal to arrive, followed by the slower S-wave, then the surface waves (Lowrie, 2007).

Based on particle motion and the direction of wave propagation, body waves are further divided into primary waves (P-waves) and secondary waves (S-waves). P-waves are compressional waves or longitudinal waves in which the particle moves parallel to the direction of propagation. P-waves can travel through solids, liquids, and even gases, and are faster than S-waves. S-waves, also known as transverse waves or shear waves, are characterized by particle motion that is perpendicular to the propagation direction (Figure 4.5). S-waves can only travel through solid media (Kearey et al., 2002; Lowrie, 2007).

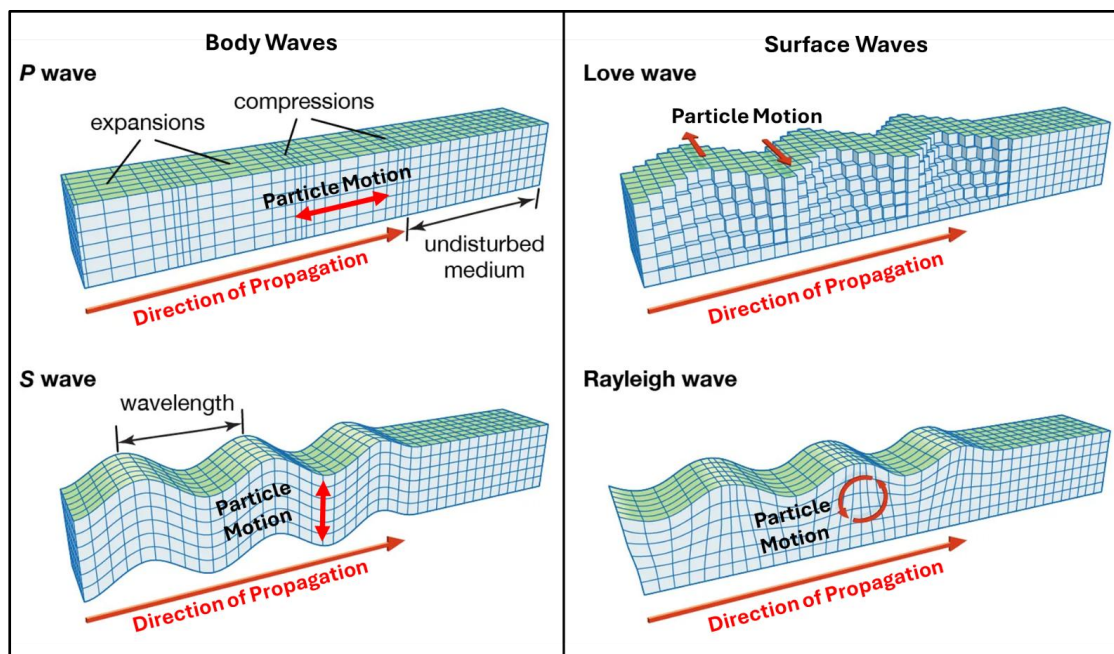


Figure 4.5: The schematic diagram depicts types of seismic waves representing particle motion and the direction of wave propagation (Cox et al., 2020).

Surface waves include Love waves (L) and Rayleigh waves (R). Love waves are created when particles vibrate in a horizontal plane that is perpendicular to the direction of wave propagation, producing intense side-to-side ground movement perpendicular to the propagation direction. They can only propagate through a layered medium, such as a softer sedimentary layer overlying a denser rock, and are generally faster than Rayleigh waves but slower than body waves (P and S waves). Love waves are particularly destructive due to their strong horizontal shear motion. The Rayleigh waves are

characterized by elliptical, retrograde particle motion in the vertical plane, combining both vertical and horizontal displacements (Bjorlykke, 2010; Cox et al., 2020). They can travel through both homogeneous and layered media and propagate slightly slower than Love waves (Figure 4.5).

The velocities of these waves depend on the elastic behavior and density of the underground material, which can be expressed by:

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (4.3)$$

$$V_p = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}} \quad (4.4)$$

where the elastic constant k is the bulk modulus and μ is the shear modulus, and ρ is the density of the material through which these waves propagate, V_p and V_s are the velocities of the primary and secondary waves, respectively. The applications of these waves are represented in Table 4.1.

Table 4.1: Seismic waves and their primary use.

Wave Type		Nature	Velocity	Primary Use
Direct		Travels directly through the uppermost layer	Low	Near-surface velocity estimation
Body Wave (P & S)	Reflected	Bounces off subsurface interfaces	Medium – High	Subsurface imaging in petroleum and geotech
	Refracted	Bends along high-velocity layers	High	Depth to bedrock, seismic velocity profiling
Surface Wave (Rayleigh & Love)		Travels along the surface	Slow	Soil profiling, shear-wave velocity estimation

4.4 Seismic Data Acquisition

Seismic data Acquisition begins with a seismic source, which is an energy-generating device such as a dynamite blast, air gun (in marine surveys), or a vibroseis, explosives, thumper, sledgehammer, etc. (in land surveys). This source sends acoustic waves into the ground, which propagate through different rock layers at varying speeds depending on their elastic properties (Aminzadeh and Dasgupta, 2013).

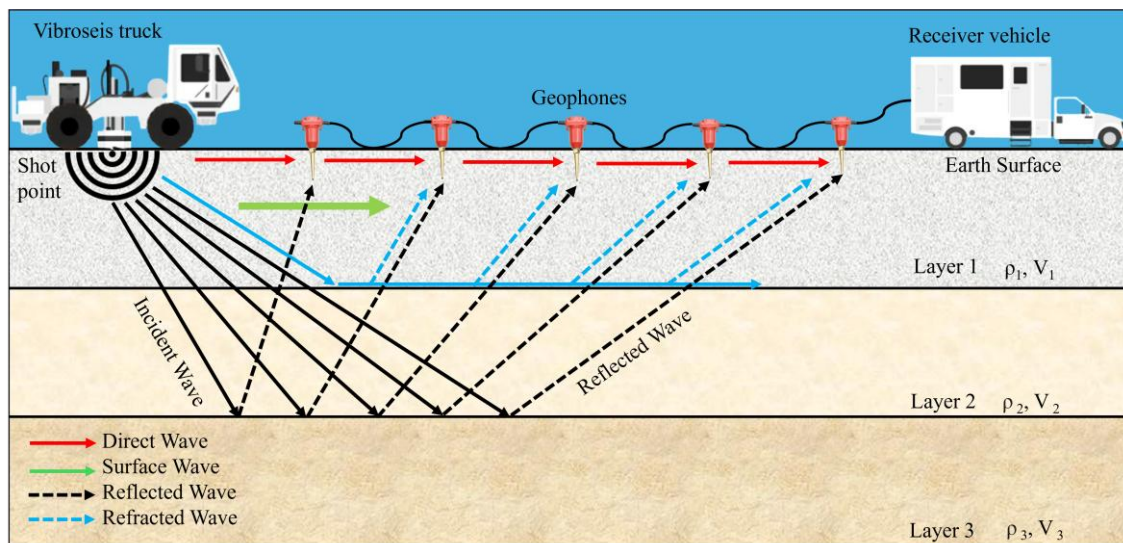


Figure 4.6: The schematic diagram represents land seismic data acquisition (Aminzadeh and Dasgupta, 2013).

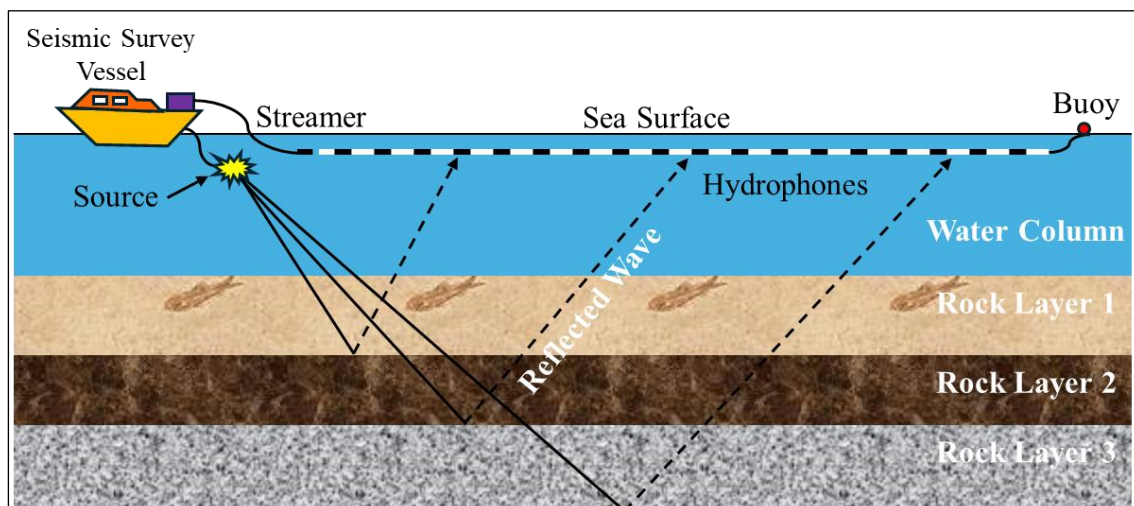


Figure 4.7: Schematic diagram of marine acquisition of seismic reflection data (Bacon et al., 2003; Onajite, 2014; Cox et al., 2020).

When these waves encounter interfaces between layers with contrasting acoustic impedances, part of the energy is reflected or refracted back toward the surface as they encounter changes in the geological layering of the Earth (Figure 4.6 & Figure 4.7) (Cox et al., 2020). At the surface, this reflected/refracted energy is captured by seismic receivers, also known as geophones (on land) or hydrophones (in water), which convert ground motion into electrical signals (Figure 4.8) (Yilmaz, 2001; Onajite, 2014). These signals are then digitized, processed, and interpreted. Accurate interpretation requires understanding the relationship between the source and receiver positions, the travel paths of the seismic waves, and the time it takes for reflections to return. By mapping the travel times and amplitudes of these reflections, geophysicists can infer subsurface features such as faults, folds, reservoir traps, and fluid contacts. The geometry of the source-receiver layout, whether in 2D or 3D configurations, greatly influences the resolution and reliability of the final seismic image.

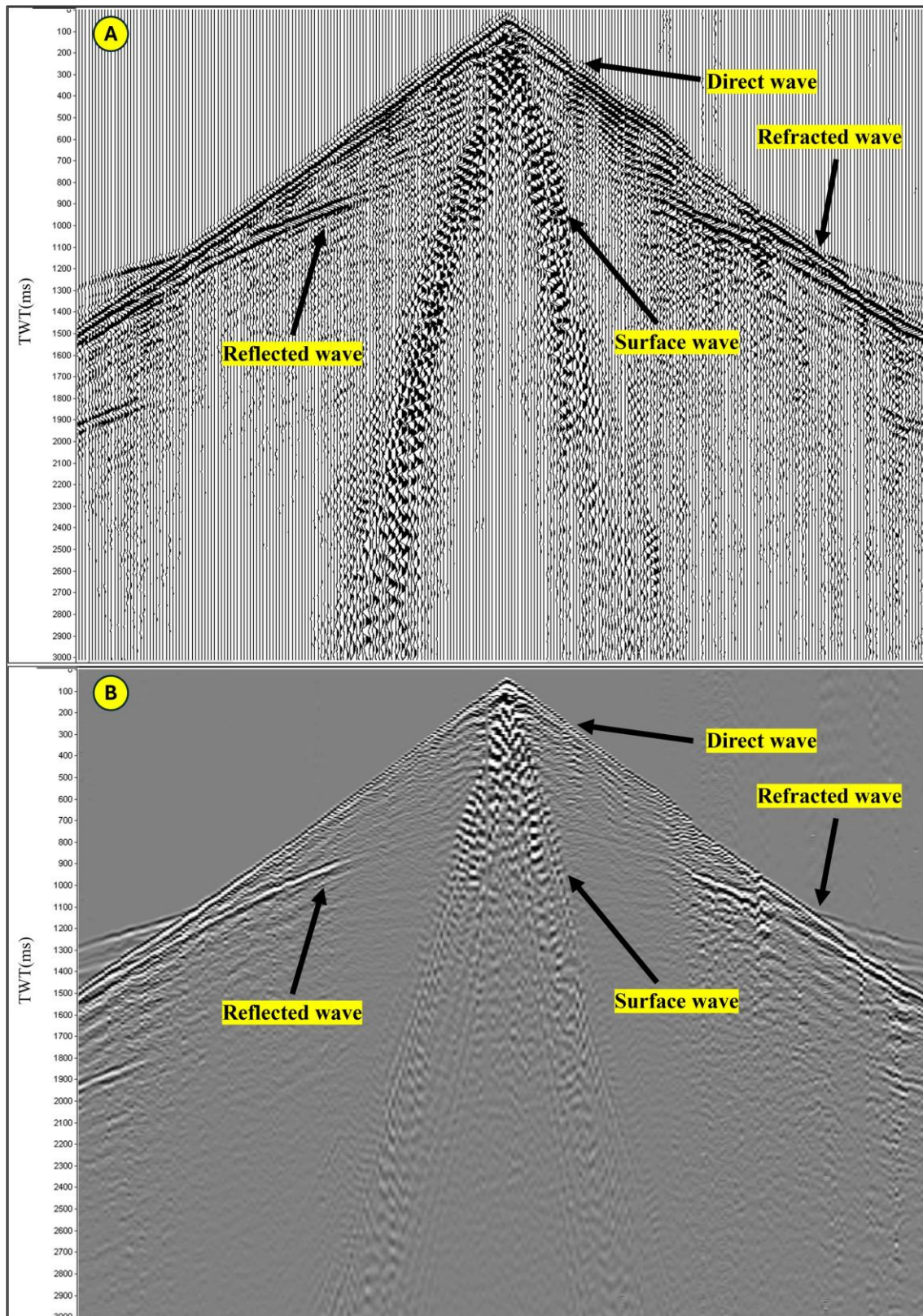


Figure 4.8: A seismic shot gather acquired in split spread geometry set-up represented in (A) wiggle trace, (B) Grey scale showing recorded direct wave, refracted wave, and reflected wave. Notably, direct, refracted, and reflected waves show higher frequencies and lower amplitudes. Whereas surface waves typically show lower frequencies but higher amplitudes.

4.4.1 Seismic Energy Sources

Seismic energy sources are essential components in geophysical exploration, as they generate the acoustic or elastic waves that propagate through subsurface layers. These waves reflect, refract, or diffract at subsurface geological boundaries and back to the surface, and are recorded by receivers (geophones or hydrophones) (Bjorlykke, 2010). The received data are processed in order to generate images of subsurface structures. Selection of an energy source depends on a variety of conditions, including survey type (marine or land), depth of investigation, resolution, environmental issues, and logistically feasible arrangements (Table 4.2).

Table 4.2: Seismic energy sources and their applications.

Energy Source	Typical Use	Environment
Explosives	Deep, high-energy surveys	Land
Vibroseis	Deep, high-energy, Controlled, repeatable surveys	Land
Sledgehammer	Shallow/near-surface	Land
Weight drop	Shallow/near-surface, repeatable	Land
Air Gun	Marine surveys	Water
Boomer/Sparker	Shallow water surveys	Water
EMP Source	Specialized applications	Land/Water

Some of the most popular energy sources in seismics are as follows:

4.4.1.1 Land-Based (onshore) Seismic Energy Sources

The most well-known on-land sources of seismic energy are dynamite, vibroseis, and the weight drop system (Figure 4.9).

Explosives (Dynamite)

Explosive or dynamite sources involve the use of small explosions (0.25–10 kg in size) in shallow boreholes (5–30 m deep). The small explosions, on detonation, produce a broad-band, high-energy acoustic wave, which allows deep penetration and is, therefore,

most effective in hard rock conditions and deep reflection work. The limiting aspect in the case of dynamite is the environmental and safety concerns, strict regulatory restrictions, and limited repeatability (Ziolkowski, 2021).

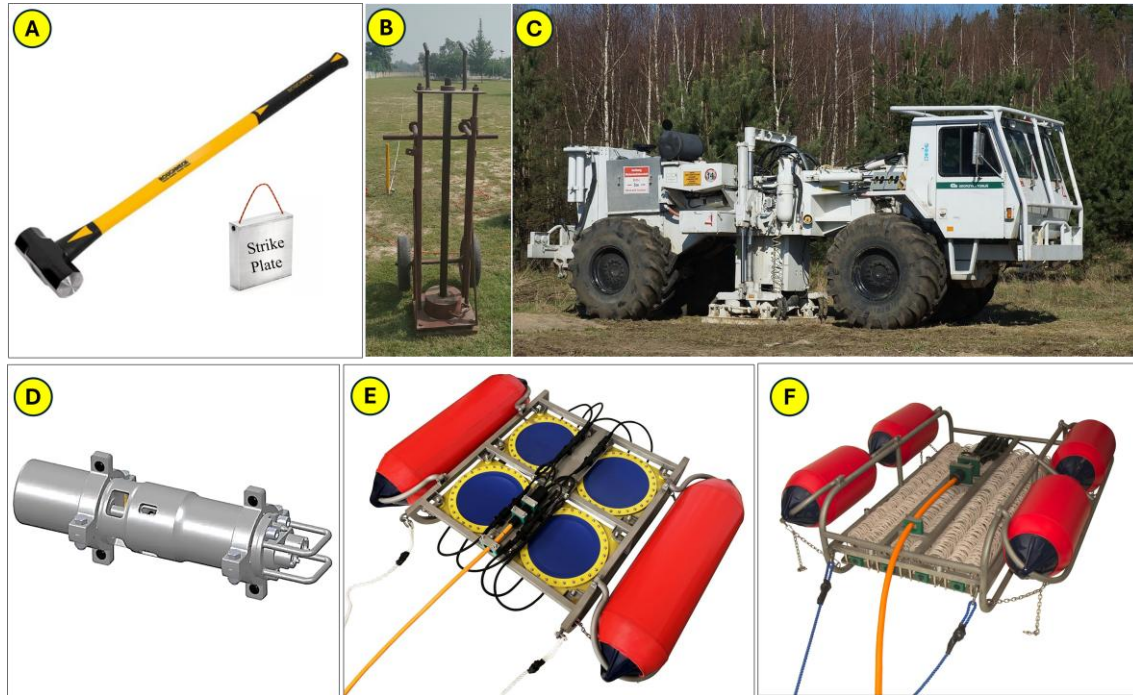


Figure 4.9: Land seismic energy sources: (A) Sledgehammer, (B) Weight drop, (C) Vibroseis; and Marine seismic sources: (D) Air gun, (E) Boomer, and (F) Sparker (Source: <https://geodevice.co>, <https://pixabay.com>)

Seismic Vibrators (Vibroseis)

Vibroseis systems, on the other hand, use truck-mounted vibrators to transmit controlled frequency sweeps (typically 10–120 Hz) through the ground using a baseplate. These are extensively used in oil and gas exploration for 2D and 3D surveys. Vibroseis is environmentally safer, enables signal stacking, and offers high repeatability, especially for 4D or time-lapse surveys. Vibroseis is common in land surveys, especially where repeated, controlled signals are needed. Their efficiency, however, is in areas with hills or areas having poor ground coupling, and they produce lower low-frequency energy compared to explosives (Bjorlykke, 2010).

Sledgehammer

The weight drop or hammer source is a less complex technique in which a heavy weight or sledgehammer hits a steel plate on the ground (Keiswetter and Steeples, 1995). This technique is generally applied in near-surface work and geotechnical exploration because it is transportable and cheap, but it has low energy and shallowness in penetration, so its use is restricted to subsurface imaging deeper than the above techniques.

Weight Drop

The weight fall seismic source is a weight falling from a height on a base plate in an effort to generate seismic waves during subsurface exploration. The impact delivers the momentum on the ground, producing seismic pulses, which are transmitted through the ground. Various mechanisms, like hydraulic systems or springs, are used to accelerate the weight drop, enhancing the energy and sharpness of the seismic waves (Yordkayhun and Na Suwan, 2012; Aas and Sinha, 2023b).

4.4.1.2 Marine-Based (offshore) Seismic Energy Sources

The most significant seismic sources in marine environments are air guns, water guns, and the boomer/sparker systems (Figure 4.9).

Air Guns

Air guns are most prevalent in marine seismic surveys, which inject compressed air (up to 2000 psi) into the water, creating a rapidly expanding bubble, producing seismic waves (acoustic pulse). They are most effective in deep subsurface imaging and are most in use in offshore oil and gas exploration. Air guns are placed in arrays so as to achieve stronger and cleaner signals, but are hazardous to the environment, especially with regard to marine biota, and are complicated in use with boats and streamers (Dondurur, 2018).

Water guns

The water guns operate similarly but utilize high-pressure water to deliver shock waves, suppressing oscillation in bubbles and generating cleaner pulses in and for shallower, higher-resolution seismic surveys. They offer, however, lower energy and shallower depth penetration compared with air guns (Hutchinson and Detrick, 1984).

Boomers and Sparkers

Boomers and sparkers are high-definition sources used in shallow marine surveying. Boomers use electromagnetic induction in generating a pulse off a steel plate, and sparkers emit electric sparks between electrodes, burning through water and creating a shock wave (Rabbal and Wilken, 2021). These are transportable systems, ideally suited for use on small vessels, and these systems obtain very good resolution in the instance of lakebed and shallow stratigraphic studies, but they are not suitable for deep exploration due to limited penetration (typically tens to hundreds of meters) (Veeken, 2013).

Alternative /Emerging Seismic Sources

Besides classical approaches, novel and specific seismic energy sources are now attracting attention.

Hydraulic impulse sources

Hydraulic impulse generators generate seismic waves through pressurized hydraulic systems that can generate instantaneous blows or pressure pulses. They are a less hazardous alternative to explosives, generating reproducible signals with a smaller environmental impact, though they are still limited in energy output and are less commonly used.

Electromagnetic Pulse (EMP) Sources

Electromagnetic (EM) seismic sources, which convert electromagnetic energy into mechanical vibrations. While non-invasive and potentially useful in controlled or borehole environments, EM sources are still in the experimental stage and currently offer limited power and field deployment capabilities.

4.4.1.3 Seismic Energy Receivers

Seismic receivers are critical components in geophysical surveys, as they detect and record the seismic waves generated by energy sources, following the waves having been transmitted through and reflected by subsurface rock strata. The primary types of seismic receivers include geophones, hydrophones, and more advanced multicomponent sensors (Figure 4.10), all developed in response to various environments and data requirements (Bjorlykke, 2010).

Geophones

On land, the most commonly used receivers are geophones, which convert ground motion into electrical signals. Geophones typically consist of a spring-mounted magnetic coil inside a casing. When seismic waves pass through the ground, the coil moves relative to the magnet, generating a voltage proportional to the velocity of ground motion. These devices are usually designed to detect vertical motion, but three-component (3C) geophones are also used to record motion in vertical and two horizontal directions, providing more comprehensive wavefield information for advanced seismic processing and interpretation. Geophones are lightweight, cost-effective, and offer high sensitivity and fidelity for land-based surveys (Onajite, 2014).



Figure 4.10: Land and Marine seismic energy receivers: (A) Geophone (B) 3C Geophone (C) Hydrophone (D) Multicomponent Geophone or ocean-bottom nodes (OBNs) (Bjorlykke, 2010).

Hydrophones

Hydrophones are used instead of geophones in marine settings. Hydrophones detect changes in water-column pressure caused by seismic waves. These are typically used in streamer cables towed by survey vessels during offshore seismic surveys. Hydrophones are sensitive to compressional (P) waves and are essential for high-resolution subsurface imaging in marine settings. They provide excellent coupling with the water medium, and thus, acoustic signals are well captured on record (Onajite, 2014).

Multicomponent sensors

More advanced surveys make use of multicomponent sensors or ocean-bottom nodes (OBNs), especially in challenging geological areas or time-lapse (4D) monitoring. These tools integrate geophones and hydrophones or are made up of accelerometers and particle velocity sensors, both picking up pressure and particle movement, and providing better imaging of subsurface structures. OBNs are laid down on the seafloor itself and are useful in areas that are unsuitable for streamer surveys, e.g., in shallower waters or near infrastructure (Chu and Yu, 2022).

4.5 Processing of Seismic Data

Seismic reflection data processing involves a series of systematic operations aimed at enhancing the quality of the seismic signals actually observed and represent the subsurface geological characteristics accurately. Data acquisition comes first in the process, followed by preprocessing, whereby format conversions, trace editing, and geometry assignment are performed in order to give descriptions on the source-receiver positions. Next, amplitude correction (e.g., spherical divergence correction) compensates for energy loss due to wavefront expansion (Dondurur, 2018). Deconvolution is then applied to compress the seismic wavelet, improve temporal resolution, and eliminate reverberations. Velocity analysis follows, which is critical for converting time-domain data into depth and for stacking traces; this step involves picking seismic velocities from semblance plots (Kearey et al., 2002). Following the determination of the velocities, normal moveout correction compensates time delays arising from different source-receiver spacings, followed by stacking, whereby a multiplicity of traces are combined, ideally increasing the signal-to-noise ratio (Aminzadeh and Dasgupta, 2013). After stacking, migration is performed to reposition dipping reflectors to their true subsurface locations, providing an accurate structural image. Additional steps, namely filtering,

multiple attenuation, and spectral balancing, are occasionally performed in intermediate to further improve data quality (Veeken, 2013). The final product is a data-processed seismic section ready for interpretation. All the above procedures deal with noise reduction, increase in continuity of the reflectors, and ensuring that the final seismic image accurately represents the subsurface geology (Yilmaz, 2001; Kearey et al., 2002; Cox et al., 2020). The simplified flowchart of seismic data processing is discussed below (Figure 4.11)

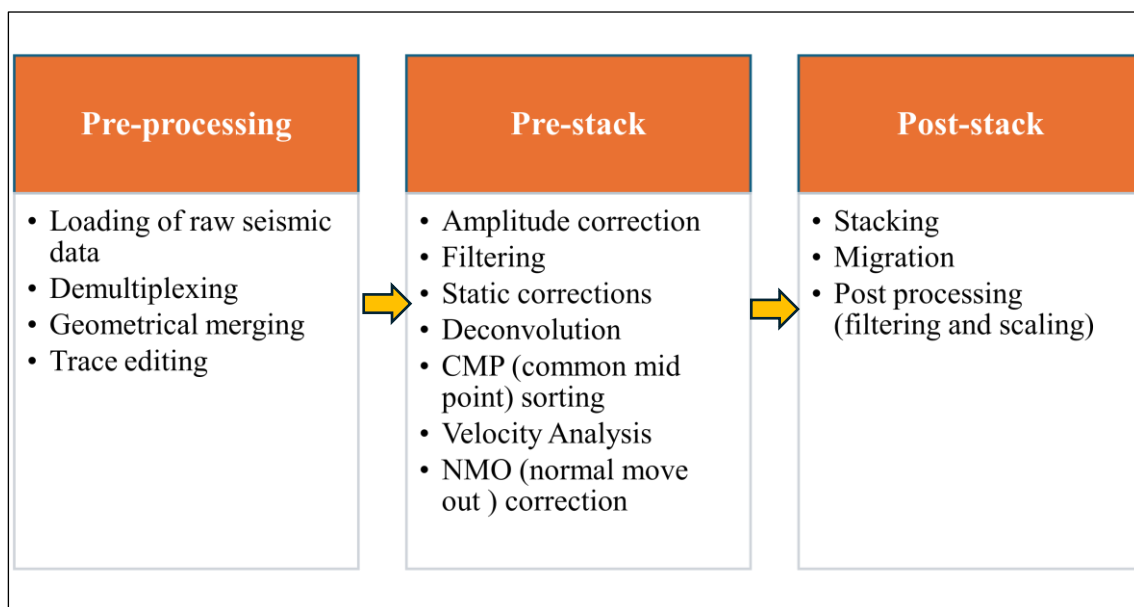


Figure 4.11: A general flow chart of seismic data processing.

4.6 Polarity of Seismic Reflection Data

Seismic data polarity refers to the sign of the reflected seismic wave signal, indicating whether a reflection represents an increase or a decrease in acoustic impedance (Z). A positive acoustic impedance ($RC+$) is caused by an increase in the acoustic impedance as the seismic wave travels from a low velocity and density material to a high velocity and density material (e.g., Shale to Limestone). Whereas, negative acoustic impedance ($RC-$) is caused by a decrease in the acoustic impedance as the seismic wave travels from

a high velocity and density material to a low velocity and density material (e.g., Limestone to Shale) (Figure 4.12) (Xu and Haq, 2022).

In the Society of Exploration Geophysicists (SEG) standard convention, a positive reflection indicates an increase in acoustic impedance and is represented as a peak. A negative reflection indicates a decrease in acoustic impedance and is represented as a trough (Figure 4.12) (Nanda, 2021).

The European (or Australian) polarity convention is the reverse of the SEG standard. A positive reflection indicates a decrease in acoustic impedance represented as a trough. A negative reflection indicates an increase in acoustic impedance represented as a peak (Figure 4.12) (Cox et al., 2020). The seismic sections presented in this thesis adhere to the standard convention set by the SEG.

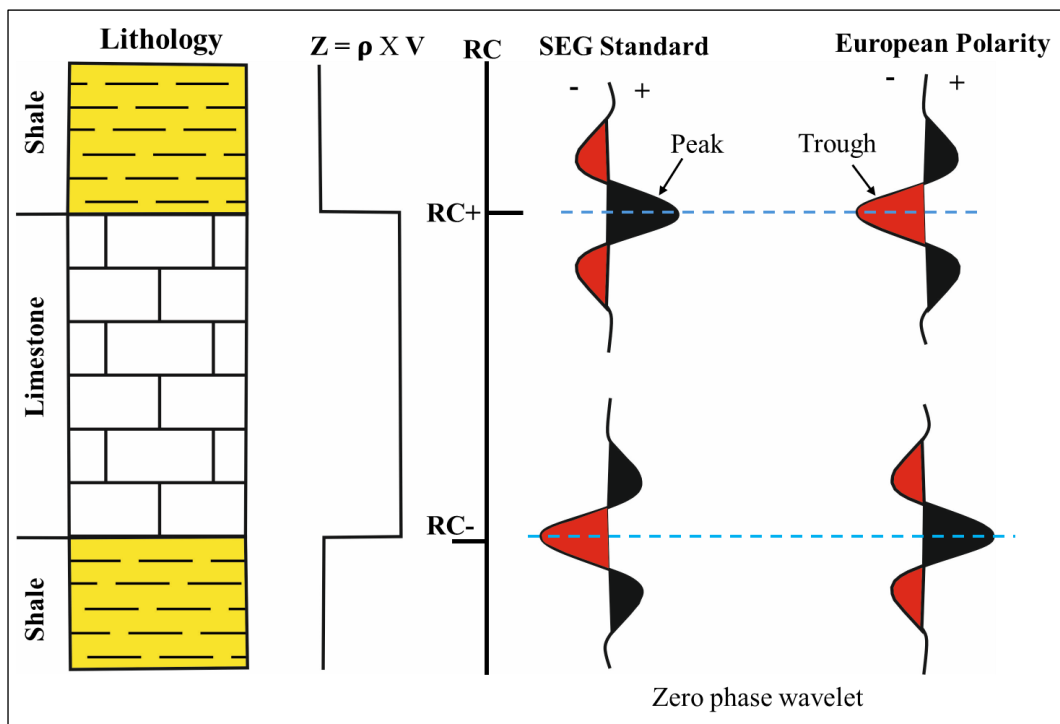


Figure 4.12: Schematic diagram depicting reflection coefficient and its polarity convention with seismic trace in SEG standard and in European polarity, after Xu and Haq (2022).

4.7 Seismic Reflection Data Interpretation

4.7.1 Sequence Stratigraphy

Sequence stratigraphy is a geologic tool used to interpret and predict the distribution of sedimentary facies in time and space by examining the stratigraphic record within a framework of relative sea-level changes. Sequence stratigraphic interpretation provides a process-based framework for identifying unconformities, depositional sequences, and systems tracts. This approach was adopted because it permits the integration of seismic reflection patterns with lithological and well-log information, thereby improving the reconstruction of basin evolution and depositional history. It involves subdividing sedimentary successions into genetically related units called sequences, which are bounded by unconformities or their correlative conformities surfaces (Catuneanu, 2022). These sequences represent cycles of deposition linked to changes in accommodation space created by sea-level fluctuations, tectonics, and sediment supply (Figure 4.13) (Emery and Myers, 1996). A typical sequence consists of systems tracts such as the lowstand, transgressive, and highstand systems tracts, each with characteristic depositional environments and stacking patterns. The key surfaces identified in sequence stratigraphy include sequence boundaries, maximum flooding surfaces, and transgressive surfaces, which serve as markers for basin evolution and sedimentary processes.

In hydrocarbon exploration, sequence stratigraphy is an important tool as it provides a predictive model that helps us in a comprehensive understanding of the distribution and connectivity of reservoirs (Aitken and Flint, 1995; Jinsong et al., 2009; Zecchin and Catuneanu, 2015; Abiola et al., 2018). The application of sequence stratigraphic techniques in various sedimentary basins worldwide has resulted in the recovery and discovery of additional hydrocarbon reserves (Nwaezeapu et al., 2018). Geoscientists can improve the selection of drilling targets by identifying significant stratigraphic surfaces

and depositional settings that are likely to be reservoirs. The sequence stratigraphic analysis involves recognizing and interpreting various stratigraphic elements, such as boundaries, systems tracts, sedimentary packages, and depth of subsurface strata (Catuneanu et al., 2011; Gómez et al., 2023). Key sequence stratigraphic surfaces, including sequence boundaries (SB), transgressive surfaces (TS), and maximum flooding surfaces (MFS), are delineated to establish the stratigraphic framework and deposits (Dalrymple and Choi, 2007; Lan et al., 2016; Ghosh et al., 2021).

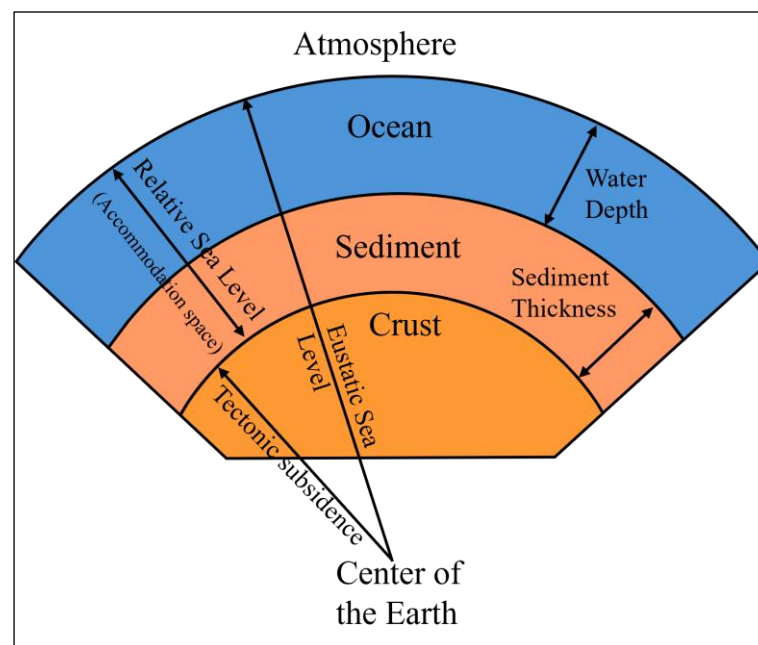


Figure 4.13: Schematic cross-section of Earth, showing definitions of important terms in sequence stratigraphy (Emery and Myers, 1996; Abiola et al., 2018).

4.7.1.1 Types of stacking patterns

There are three distinct stacking patterns (progradation, aggradation, and retrogradation) that relate directly to the sediment supply, accommodation, and relative sea-level changes (Table 4.3) (Emery and Myers, 1996). These three stacking patterns are fundamental to interpreting stratigraphic sequences and understanding the spatial and temporal evolution of sedimentary basins.

Progradation – Progradation is the seaward movement of depositional sediment sequences, generally in response to excess sediment supply over accommodation space available. This leads to the outward development of sedimentary facies, e.g., deltas or shorelines, and typically involves coarsening-upward successions. It frequently happens that relative sea levels are stable or rising slowly and are linked to regressive phases of a depositional system, e.g., during highstand systems tract (Figure 4.14) (Van Wagoner et al., 1988).

Aggradation- aggradation involves the vertical stacking of sediments with minimal lateral movement, indicating that sediment supply and accommodation space are roughly balanced. This process preserves the existing depositional environment through time and is common in settings with stable or slowly rising sea levels (Figure 4.14) (Emery and Myers, 1996).

Retrogradation- Retrogradation, on the other hand, happens when accommodation space increases faster than sediment can fill it, usually due to a rapid sea-level rise. This leads to a landward shift of depositional environments and results in fining-upward sequences, as deeper marine sediments overlie shallower facies. Retrogradation is typically associated with the transgressive systems tract (Figure 4.14) (Van Wagoner et al., 1988).

Table 4.3: Vertical stacking of parasequence sets and their interpretation.

Process	Sea-Level Trend	Sediment vs. Accommodation	Facies Shift	Typical Sequence
Progradation	Stillstand or Fall	Sediment supply > Accommodation space	Seaward	Coarsening upward
Aggradation	Stable or Slow Rise	Sediment supply $\approx$ Accommodation space	Stagnant	Uniform stacking
Retrogradation	Sea-Level Rise	Sediment < Accommodation space	Landward	Fining upward

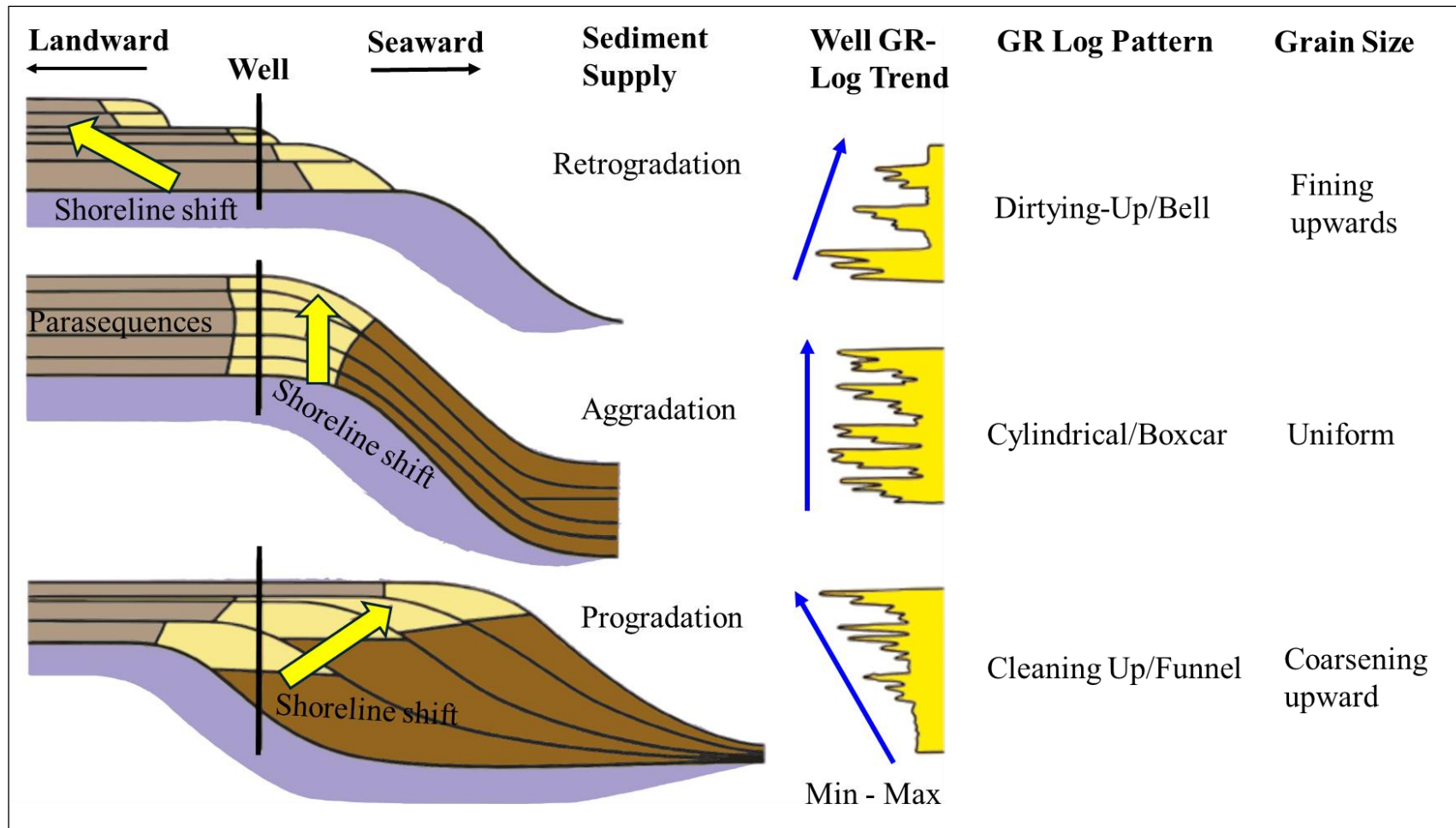


Figure 4.14: Vertical stacking of parasequence sets, with corresponding grain size distribution and gamma ray (GR) log patterns (Van Wagoner et al., 1988; Emery and Myers, 1996).

4.7.1.2 Types of stratal terminations

In seismic reflection data, sequence stratigraphy is interpreted by identifying key reflection terminations such as truncation, toplap, onlap, downlap, and offlap. These terminations reflect different depositional and erosional processes that define the architecture of sedimentary sequences. Truncation occurs where strata are cut off by an overlying erosional surface, indicating a break in deposition and possible removal of previously deposited material. Toplap refers to the termination of inclined strata, or clinoforms, against an overlying surface with a gentler dip, typically suggesting nondeposition or minimal erosion at the top of prograding units. Onlap is identified when low-angle strata terminate against a steeper underlying surface, often marking the landward migration of deposition during a transgression (Emery and Myers, 1996). Conversely, downlap is where inclined strata terminate against a lower-angle surface, usually representing a shift from active slope deposition to an area of sediment starvation or nondeposition, commonly found in marine or lacustrine settings (Van Wagoner et al., 1988). Offlap, on the other hand, involves the progressive seaward shift of updip terminations of sedimentary units within a conformable sequence. This pattern exposes parts of older units and indicates a fall in relative sea level, making offlap a key indicator of forced regression (Figure 4.15).

4.7.1.3 Types of System Tracts

There are significant, four main sequence system tracts or events that are recognised, including the Falling-Stage Systems Tract (FSST), Lowstand Systems Tracts (LST), Transgressive Systems Tract (TST), and Highstand Systems Tracts (HST), which are separated by stratigraphic surfaces or sequence boundaries (unconformities). These systems tracts are categorized based on their place of deposition patterns (landward or

seaward) with reference to the change in sea level, accommodation space, and sediment supply (Figure 4.16).

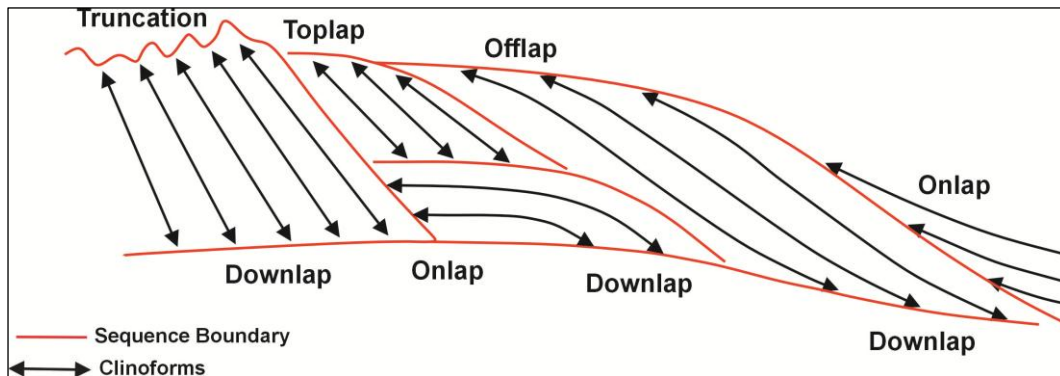


Figure 4.15: Types of stratal terminations (Emery and Myers, 1996; Catuneanu, 2022).

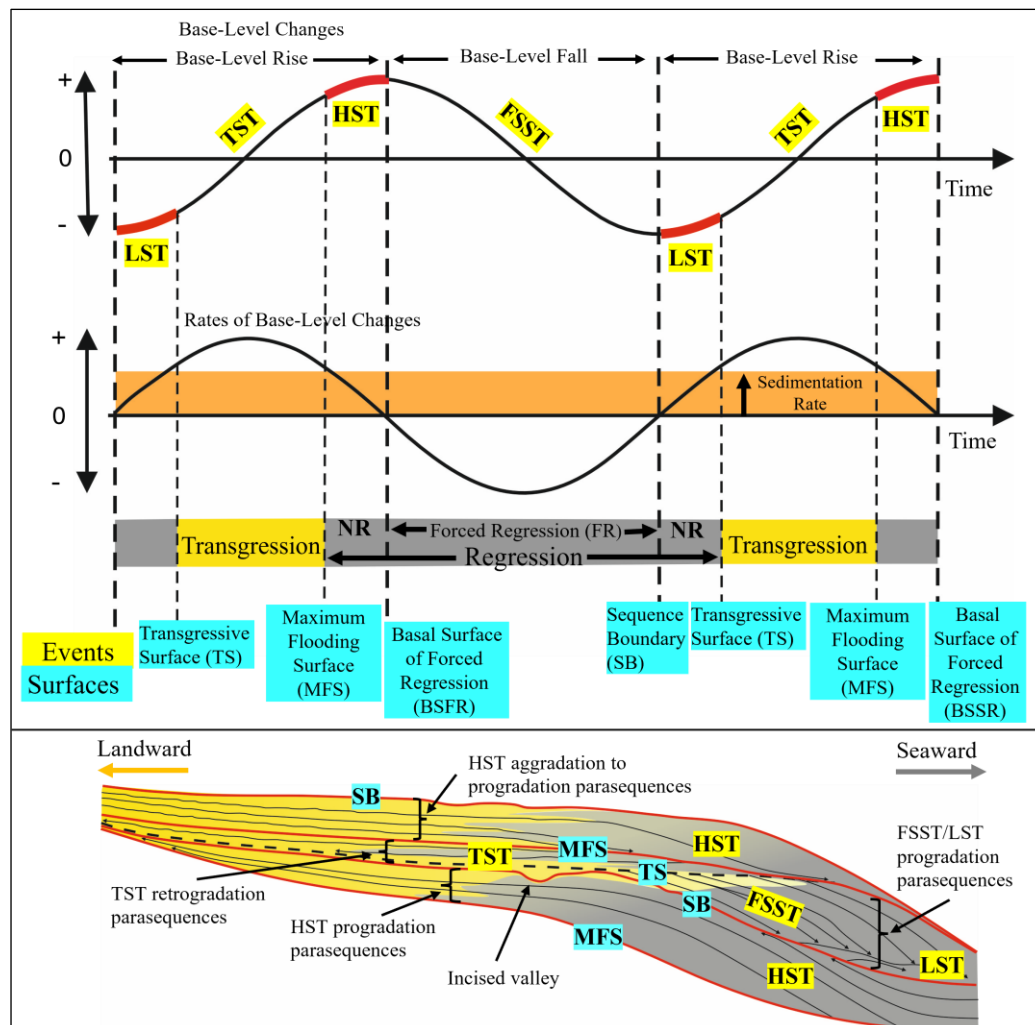


Figure 4.16: The schematic diagram represents system tract events and sequence stratigraphic surfaces developed in response to changes in base-level (sea-level) with time; after (Catuneanu et al., 2011; Catuneanu, 2022; Abdalla et al., 2023).

The falling-stage systems tract (FSST) and lowstand systems tracts (LST), which represent periods of seaward progradation of sediment accumulation characterized by the deposition of sediments when sea level (base level) is at its falling or its lowest stage. As sea level falls, erosion and redeposition of sediments occur, often forming incised valleys filled with coarser material. During this phase, the basin is filled with sediments eroded from uplifted areas and transported by fluvial systems. The transgressive systems tract (TST) represents the period of rising sea levels following a low stand. As the sea level rises, finer sediments are deposited towards landward over the coarser lowstand deposits, often forming a retrogradational stacking pattern. Highstand systems tracts (HST) indicate relative sea-level periods at high stability and aggradation. The highstand systems tract (HST) is marked by a progradational stacking pattern as sediment supply keeps pace with or exceeds the rate of sea-level rise, leading to the build-out of deltas and other shoreline features (Figure 4.16) (Paul Wright and Marriott, 1993; Krapez, 1996; Karisiddaiah et al., 2002; Catuneanu et al., 2012). Sequence stratigraphic analysis with integration of well data, including lithological logs and biostratigraphic information, helps constrain the interpretations and validate the sequence stratigraphic correlations (Isyaku et al., 2016).

4.7.2 Seismic Facies Analysis

Seismic facies analysis enables depositional environments to be inferred from reflector geometry, amplitude, continuity, and frequency characteristics. However, seismic facies alone cannot uniquely determine lithology and therefore require calibration with well-log data and regional geological information (Xu and Haq, 2022; La Marca and Bedle, 2022). It is also possible to utilize the geometry of seismic reflections to understand the stratigraphy, post-depositional deformation form, burial history, depositional units, topography, and reliefs of unconformities (Al-Masgari et al., 2021).

The essential elements that constitute components of the seismic facies and depositional setting are their configuration, reflector geometries, lateral continuity, amplitude, frequency etc. (La Marca-Molina et al., 2019; Wolpert et al., 2022; Winata et al., 2023; Jiang et al., 2024) (Figure 4.17).

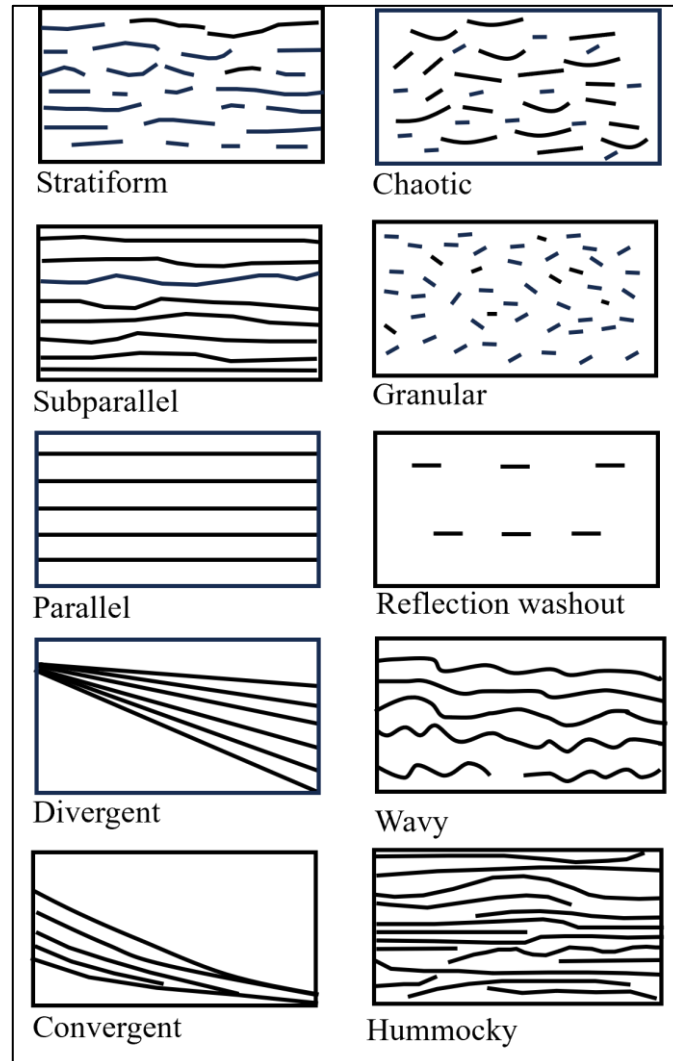


Figure 4.17: Seismic reflection patterns after Xu and Haq (2022).

When sandy deposits are present, particularly at lithological contrasts, high amplitude reflections are frequently observed. Meanwhile, fine-grained sediments are known to exhibit low-amplitude reflections. The presence of parallel, subparallel, and wavy reflectors indicates that the depositional rates on a surface that is subsiding uniformly, such as a shelf or basin plain, are relatively consistent (Yin et al., 2020). When

discontinuous, the reflections signify channel sand deposits. Divergent reflectors are indicative of lateral changes in depositional rates or gradual tilting of a depositional surface where deposits are being made. The phenomenon of repeated lateral and vertical migration is frequent in submarine channels, particularly turbidite channels. Abreu et al. (2003) and Posamentier and Kolla (2003) found that vertical stacking is more prevalent than lateral stacking and that it is typically associated with erosional surfaces. Moreover, coarse-grained fluvial, turbidite channels having debris flow or mass transport deposit fills may be the cause of chaotic seismic reflectors (Dolson et al., 1999; Larsen et al., 2023).

4.7.3 Horizon flattening

Horizon flattening in seismic data interpretation is a potential technique that allows for the analysis of stratigraphic and depositional features, before and after the deposition of a particular formation. It helps reconstruct depositional direction, environment, tectonics, and sediment dispersal patterns. Horizon flattening involves shifting seismic data vertically so that a particular seismic horizon of interest becomes flat at a constant time or depth level. This transforms the seismic section from a two-way travel time (TWT) or depth domain to a relative stratigraphic domain, often referred to as the flattened domain or horizon-relative space (Figure 4.18 and Figure 4.19).

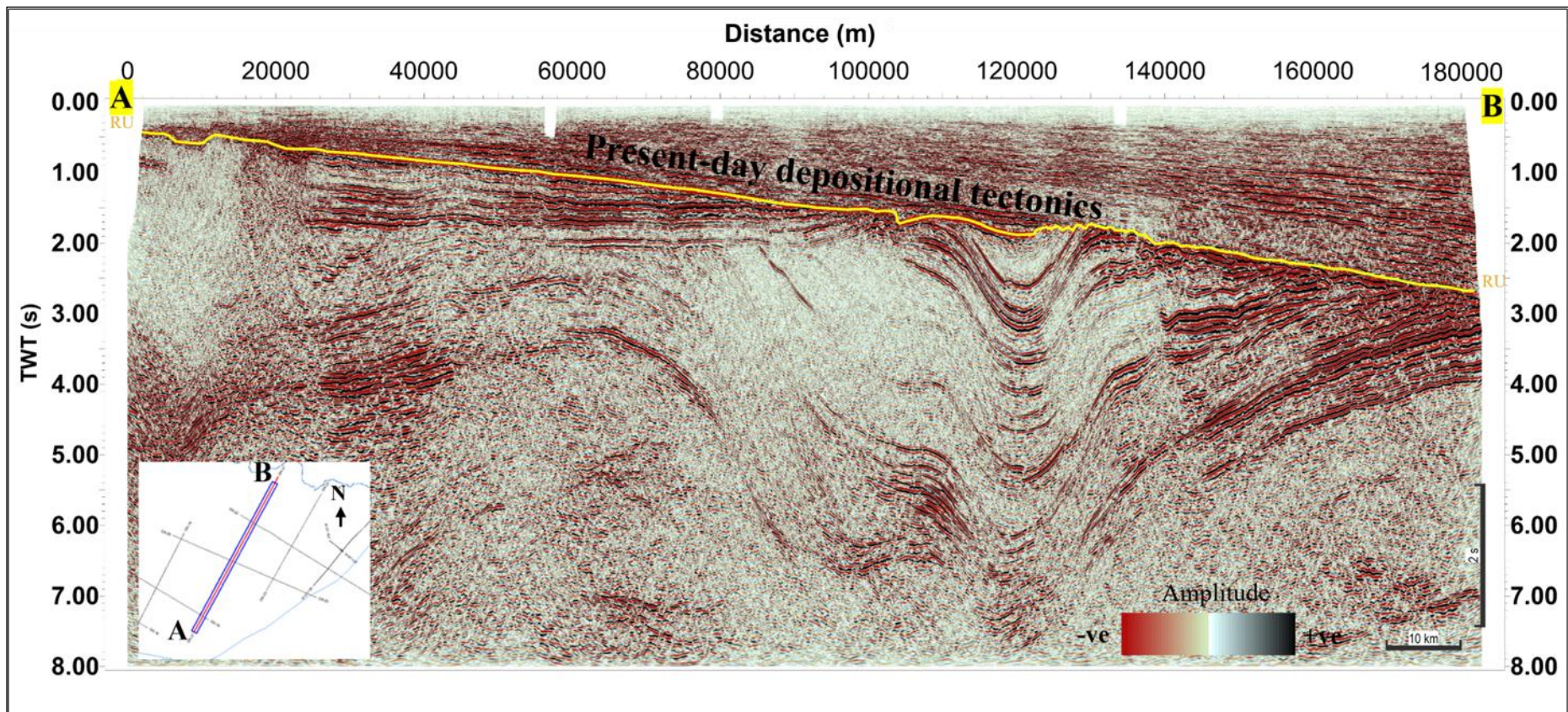


Figure 4.18: An Unflattened seismic section represents the current scenario of deposited sediment sequences.

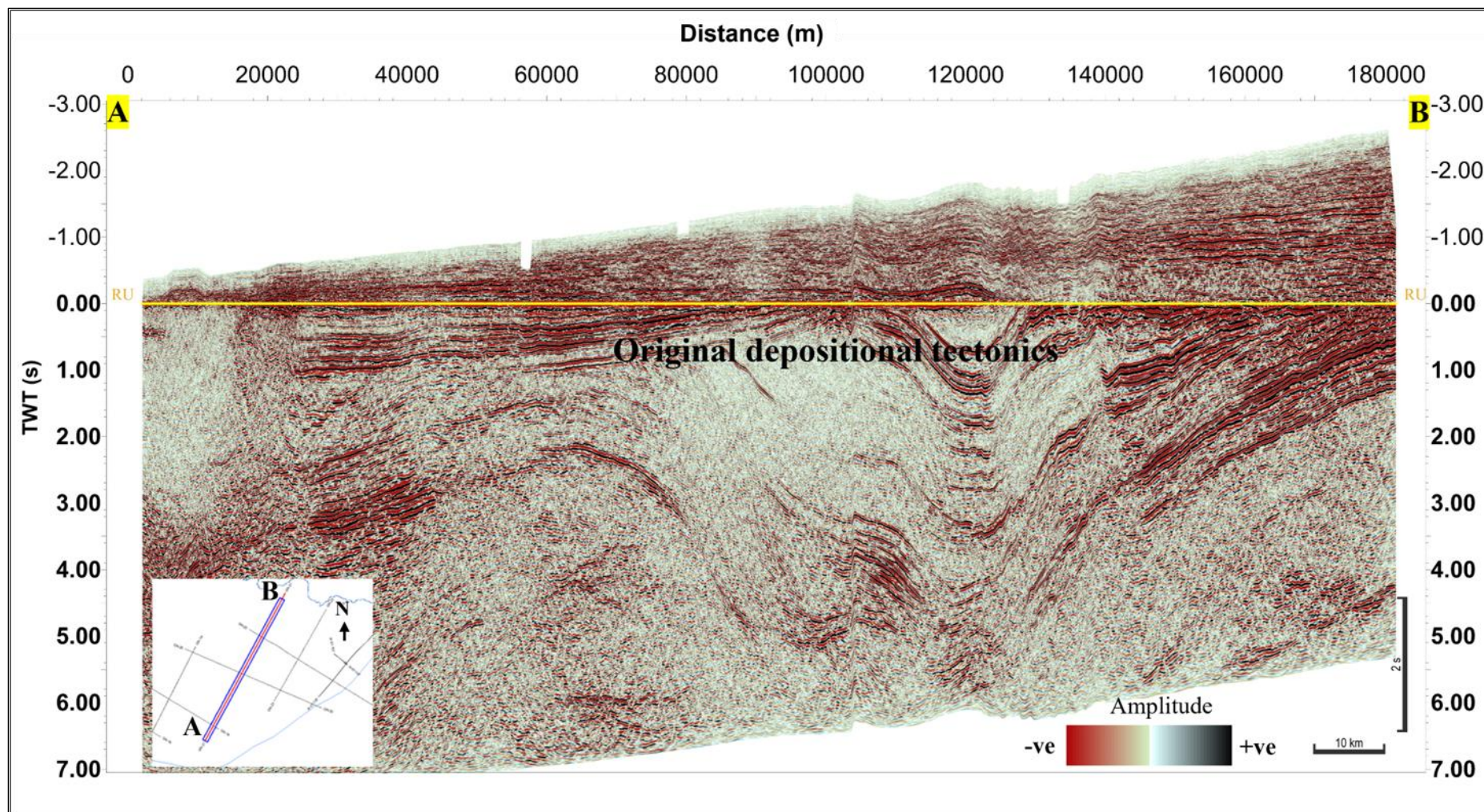


Figure 4.19: The Flattened seismic section along the reference Regional Unconformity (RU) horizon depicts the original sediment depositional architecture before the deposition of the sediments above the RU.

4.7.4 Spectral Decomposition

Spectral decomposition is a frequency-based seismic attribute that breaks down a seismic trace into its constituent frequency components, providing a time-frequency representation of the subsurface. It is often referred to as time-frequency decomposition, which is an essential seismic interpretation technique that is widely used in attribute analysis for subsurface mapping (Partyka et al., 1999; Castagna et al., 2003; Farfour et al., 2018).

The principle of spectral decomposition is based on the idea that different geological features respond differently at various frequencies due to tuning effects and thickness variations (Hossain, 2020). It improves the visualization of stratal slices, with structural and stratigraphic depositional features that we cannot envisage in seismic amplitude slices (Zeng, 2006; Wooltorton, 2016; Banerjee and Ahmed Salim, 2020; Silver and Bedle, 2021). This method is extensively used in the oil & gas industry to find hydrocarbon prospects (Almasgari et al., 2020; Tian, 2021). Puryear and Castagna (2008) determined thin-layer thickness and stratigraphic interpretation using spectral inversion.

The principle of spectral decomposition is to break down the seismic trace into constituent dominant frequencies (Castagna and Sun, 2006; Wright et al., 2018; Silver and Bedle, 2021), and later on the result is combined in the color composite image using Red (R), Green(G), Blue(B) blending for low, medium and higher frequencies, respectively (La Marca Molina et al., 2020; Murat Alyaz et al., 2023) (Figure 4.20). The use of red-green-blue (RGB) color blending is an especially efficient method for displaying responses to multiple frequency decompositions (McArdle and Ackers, 2012). It was discovered that the decomposed seismic frequencies can be utilized to estimate the

thickness of thin layers, which cannot be resolved in the time domain (Castagna and Sun, 2006; Farfour et al., 2018).

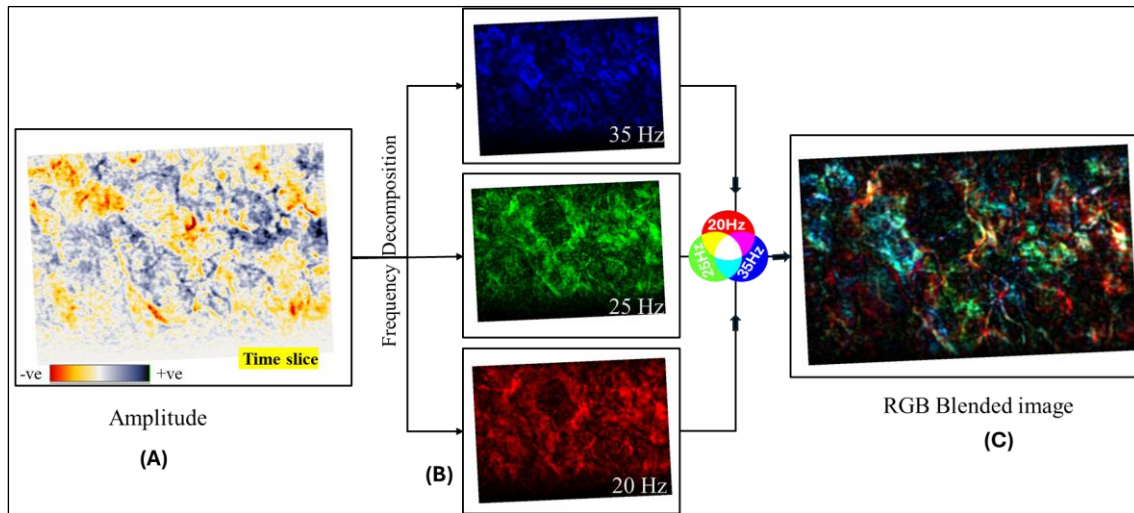


Figure 4.20: Schematic diagram of spectral decomposition and RGB colour blending workflow, whereby three different dominant frequency magnitude responses are assigned Red (R) as low, Green (G) as medium, and Blue (B) as high colour schemes and blended with the result highlighting variation in frequency, variation in colour and intensity, that we cannot observe in the amplitude slide.

This blending highlights certain hidden subsurface features and reservoir architecture (Das et al., 2013; Kenneth Samuel and Righteous, 2019). The approaches that can be utilized to carry out spectral decomposition include Fast Fourier Transform (FFT), the Short-Term Fourier Transform (STFT), the Continuous Wavelet Transform (CWT), and the Matching Pursuit Decomposition (MPD) (Castagna et al., 2003; Li and Zheng, 2008; Castro de Matos et al., 2010; Puryear et al., 2012; Shokrollahi et al., 2013; Roden et al., 2015; Chopra and Marfurt, 2016; Lyu et al., 2020; Hossain, 2020; Cubizolle et al., 2022). Every single one of these approaches comes with its own individual set of benefits and drawbacks (McArdle and Ackers, 2012; Piranti et al., 2020). MPD involves the decomposition of complex seismic traces into a combination of linear expansion of waveforms (Mallat and Zhang, 1993). While FFT generates a single frequency spectrum for the entire seismic signal, whereas the STFT analyzes the frequency content of the signal segment on multiple time periods (Li et al., 2021).

The STFT of a signal $x(\tau)$ is defined as:

$$STFT(t, f) = \int_{-\infty}^{\infty} x(\tau) \omega^*(\tau - t) e^{-j2\pi f \tau} d\tau \quad (4.1)$$

Where, $x(\tau)$ is the seismic signal, $\omega^*(\tau - t)$ is a window function centred at time t , and “*” stands for conjugate, $e^{-j2\pi f \tau}$ is a complex exponential used for the Fourier transform, $STFT(t, f)$, which gives the amplitude spectrum at time t and frequency f .

The wavelet transforms (WT) based spectral decomposition has become a popular method for decomposing a signal to analyse its frequency distribution at multiple resolutions as it varies through time. Unlike the Short-Time Fourier Transform (STFT), which relies on a fixed-size time window, the WT employs variable window sizes, making it more adaptable to different frequency components (Li and Lu, 2014; Lyu et al., 2020). A widely used form of this method is the Continuous Wavelet Transform (CWT). The CWT algorithm is believed to be able to overcome the limitation of window length (Wu and Liu, 2009). Originally, it was introduced by Grossmann and Morlet (1984). However, the CWT gained significant recognition in the signal processing community after the pioneering works of Daubechies (1988) and Mallat (1989), who established its strong foundations in discrete signal processing. A key advantage of the CWT over the STFT, beyond the flexibility of windowing, is its ability to provide better frequency resolution at low frequencies and better time resolution at high frequencies (Chakraborty and Okaya, 1995; S. Sinha et al., 2005). In CWT, the wavelet dilates so that the time support varies with frequency. Smaller time support enhances frequency support and shifts it toward higher frequencies, while a larger time support reduces frequency support, shifting it toward lower frequencies (Partyka et al., 1999; Castagna et al., 2003; Matos et al., 2011; Durot et al., 2017; Cubizolle et al., 2022; Murat Alyaz et

al., 2023). This illustrates the inherent trade-off: as time resolution increases, frequency resolution decreases, and vice versa (Mallat, 2009).

Mathematically, a wavelet is defined as a function $\psi(t) \in L^2(\mathbb{R})$, with zero mean, and localized in both time and frequency. By dilating and translating this mother wavelet $\psi(t)$, a family of wavelets is generated, enabling the multiscale analysis central to the CWT.

$$\psi_{\sigma,\tau}(t) = \frac{1}{\sqrt{\sigma}} \psi\left(\frac{t-\tau}{\sigma}\right) \quad (4.2)$$

Here, $\sigma > 0$ represents the dilation parameter (or scale), while $\tau \in \mathbb{R}$ denotes the translation parameter. The wavelet is normalized such that its L^2 -norm $|\psi|$ is equal to unity. The CWT is then mathematically defined as the inner product of the signal $s(t)$ with the family of wavelets $\psi_{\sigma,\tau}(t)$.

$$\text{CWT}(\sigma, \tau) = \int_{-\infty}^{\infty} S(t) \left(\frac{1}{\sqrt{\sigma}} \right) \psi^* \left(\frac{t-\tau}{\sigma} \right) dt \quad (4.3)$$

where, ψ^* denotes the complex conjugate of ψ , and $\text{CWT}(\sigma, \tau)$ represents the time–scale map (scalogram).

CWT is widely utilized in spectral analysis. However, the CWT method generates a time scale spectrum (by dilating and compressing wavelets), instead of a time-frequency spectrum called a scalogram (Wu and Liu, 2009). When a scalogram is converted into a time–frequency spectrum using the center frequency of each scale, it often results in erroneous attenuation. The Time–Frequency Continuous Wavelet Transform (TFCWT) by S Sinha et al. (2005) resolves this issue by offering a more robust method for time–frequency localization. As TFCWT is inherently derived from the CWT, the adaptive dilation and compression of the wavelet provide an optimal window length that varies

with the frequency content of the signal. A comprehensive discussion on the TFCWT is presented in Chapter 7.

4.8 Gravity Method

Gravity methods are one of the oldest and most widely used geophysical techniques in subsurface exploration. These methods measure variations in the gravitational field of the Earth caused by differences in rock densities in the subsurface (density ranges for some common rocks are shown in Table 4.4. Because gravitational acceleration is directly influenced by mass, areas with denser rocks (e.g., mafic intrusions or ore bodies) produce stronger gravity signals, while less dense features (e.g., sedimentary basins or salt domes) result in weaker signals (Mallick et al., 2012). Gravity surveys are non-invasive, cost-effective, and particularly useful for mapping large-scale geological structures such as sedimentary basins, faults, and igneous intrusions (Vasanthi and Santosh, 2021).

Table 4.4: Average density range associated with common rocks (after Sharma, 1997).

Rock	Density (gm/cm ³)	Reason for Density Range
Sediments	1.7-2.3	Low density due to high porosity, poor compaction, and an unconsolidated nature.
Sandstone	2.15-2.6	Density varies with quartz content, cementation, and porosity.
Shale	2.1-2.75	Controlled by clay mineral composition, compaction, and organic matter content.
Gneiss	2.65-2.75	Metamorphic mineral assemblage and degree of metamorphism.
Granite	2.52-2.81	Density variation due to felsic mineral composition (quartz and feldspar).
Basalt	2.7-3.3	Higher density due to mafic minerals such as pyroxene and olivine.
Limestone	2.5-2.75	Density depends on calcite content, porosity, and degree of recrystallization. Non-porous higher density
Quartzite	2.60-2.70	High quartz content and low porosity produce a narrow density range.
Gabbro	2.85-3.12	Coarse-grained mafic intrusive rock with high density from pyroxene and plagioclase.

In practice, gravity data acquired at the surface of the Earth are influenced not only by subsurface density contrasts but also by topography, elevation, and the shape of the Earth. Therefore, several corrections are applied to raw gravity measurements to isolate the geologically meaningful component (Nyaberi, 2023).

The Bouguer anomaly (δg_B) is the corrected gravity value after applying all the corrections, including free air (elevation) correction, tidal correction, Bouguer plate correction, etc. It removes the effects of terrain and elevation to better reflect subsurface density variations. The Bouguer anomaly above mean sea level is calculated as:

$$\delta g_B = g_{obs} + (\delta g_{FA} - \delta g_{BP} + \delta g_{TC} + \delta g_{tide}) - g_n \quad (4.4)$$

where, δg_B is Bouguer gravity anomaly, g_{obs} and g_n are the observed and normal (theoretical) gravity values, δg_{FA} is Free-air correction (elevation effect), δg_{BP} is Bouguer plate correction (mass between station and sea level), δg_{TC} is Terrain correction (local topographic effects), and δg_{tide} is a tidal correction (Lowrie, 2007).

The resulting Bouguer anomaly helps delineate features like sedimentary basin thickness, granite intrusions, or dense ore bodies (Table 4.5). Positive anomalies may indicate denser material (e.g., mafic rocks), while negative anomalies suggest low-density materials (e.g., sediments or salt) (Figure 4.21).

Residual gravity anomaly (short wavelength anomalies due to shallow structures) is obtained by removing the regional gravity trend (Figure 4.22), caused by deeper, large-scale structures or curvature of the Earth, from the Bouguer anomaly. This isolates shallower, local density variations, making residual anomalies ideal for near-surface studies where localized geological variations are of interest, identifying small-scale

targets such as faults, dykes, or mineral deposits and hydrocarbon exploration (Table 4.5).

Mathematically, it is expressed as:

$$g_{\text{residual}} = g_{\text{Bouguer}} - g_{\text{regional}} \quad (4.5)$$

The regional gravity anomaly represents the broader, long-wavelength components of the gravity field caused by deep-seated structures, such as variations in Moho depth, crustal thickness, or deep lithospheric features (Table 4.5). Hence, in consequence, the gravity anomaly associated with sources from shallow depth typically has a high frequency (short wavelength), while the anomaly from deeper sources has a low frequency (long wavelength) (Tiberti et al., 2005; McLean et al., 2009; Ravi Kumar et al., 2013; Nair and Pandey, 2018).

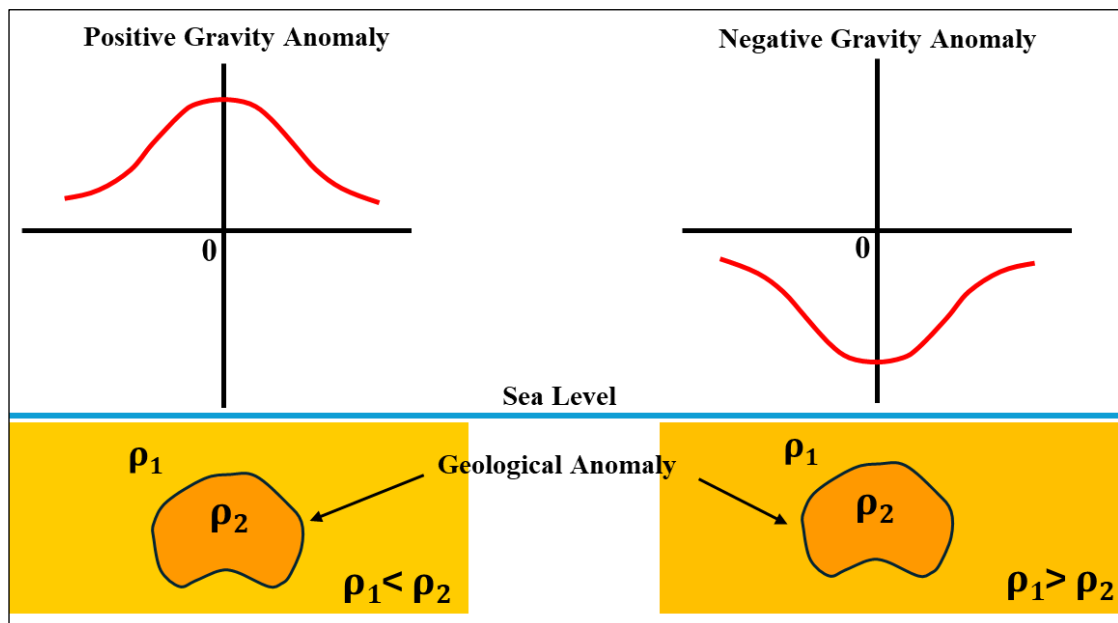


Figure 4.21: Observed gravity anomalies for different subsurface geological bodies having density (ρ_2). Positive gravity anomaly delineates when body density (ρ_2) is greater than that of the host medium density (ρ_1), and Negative gravity anomaly is represented when body density (ρ_2) is less than that of the host medium density (ρ_1).

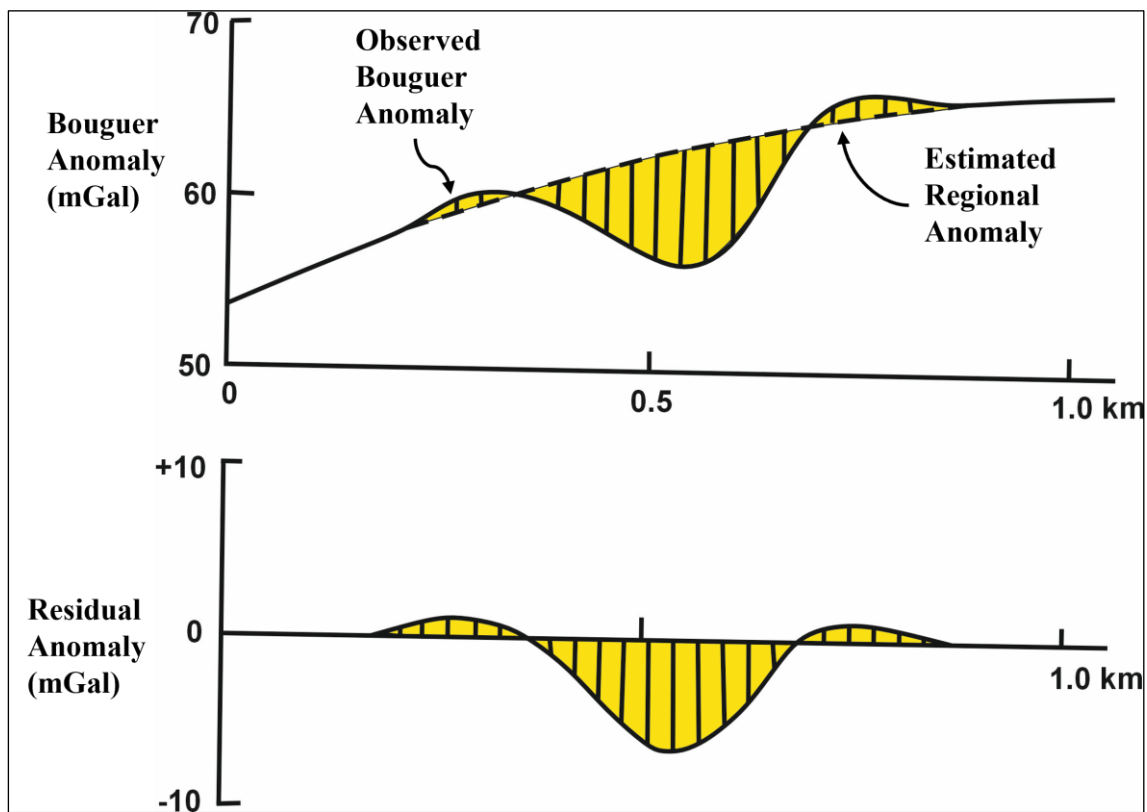


Figure 4.22: The separation of the regional and residual anomalies from the observed Bouguer anomaly (Kearey et al., 2002).

Table 4.5: Applications of gravity anomaly interpretation.

Gravity Component	Depth Sensitivity	Key Applications
Bouguer	Surface to mid-depth	Mapping sedimentary basins, structural highs/lows
Residual	Shallow-depth targets	Locating faults, dykes, oil and gas, and mineral bodies
Regional	Deep lithospheric scale	Studying crustal structure and tectonics

The flow chart to separate regional and residual fields is represented in Figure 4.23. However, the detailed implications of the results of these anomalies from the Ganga Valley basin are summarized in Chapter 6.

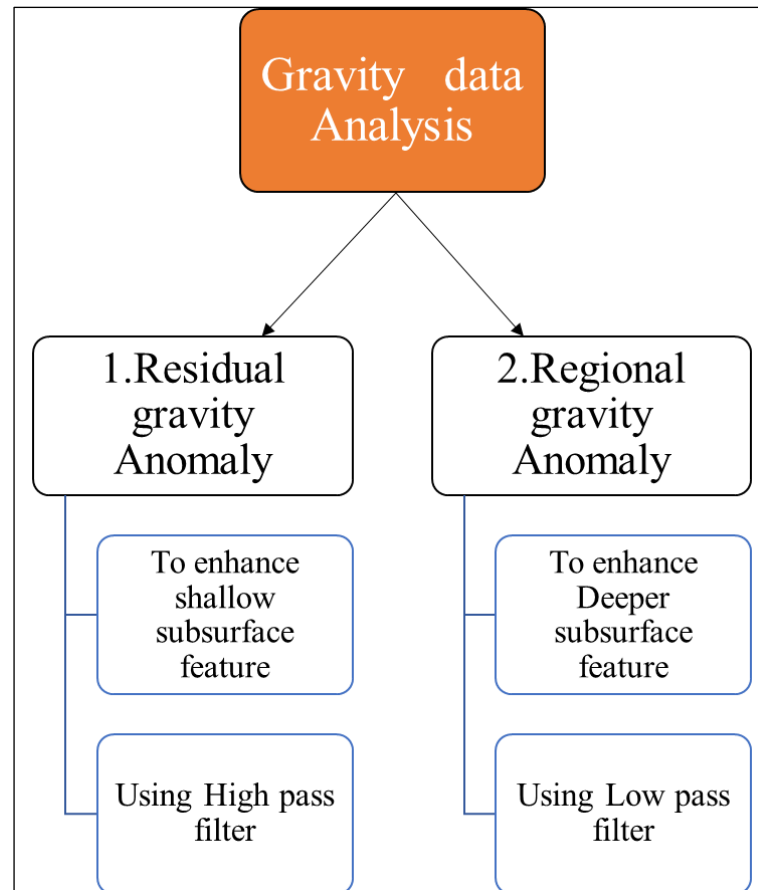


Figure 4.23: The flow chart to separate residual and regional gravity anomalies.

Although the gravity method is a non-destructive and passive technique. It effectively works over land, air, and marine environments. Provides data over large areas and inaccessible terrain. However, the method has certain limitations. A major drawback is its poor vertical resolution compared to seismic methods, which makes it less effective for detailed imaging of subsurface layering. Interpretation is inherently non-unique, as different subsurface density distributions can produce similar gravity anomalies. Furthermore, accurate interpretation relies heavily on precise terrain and elevation corrections, without which the results may be misleading. Therefore, in this thesis work, we have performed a gravity analysis with seismic data to achieve comprehensive imaging of subsurface layering of the Ganga Basin.

Chapter 5 : Datasets

5.1 Introduction

This thesis primarily utilizes post-stacked time-migrated 2D/3D Seismic, Well logs, and Gravity data sets for a comprehensive understanding of the subsurface architecture and depositional environment of the Ganga basin.

Seismic data is a crucial element for understanding the hidden subsurface structural features, disposition of the geological strata, depositional trends, and stratigraphic thicknesses. This information is essential for identifying prospective areas and structural plays for hydrocarbon exploration. By combining insights from 2D and 3D seismic data, potential hydrocarbon reservoirs, such as sandstone bodies within fluvial or deltaic sequences, can be identified and mapped with greater confidence, aiding in prospect generation and resource evaluation (Nanda, 2016).

Well-log calibration and gravity modelling provide independent constraints on the interpreted horizons and basement configuration. Although uncertainties remain due to limited deep well control and the inherent non-uniqueness of gravity inversion. Nevertheless, integrating seismic interpretation, well-log analysis, gravity modelling, and spectral decomposition substantially reduces interpretation uncertainty and improves confidence in the tectono-stratigraphic framework and hydrocarbon prospectivity of the Ganga Basin.

However, to improve the transparency of the adopted datasets, the reliability, uncertainties, and constraints associated with the principal interpretation techniques are summarized in Table 5.1

Table 5.1: Reliability and uncertainty assessment of the integrated datasets and methodology.

Method	Purpose	Assumptions & Parameter Choices	Reliability	Uncertainty
Seismic Interpretation	To delineate the tectono-stratigraphic framework, identify seismic sequences, unconformities, faults, and hydrocarbon traps.	Horizons interpreted using reflector continuity, seismic facies, amplitude, reflection terminations, and calibrated with seismic-to-well ties, synthetic seismograms, and formation tops.	High reliability within calibrated intervals through well-log correlation and intersecting seismic profiles; deeper Proterozoic sequences interpreted using regional seismic correlation.	Limited deep well penetration results in increased uncertainty in the interpretation of deeper Proterozoic sequences. Resolution is constrained by the quality and bandwidth of post-stack seismic data.
Gravity Modelling	To constrain basement geometry and investigate deep subsurface structures beyond the penetration of available wells.	Initial density values derived from well logs and interval velocities; densities refined through iterative forward modelling to match observed Bouguer gravity anomalies.	Models constrained using seismic horizons, well-log-derived densities, regional geology, and spectral depth estimates.	Gravity inversion is inherently non-unique; multiple density models may fit the observed anomaly. Basement depth remains uncertain where direct well control is absent.
Well-Log Analysis	To calibrate seismic interpretation and constrain lithology, interval velocities, and density for gravity modelling.	Formation tops, sonic and density logs, and synthetic seismograms are used for calibration.	Provides direct subsurface information within drilled intervals and improves seismic interpretation.	Existing wells penetrate only the upper sedimentary succession and do not reach the deeper Proterozoic sequences, limiting direct validation.
Spectral Decomposition	To enhance subtle depositional features that are difficult to recognize on conventional seismic sections.	Time-Frequency Continuous Wavelet Transform (TFCWT) and RGB spectral blending.	Interpretation validated using 3D seismic interpretation and sequence stratigraphy.	Results depend on seismic bandwidth, dominant frequency, and signal-to-noise ratio.

5.2 2D Seismic Reflection Data

This study utilizes 2D seismic datasets acquired by Oil and Natural Gas Corporation Limited (ONGC) during multiple exploration campaigns in the Ganga Basin (Figure 5.1). Although a vintage seismic line is shown for reference (Figure 5.1), its quality is insufficient for detailed seismic interpretation. Therefore, we have primarily utilized 2D seismic data acquired by ONGC during the 2017-2018 under the National Seismic Programme (NSP), which offers significantly improved data quality across the basin.

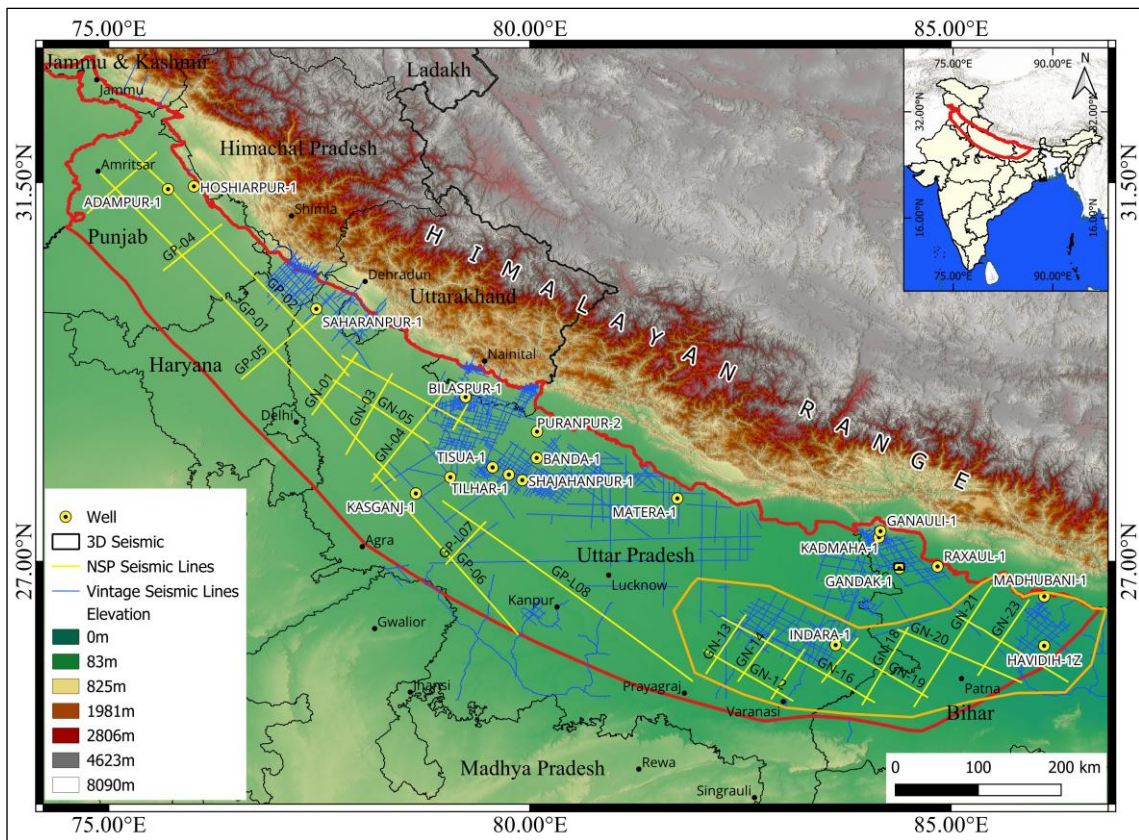


Figure 5.1: Location map of the Ganga-Punjab basin illustrating the distribution of vintage 2D/3D seismic data and NSP-acquired 2D seismic lines.

Our focus area lies in the eastern Ganga Basin, where we analysed a total of 12 NSP 2D seismic lines, covering a total length of approximately 1,508 km (Figure 5.2 and Table 5.2). Data sets were recorded in seismic reflections for up to 8 seconds of two-way travel time (TWT) with a sampling interval of 2 milliseconds in SEG-Y format. Seismic data adhere to the Society of Exploration Geophysicists (SEG) standard polarity convention,

where an increase in acoustic impedance is represented by a positive reflection (peak) and a decrease by a negative reflection (trough). Detailed key acquisition parameters are summarized in Table 5.3.

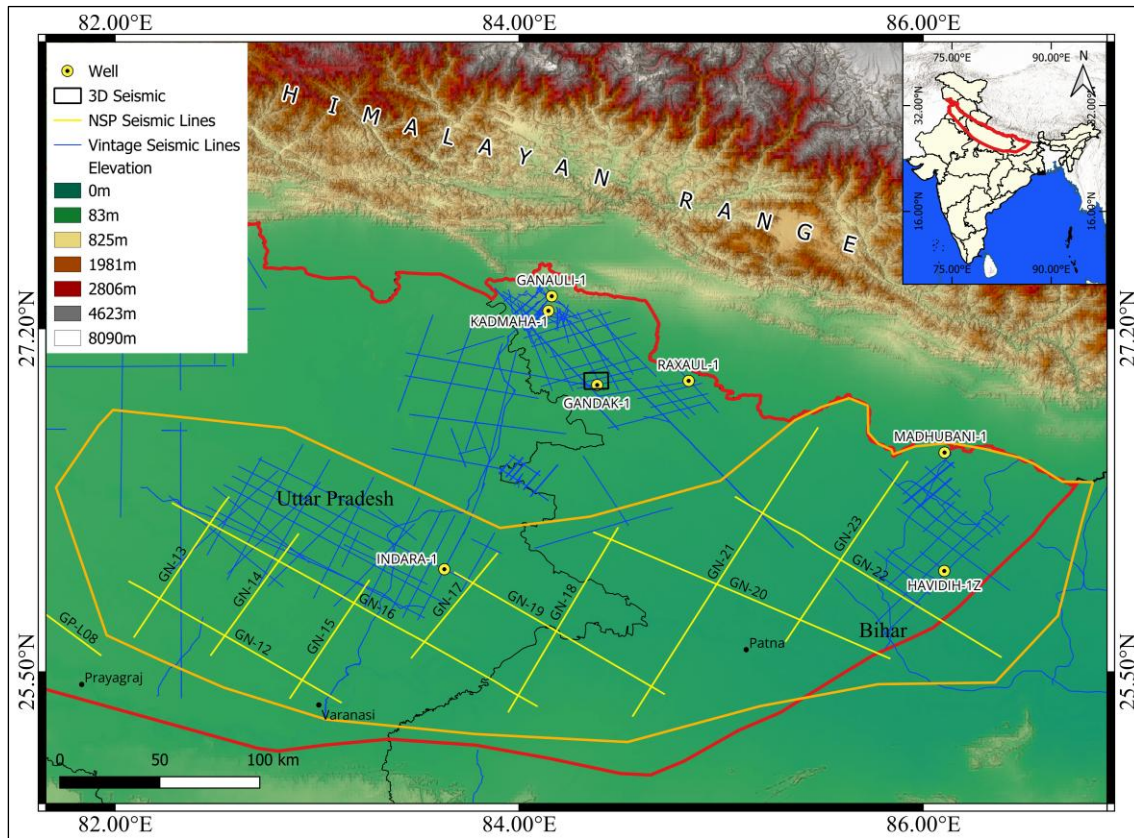
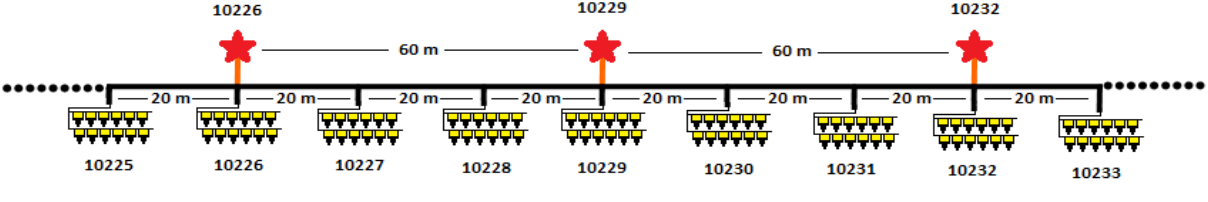


Figure 5.2: Location map of the East Ganga basin illustrating the distribution of vintage 2D/3D seismic data and NSP-acquired 2D seismic lines. The primary study area, where both 2D and 3D seismic data have been utilized, is highlighted by an orange and black polygon.

Table 5.2: 2D seismic reflection survey lines employed in this thesis.

2D NSP seismic lines	Length (km)
GN-12	124.39
GN-13	89.68
GN-14	79.18
GN-15	75.40
GN-16	212.28
GN-17	71.22
GN-18	114.43
GN-19	123.44
GN-20	162.11
GN-21	182.50
GN-22	158.07
GN-23	115.39
Total	1508.08

Table 5.3: Acquisition parameters for 2D seismic acquisition under NSP

Survey Layout and Template:			
Survey Layout		Acquisition Geometry	Symmetric Split Spread
Receiver Spacing	20 m	Channels per shot	~ 900
Source Spacing	60 m	Near offset	20 m
Numbering convention		Far offset	9000 m
			
Source	10226, 10229, 10232....	Nominal fold	150
Receiver	10001, 10002, 10003, 10004, 10005, 10006, 10007.....	No. of Auxiliary channels	3
		Aux channel 1	Time Break
		Aux channel 2	Uphole Time
		Aux channel 3	Timing
Receivers		Sources	
Geophone Type	SM-6	Source Type	Dynamite (Class-II Explosives)
String Type	12x1		
Natural Frequency	4.5Hz $\pm$ 0.5%	Number of Holes:	Single
Damping Coefficient	70%	Optimum Hole Depth & Charge Size	30m, 5Kg
Phone Sensitivity	28.8 $\pm$ 5% V/m/s	Pattern Hole Depth, Charge Size	N/A
Receiver array	Bunched	Charge Length	2.5kg-0.5m & 1.0kg-0.3m
Polarity	SEG Normal	Drilling Rig	Rotary (Manual)
Acquisition Parameters:			
Recorder	RT System 2		
Record Length	8 s		
Sample Rate	2 ms		
Alias Filter	Out		
Low Cut Filter	3 Hz		
Notch Filter	Out		
Alias Filter Type	Linear		

5.3 3D Seismic Reflection Data

3D seismic data is significant in understanding depositional environments, offering a detailed and comprehensive view of subsurface geological formations (Jia et al., 2014). This advanced imaging technology enables geoscientists to analyze the spatial distribution and characteristics of buried sedimentary layers with high precision, significantly enhancing the interpretation of paleo-depositional processes and environments (Posamentier, 2004; Sarkar et al., 2010; Zhu et al., 2016).

3D seismic data helps in the identification and mapping of sedimentary facies and their geometries (Bourget et al., 2014). Capturing seismic reflections in three dimensions allows for the visualization of complex depositional features such as channels, point bars, deltas, reefs, and turbidite systems (Bitrus et al., 2016). These features often have distinct seismic signatures that can be used to infer the depositional architecture, sediment transport mechanisms, and paleogeography. For instance, fluvial systems may be identified by their meandering or braided channel patterns, while deltaic environments exhibit progradation clinoforms (Reijenstein et al., 2011).

We leverage post-stacked time-migrated 3D seismic data volume acquired by ONGC in 2005. This data offers a spatial view of the subsurface horizons encompassing an area of roughly 104.65 sq. km. The 3D volume consists of lines running N-S with azimuth 177.28° (inlines) and E-W having azimuth 87.28° (crosslines). There are 346 inlines spaced at 35 m, each 8.9 kilometers long, and 508 crosslines spaced at 17.5 m, each 11.7 kilometers long (Figure 5.3). 3D data sets were also recorded in seismic reflections for up to 8 seconds of two-way travel time (TWT) with a sampling interval of 2 ms in SEG Y format.

All the available 2D & 3D data were loaded in the WGS84/UTM zone 44N projection datum in the KINGDOMTM platform. The survey has SEG normal polarity, meaning that

a peak with black color represents the increasing amplitude (positive amplitudes), while a trough with red color represents decreasing amplitude (negative amplitudes).

5.4 Well Data

Ganga - Punjab basin exhibits 26 exploratory wells (Figure 3.3). Although the available exploratory wells provide valuable lithological and petrophysical information, they penetrate only the upper sedimentary succession and do not constrain the deeper Proterozoic units interpreted in this study. Therefore, the well data were primarily used for seismic-to-well calibration, density estimation, and stratigraphic correlation, whereas the deeper interpretations rely on integrated seismic and gravity analysis.

In this thesis work, I have utilized available petrophysical data sets for the wells Indara-1 and Havidih-1Z. Both wells are essential components of the geological investigation within the Ganga Basin region (Figure 5.4 and Figure 5.5). These wells, drilled to depths of 1700 m and 1900 m, respectively, are approximately 250 km apart (Figure 5.2). Both wells offer significant insights into the lithological composition and subsurface characteristics of the studied area. The analysis of wireline logs from these wells facilitates comprehension of the geological formations, hydrocarbon potential, and structural features within the Ganga Basin.

Subsurface data from the Indara-1 well reveal a comparable yet distinct stratigraphic succession. The near-surface Quaternary Alluvium comprises unconsolidated sand and clay. The overlying Upper Siwalik Formation is dominated by fine-grained micaceous to calcareous sandstone and clay/claystone. The Middle Siwalik consists of alternating layers of sandstone, claystone, clay, and siltstone. The Lower Siwalik sequence is primarily composed of claystone, sandstone, and siltstone.

Beneath the regional unconformity, the Karnapur Formation is largely sandstone-dominated. This is underlain by a unit interpreted as Tilhar + Ujhani (?), comprising sandstone, clay, claystone, and siltstone. The Bahraich Formation, positioned stratigraphically above the basement, consists of shale, sandstone, claystone, and siltstone. The Archean Basement is encountered at a depth of 1693 meters and comprises basic igneous rock, specifically gabbro (Figure 5.4).

The Havidih-1Z well provides a detailed stratigraphic record from the recent alluvial deposits through to the Tilhar Formation. The uppermost units, encompassing recent alluvium to the Upper Siwalik strata, are composed primarily of micaceous sandstone interbedded with claystone, limestone/dolomite, minor siltstone, and occasional lignite. The Middle Siwalik Formation exhibits lithological variability across depth intervals, characterized by interbedded claystone, micaceous sandstone, limestone, and dolomite.

This composition continues into the Lower Siwalik, with dominant claystone and micaceous sandstone, interspersed with siltstone and carbonate layers.

Below the regional unconformity, the lithology transitions to predominantly claystone with interbeds of sandstone, limestone, and dolomite. In the Karnapur section, a sequence of interbedded claystone and sandstone gives way to a thick claystone unit containing minor siltstone and carbonate content between depths of 1608 and 1625 meters. The basal Tilhar Formation is marked by interbedded claystone, limestone, and dolomite, with minor occurrences of sandstone and siltstone (Figure 5.5). A correlation is established between these two wells as sketched in Figure 5.6.

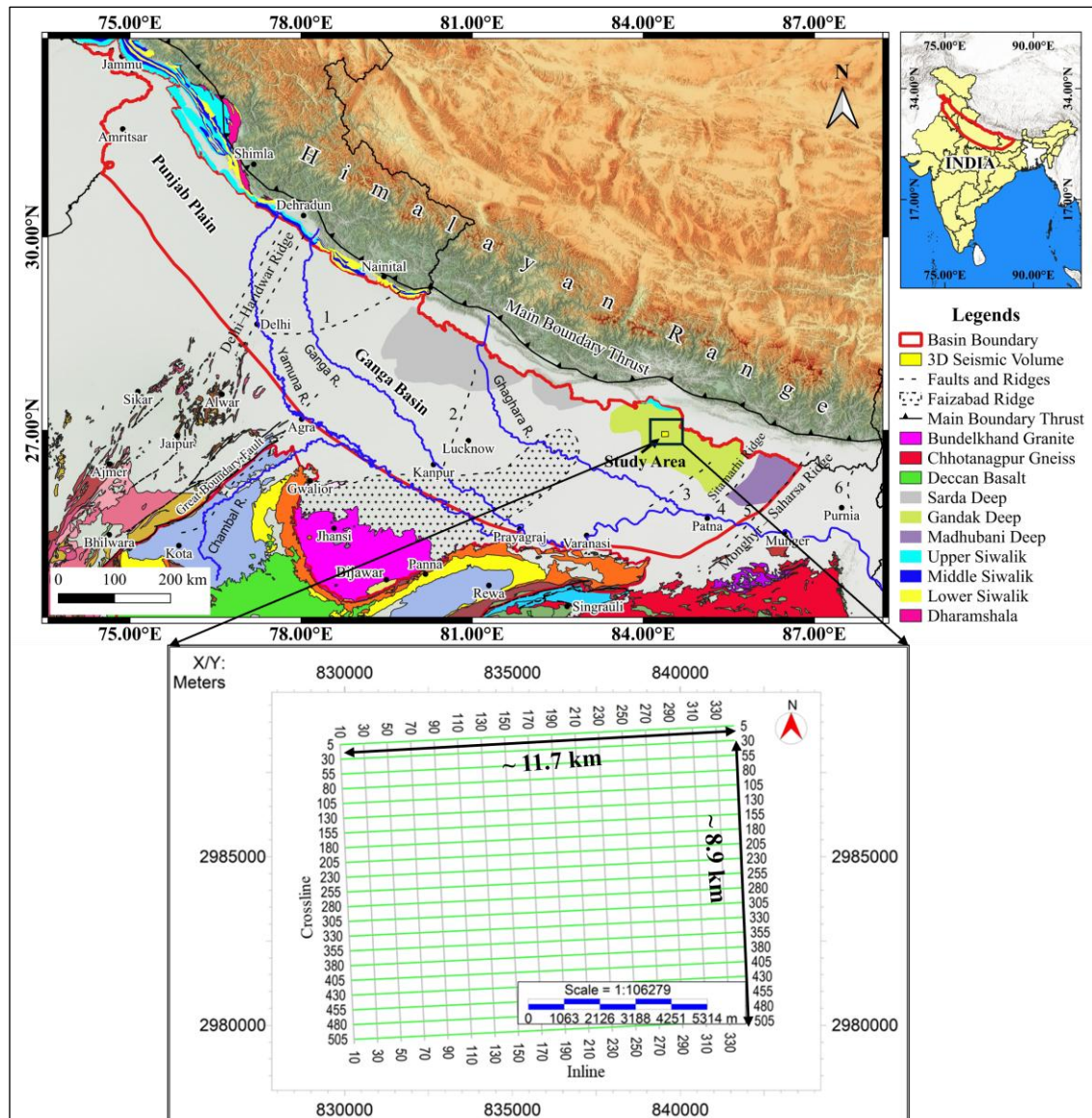


Figure 5.3: The lithostratigraphic map depicts the lithology and tectonic structures of the Ganga Valley basin. A box in yellow colour represents the 3D seismic volume located in the Gandak depression. 1. Delhi Moradabad Fault, 2. Lucknow Fault, 3. West Patna Fault, 4. East Patna Fault, 5. Monghyr-Saharsa Ridge Fault, 6. Malda-Kishanganj Fault; R. River

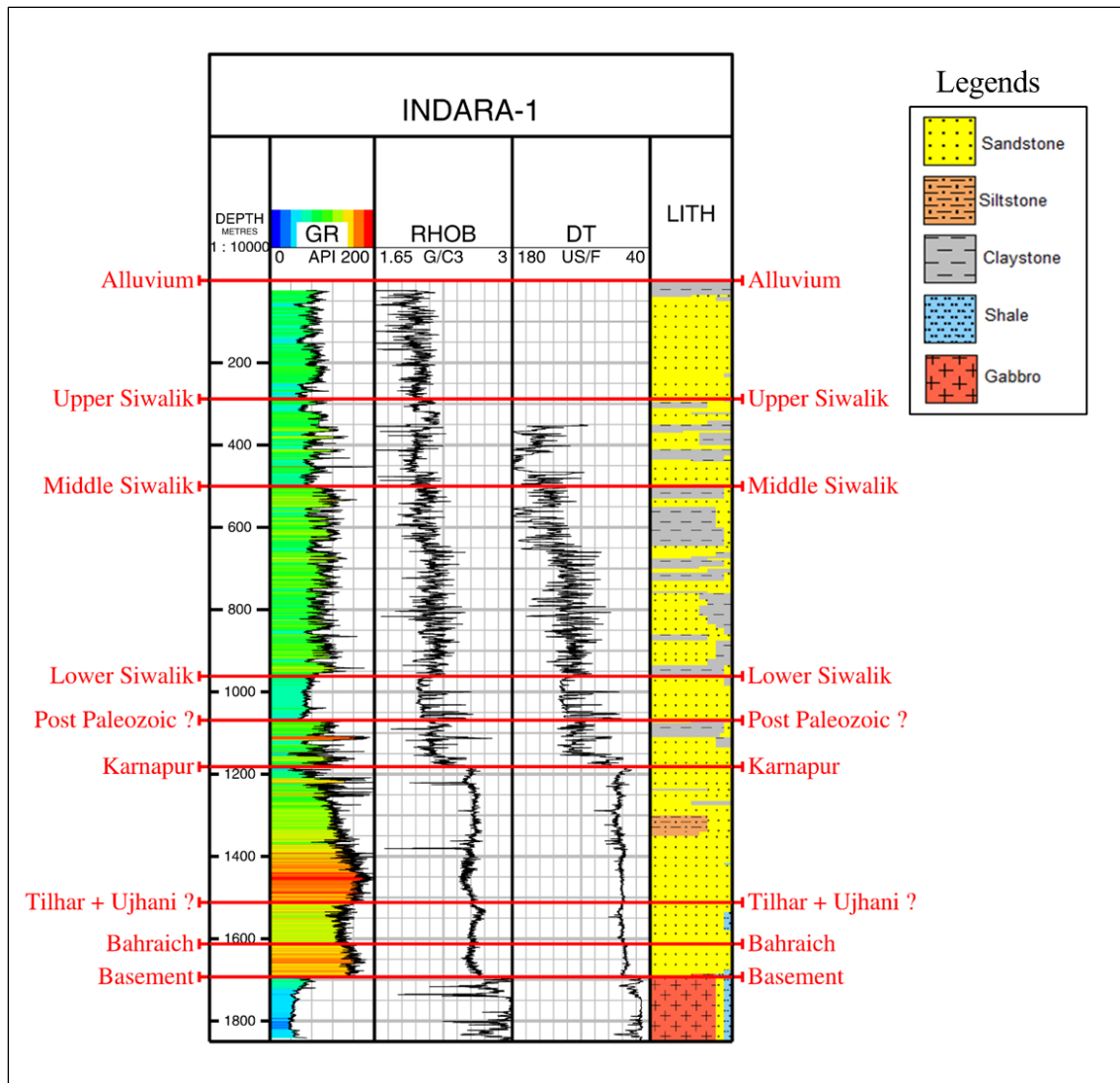


Figure 5.4: Electrolog of well Indara-1.

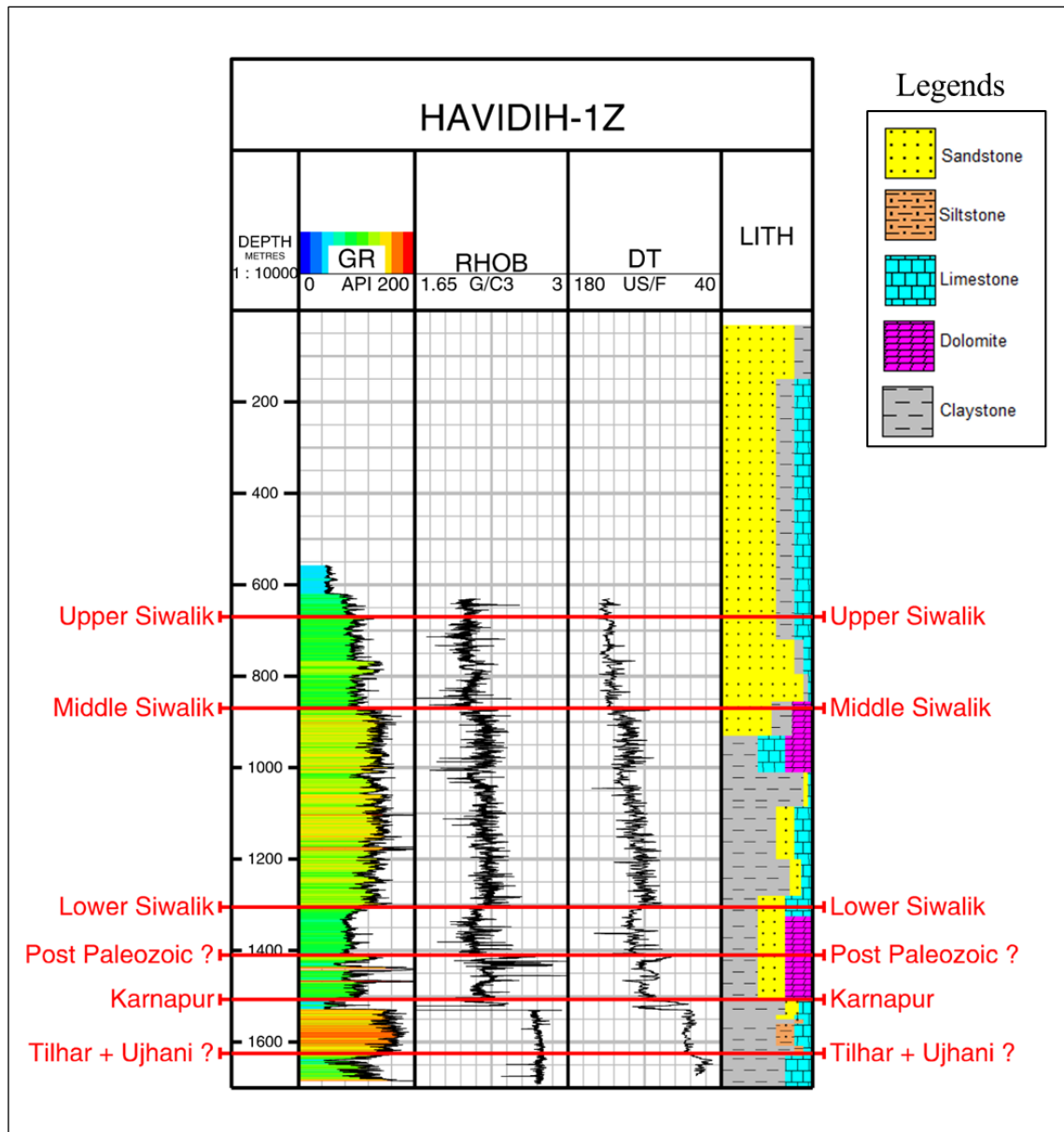


Figure 5.5: Electrolog of well Havidih-1Z.

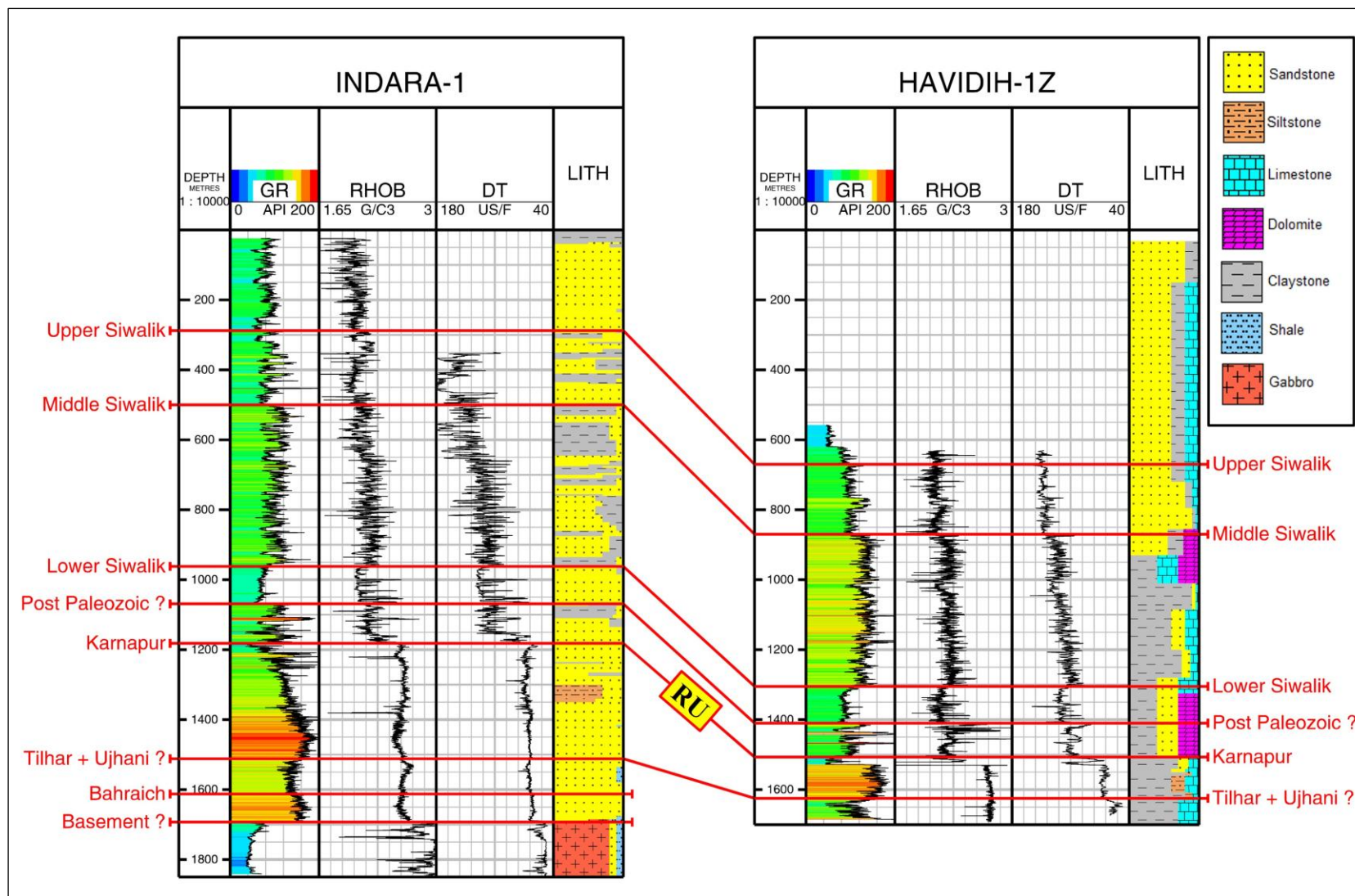


Figure 5.6: Electrolog correlation between HavidiH-1Z and Indara-1 wells.

5.5 Gravity Data

In this thesis, satellite Bouguer Anomaly data were utilized to identify the subsurface anomaly structures in the Ganga basin and its surrounding areas to delineate its tectonics (Figure 5.7). These grids were derived from the Earth Gravitational Model (EGM 2008) provided by the International Gravimetric Bureau (BGI) (<https://bgi.obs-mip.fr/>). It is a regional dataset with a resolution of 2.5' x 2.5' arc minute and an accuracy of ± 5 mGal (Ravi Kumar et al., 2013). In the Bouguer gravity anomaly map, GH and GL referred to the gravity highs and lows, respectively. These prominent high and low appear to be related to the undulations in the basement depth or density variations in the basement rocks. However, their likely sources are discussed while described by residual components along the selected seismic lines in Chapter 6.

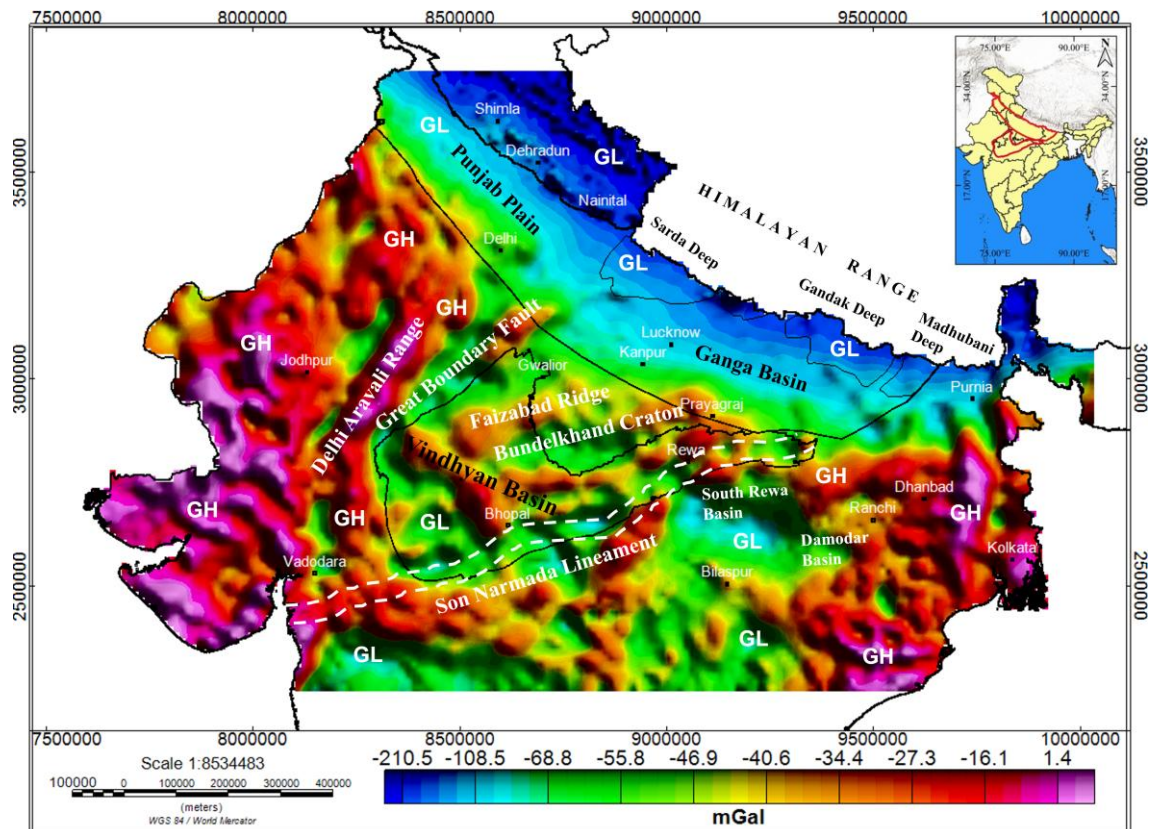


Figure 5.7: The Bouguer gravity anomaly map of the Ganga basin and its surrounding areas obtained from Earth Gravitational Model (EGM2008). Regional tectonic elements, gravity highs (GH) and gravity lows (GL) are marked on the map.

Spectral analysis and wavenumber-guided filtering enable the differentiation of deep and shallow sources responsible for gravity anomalies. This technique is used to separate the Bouguer gravity data into regional and residual anomalies (Saltus et al., 2006; Grandis and Dahrin, 2014; Jacques Nguimbous-Kouoh et al., 2019; Pourreza and Hajizadeh, 2019). The gravity anomaly associated with a source from shallow depth typically shows high frequency (or short wavelength), while the anomaly from a deeper source exhibits low frequency (or long wavelength) (Tiberti et al., 2005; McLean et al., 2009; Ravi Kumar et al., 2013; Nair and Pandey, 2018).

Figure 5.7 highlights several significant gravity anomalies, including gravity lows associated with the Son-Narmada lineament, South Rewa basin, and Bundelkhand craton in the southern region, while other tectonic features, such as the Great Boundary fault, Delhi-Aravali ridge, Faizabad ridge, and Monghyr-Saharsa ridge, exhibit elevated gravity values within the basin (Ravikumar et al., 2020). The Bouguer gravity field values in the current study area and surrounding regions are decreasing northwards from -3 to -210 mGal. Typically, prominent highs and lows on a gravity map relate to the undulations in the basement depth or density variations in the basement rocks.

A residual gravity anomaly map was generated to highlight hidden gravity characteristics in the basin. The residual gravity anomaly map (Figure 5.8) is created by using a high-pass filter of a cut-off wavelength to look at the shallow subsurface feature. This map highlights several isolated gravity high and low zones in the basin. The residual gravity map brought out the extension of the Faizabad ridge and the Great Boundary Fault to the Himalayan orogeny.

This map also brought out several isolated gravity highs and lows features in the deeper part of the basin. Based on the gravity data few notable tectonic features are realigned accordingly in the map. Some of the tectonic features (fault and ridges) that can be

correlatable on this map are the Great Boundary Fault, Delhi-Moradabad Fault (D.M.F.), Bundelkhand Faizabad ridge, Monghyr-Saharsa Ridge (M.S.R.), Sitamarhi Ridge (S.R.), Gandak Depression, Sharda Depression, Madhubani Depression, and Narmada Son lineament.

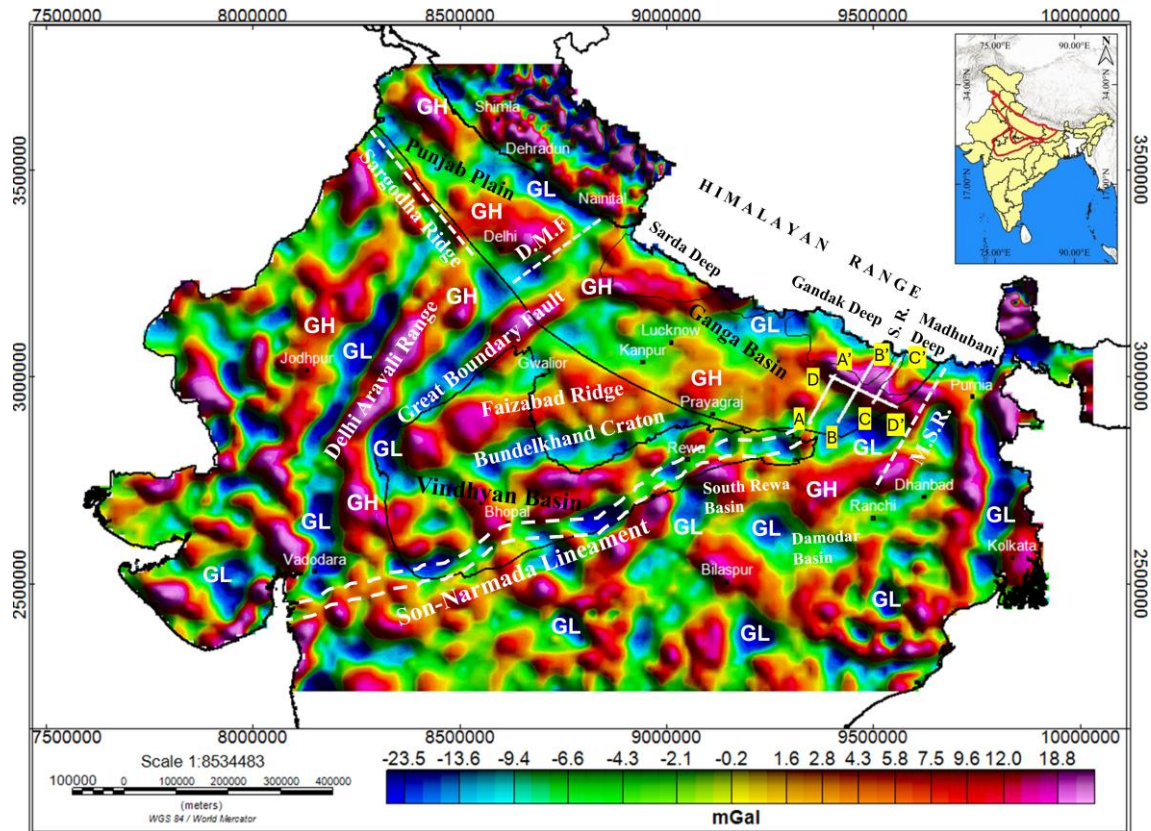


Figure 5.8: A residual gravity anomaly map for the Ganga basin and its surrounding area is prepared by applying a high-pass cut-off filter for wave number > 0.004 . The regional tectonic elements, GHs, and GLs are marked on the map. Gravity profiles along AA', BB', CC', and DD' (white-coloured solid lines) were extracted for modelling using the seismic profiles. Delhi-Moradabad Fault is abbreviated as D.M.F, Monghyr-Saharsa Ridge as M.S.R., and Sitamarhi Ridge as S.R.

A regional gravity anomaly map reveals hidden deep gravity characteristics in the basin.

The regional gravity anomaly map (Figure 5.9) is created by using a low-pass filter of cut-off wavelength < 0.004 to look at the deep-seated subsurface feature. The map shows the lowest gravity lows (GL) of approximately -219 mGal along the Himalayan front, which are attributed to the presence of low-density sediments in the foredeep and the thick crust beneath the Himalayas. This map highlights several isolated gravity highs in

the western boundary, possibly due to lithospheric flexure and related crustal bulge (Ravi Kumar et al., 2013).

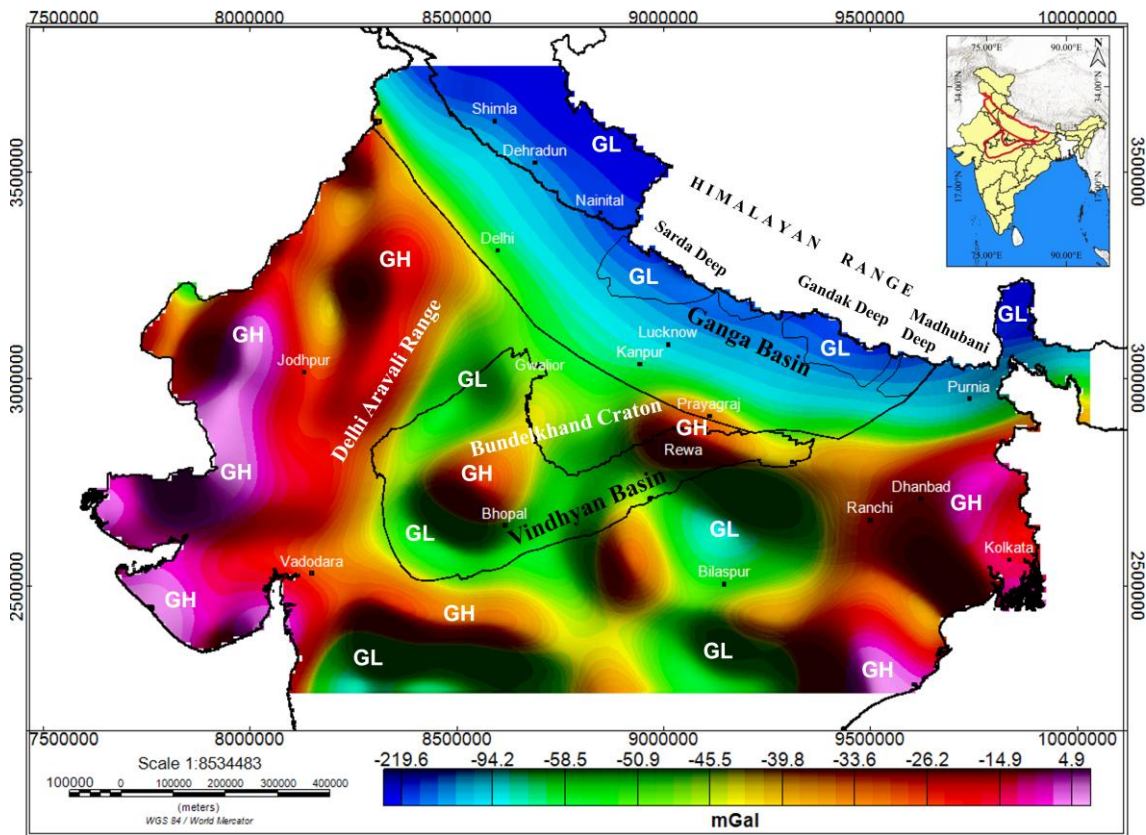


Figure 5.9: Low-pass filtered regional gravity anomaly for wave number < 0.004 , equivalent to showing deep-seated sources related to Moho and below.

5.6 Seismic Data Interpretation

5.6.1 2D Seismic Data Interpretation

5.6.1.1 Synthetic seismogram (well-to-seismic tie)

A synthetic seismogram is a model-generated seismic trace that simulates how seismic waves would reflect from subsurface geological layers, based on well log data, primarily acoustic impedance derived from density and velocity logs (Nanda, 2021). It plays a crucial role in seismic interpretation by bridging the gap between well data and seismic reflection data. The synthetic seismogram is created by convolving a wavelet, often a Ricker or Ormsby wavelet, with the reflectivity series computed from variations in

acoustic impedance ($AI = \rho \times V$, where ρ is density and V is velocity) across geological boundaries (Wright et al., 2012; Maurya et al., 2019). This simulated trace is then correlated with actual seismic records to accurately tie geological markers from well data to seismic reflectors, a process known as well-to-seismic tie. This correlation enhances the reliability of structural and stratigraphic interpretations by allowing interpreters to precisely identify the depth and thickness of subsurface formations (Sheriff and Geldart, 1995; Yilmaz, 2001).

In this study, a synthetic seismogram analysis was carried out using sonic and density logs from the wells Indara-1 and Havidih-1Z, which are the nearest wells to the study area, located on vintage 2D seismic line UP80-25 and Br-07-100, respectively. The correlation coefficient of the synthetic and seismic traces on the Indara-1 and Havidih-1Z wells was 0.595 and 0.629, respectively. Well-to-seismic tie-up results are presented in Figure 5.10 and Figure 5.11.

The composite synthetic seismic trace shows how the depth information relates to seismic time, and the plots of individual wavelets show the contribution of each impedance interface to the individual reflections. Consequently, different formation tops were marked at different TWTs in the seismic sections UP81-25 and Br-07-100, and the correlations were made.

Seven formations top horizons, i.e., 'Bahraich Top', 'Ujhani Top', 'Tilhar Top', 'Karnapur Top (Regional Unconformity)' and 'Lower Siwalik Top', 'Middle Siwalik Top', and 'Upper Siwalik Top' were picked on seismic sections UP80-25 and Br-07-100 based on well information (Figure 5.12 and Figure 5.13). These formation tops (horizons) were further extended into the all over 2D NSP seismic sections and 3D seismic data.

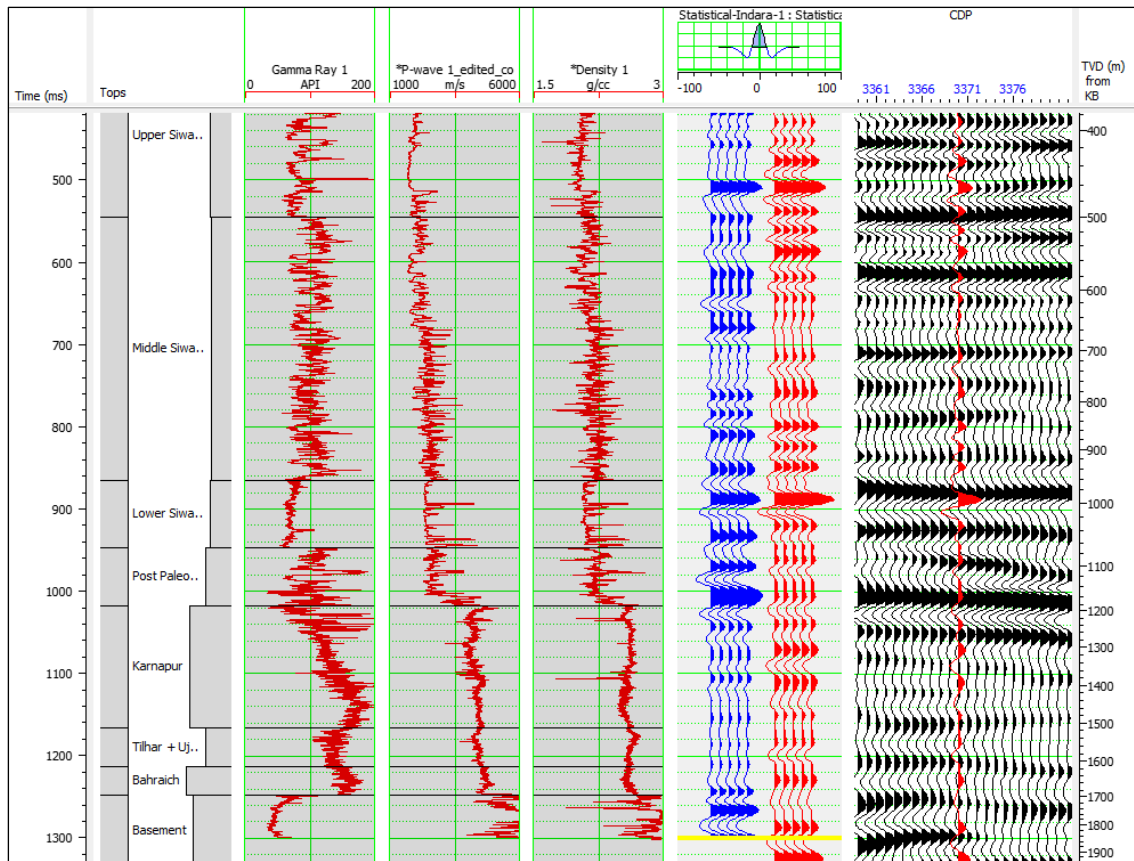


Figure 5.10: Synthetic seismogram of well Indara-1.

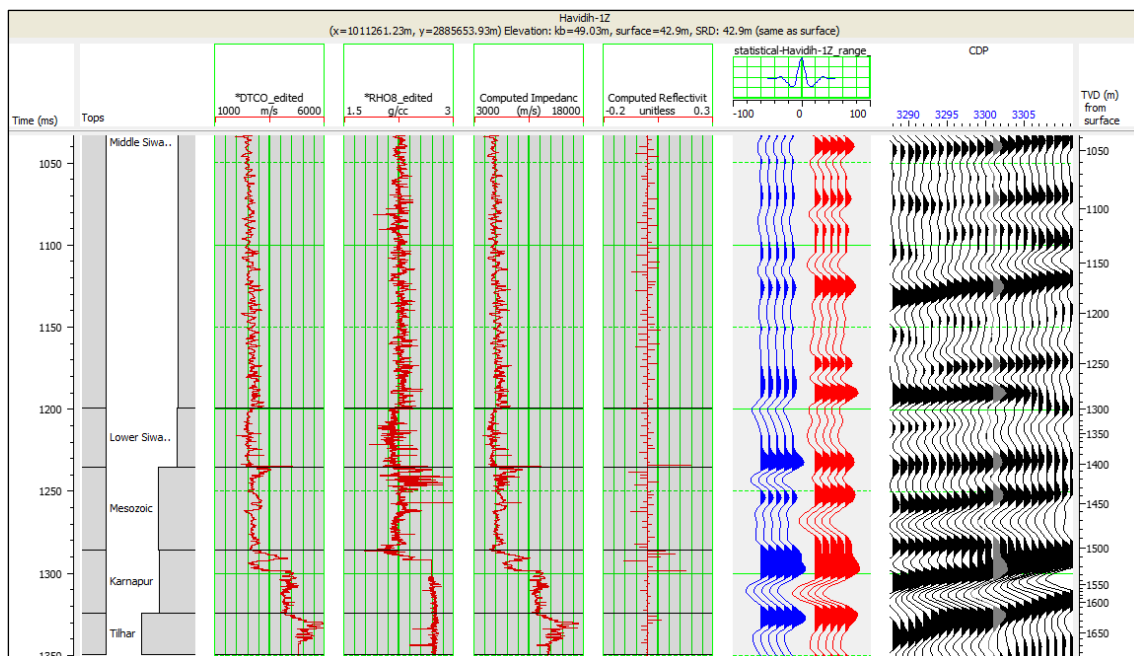


Figure 5.11: Seismic stratigraphic tie-up to the HAVIDIH-1Z well.

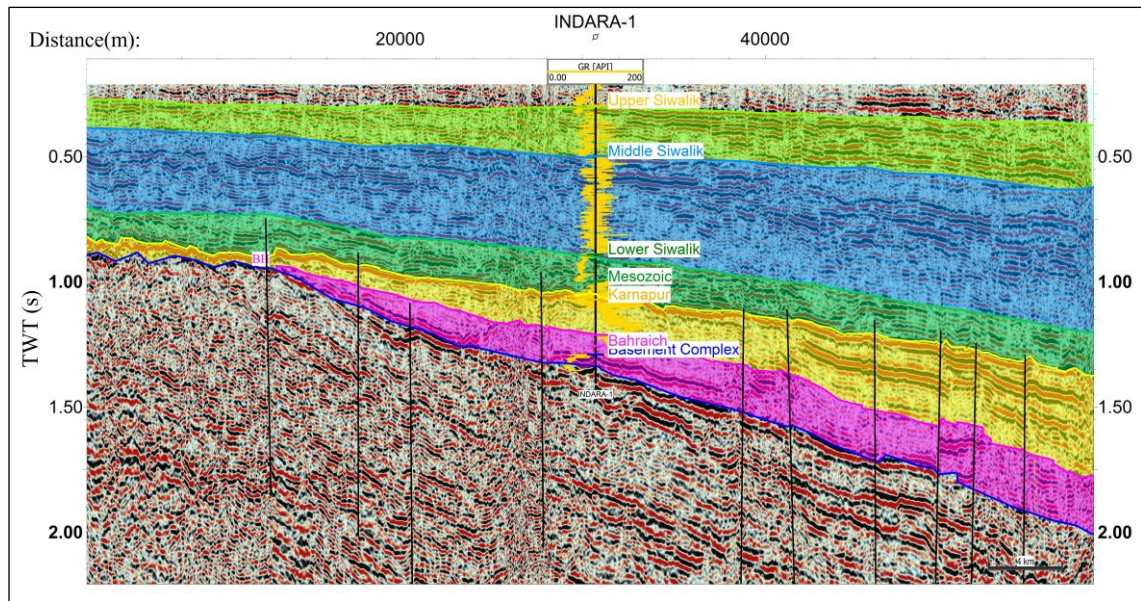


Figure 5.12: Seismic stratigraphic tie-up (well to seismic tie) to the Indara-1 well along the seismic section UP80-25.

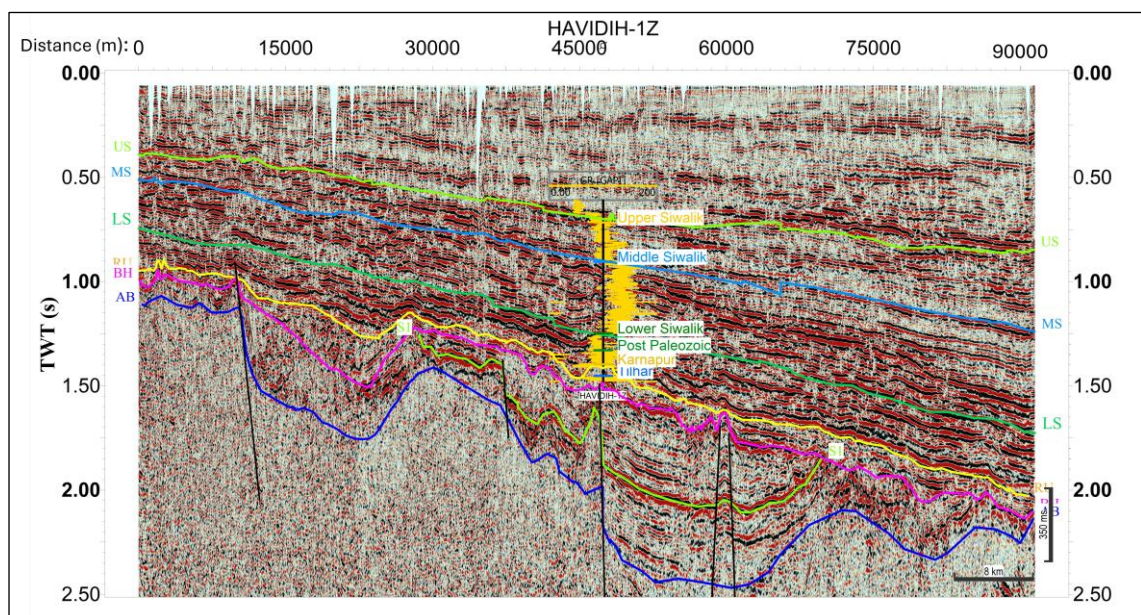


Figure 5.13: Seismic stratigraphic tie-up (well to seismic tie) to the Havidih-1Z well along the seismic section Br-07-100.

Furthermore, arbitrary seismic sections connecting wells Indara-1 and Havidih-1Z, as well as NSP seismic lines, were drawn to examine the regional extension of subsurface

tectonics in the Ganga basin (Figure 5.14 and Figure 5.15). These images highlight several ridges and faults in the Ganga basin.

These images reveal comparable sedimentary and tectonic features, prominently highlighting intense compressional tectonics. This deformation has resulted in the formation of a significant synclinal fold adjacent to the Monghyr–Saharsa Ridge in the East and the Faizabad Ridge in the West. Geological interpretation indicates that this large syncline is likely filled with Meso- to Paleoproterozoic metasedimentary rocks.

The Early Paleozoic and Cenozoic sequences are distinctly separated by the regional unconformity (RU), also referred to as the Tertiary-pre-Tertiary (T-PT) surface. The upper portions of the Early Paleozoic strata were subjected to erosion and truncation across the basin, forming a foundational platform for the deposition of Tertiary Siwalik sediments. The truncation and subsidence along the northern margin of the Indian craton significantly influenced the structural evolution of the Ganga Basin, leading to the development of a broad northeastward-dipping monocline in the study area. In the seismic section (Figure 5.14), the deepest part of the basin reaches approximately 7.5 seconds (TWT). Potential hydrocarbon-bearing zones may include stratigraphic traps or combination traps within the Paleozoic interval, bounded by regional unconformity. Additionally, a structural trap is observed in the central portion of the section, presenting as an anticline truncated by the RU (Figure 5.14). In some areas, these traps may be further bounded or influenced by nearby faults or structural high associated with buried ridges

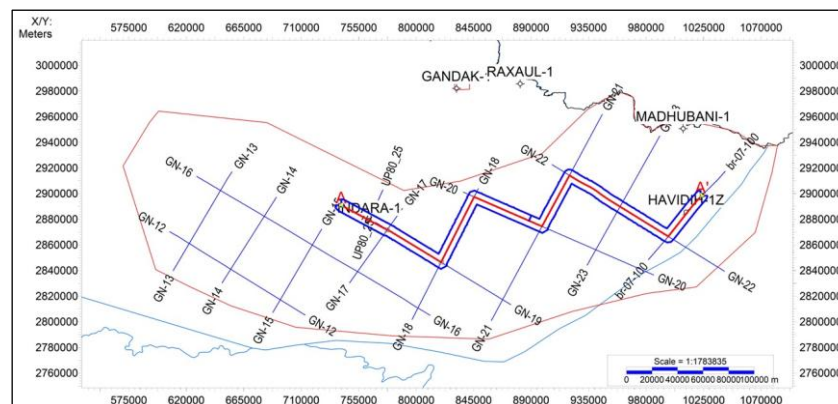
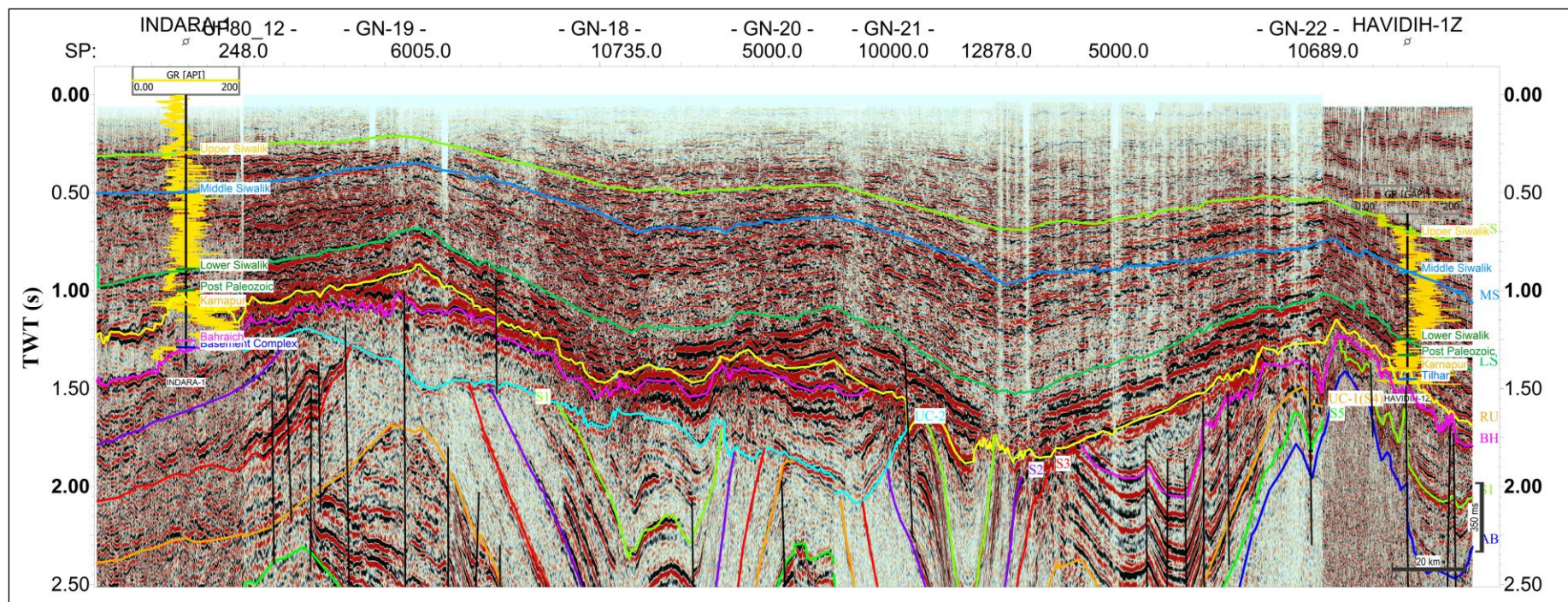


Figure 5.14: Composite line crossing Indara-1 and Havidih-1Z wells.

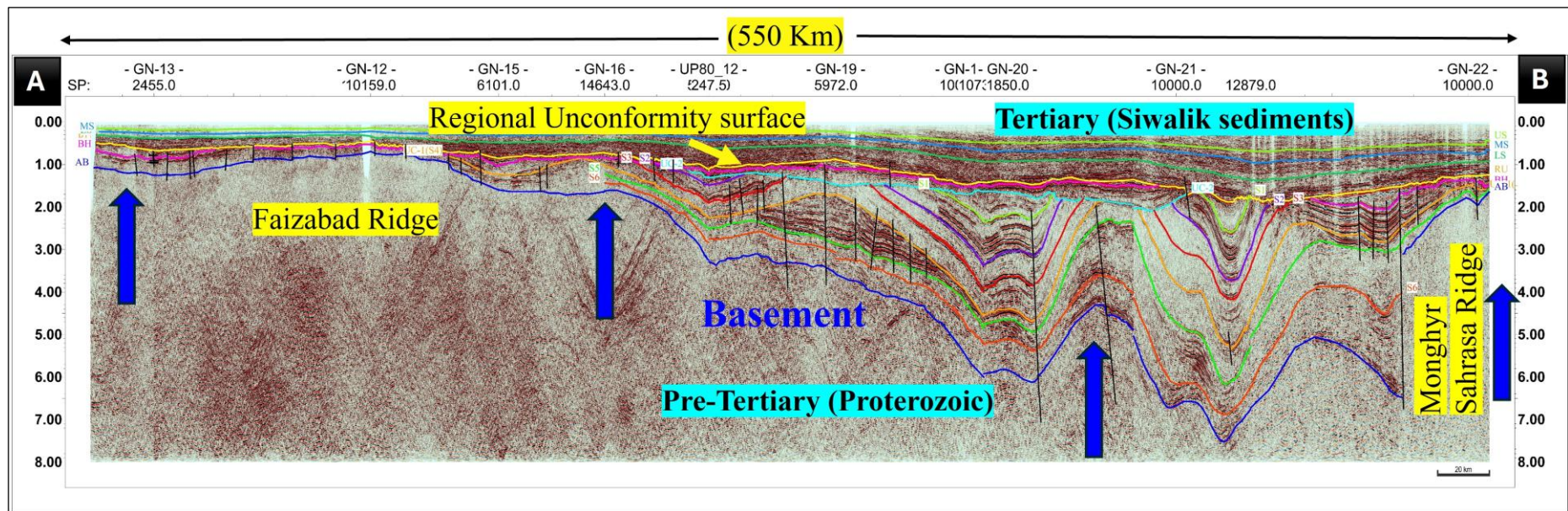
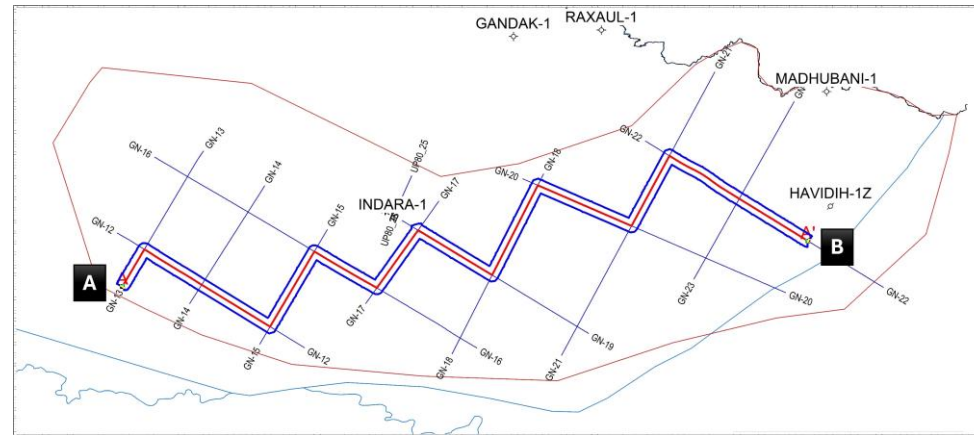


Figure 5.15: Arbitrary seismic line with NSP data.

5.6.1.2 Isochore map analysis (TWT structure maps)

An analysis of isochore maps in the selected seismic sections involves studying the variations in seismic reflection arrival times (TWT) across a study area. Isochore maps display the distribution of these arrival times, representing subsurface features such as faults, folds, and the thickness of stratigraphic layers. Additionally, time structure maps can aid in prospecting for hydrocarbon reservoirs by highlighting areas of interest based on structural and stratigraphic features. For this analysis, we have interpolated the picked seismic 2D horizons in all over the regions, followed by Upper Siwalik (US, Figure 5.16), Middle Siwalik (MS, Figure 5.17), Lower Siwalik (LS, Figure 5.18), Karnapur formations (Regional Unconformity) (RU, Figure 5.19), Bahraich formation (BH, Figure 5.20) and Archean basement (AB, Figure 5.21). It was observed that these formations are dipping of towards the NE direction in the east Ganga basin.

Reflecting horizons Upper Siwalik, Middle Siwalik, and Lower Siwalik have doubtful phase tie-up, as they are confined to dynamically non-persistent reflections in thick Siwalik sediments. Siwalik sediments (above the Regional Unconformity) consist of discontinuous, thin-bedded, varied amplitude strength reflections with monocline dip towards the NE (Figure 5.24). The horizons (Upper Siwalik, Middle Siwalik, and Lower Siwalik) were traced at times from 0.11 to 2.66 s. Siwalik sediments were encountered in all the wells in the area.

The reflecting horizons corresponding to the Upper, Middle, and Lower Siwalik formations (Figure 5.16, Figure 5.17, and Figure 5.18) exhibit uncertainty in horizon picking, primarily due to their association with dynamically non-persistent reflections within the thick Siwalik sedimentary sequence. These sediments are characterized by discontinuous, thin-bedded reflectors with variable amplitude strength and a monocline

dip towards the northeast. The Siwalik horizons have been intermittently traced within the two-way travel time (TWT) range of 0.11 to 2.21 s.

The Regional Unconformity (RU) is marked by a strong and continuous reflection across the basin, with two-way travel times (TWT) ranging from 0.35 to 2.89 s (Figure 5.19). At greater depths, the Bahraich Formation is observed with reflection times between 0.43 and 2.78 seconds (Figure 5.20). Notably, the isochore map indicates a maximum basement depth corresponding to 7.80 s TWT. The arrival time for the Archean basement varies significantly across the basin, ranging from 0.29 to 7.80 seconds (Figure 5.21).

Moreover, the time thickness of Proterozoic sediments was estimated between the Bahraich Formation and the Regional Unconformity (Figure 5.22), as well as between the Regional Unconformity and the Archean Basement (Figure 5.23). Figure 5.22 reveals that the maximum sediment thickness between the Bahraich Formation and the Regional Unconformity ranges from 0.70 to 0.88 s (TWT), with a consistent southwest–northeast (SW–NE) trend. This substantial and uniform sedimentary deposit may represent a prospective zone for hydrocarbon exploration in the Ganga Basin.

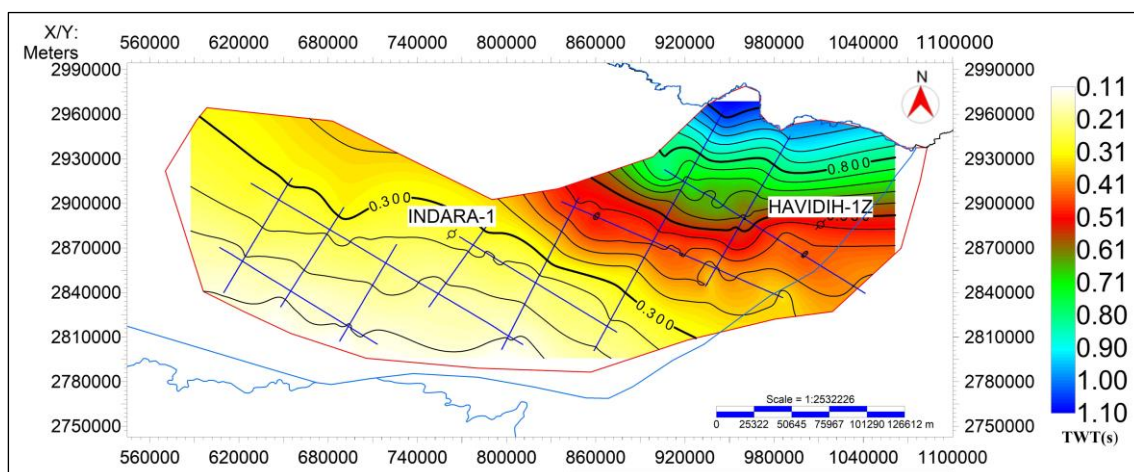


Figure 5.16: Isochore map of Upper Siwalik (US).

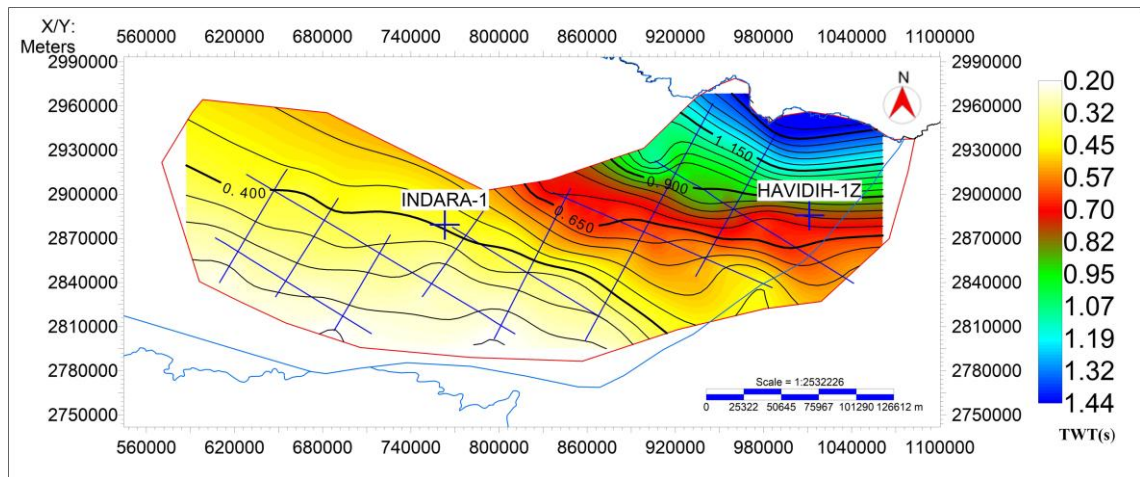


Figure 5.17: Isochore map of Middle Siwalik (MS).

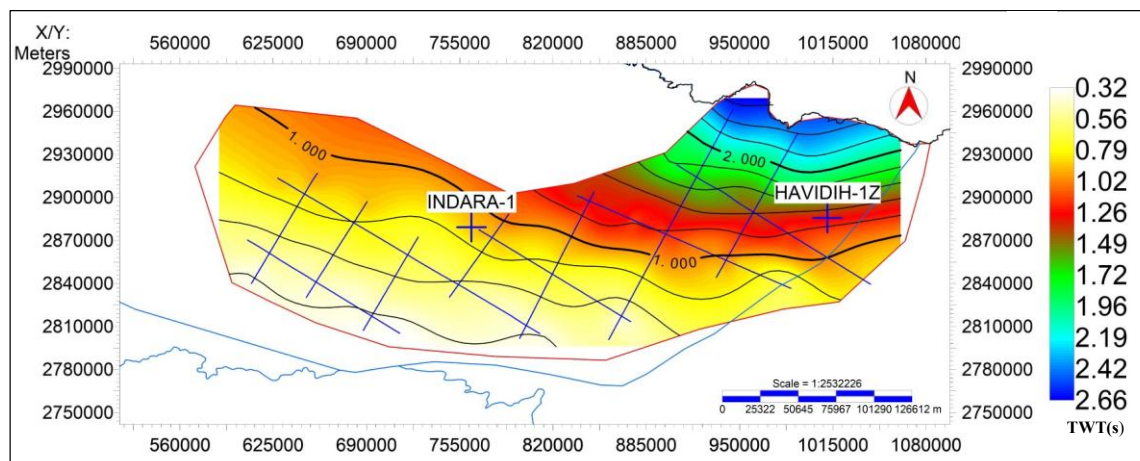


Figure 5.18: Isochore map of Lower Siwalik (LS).

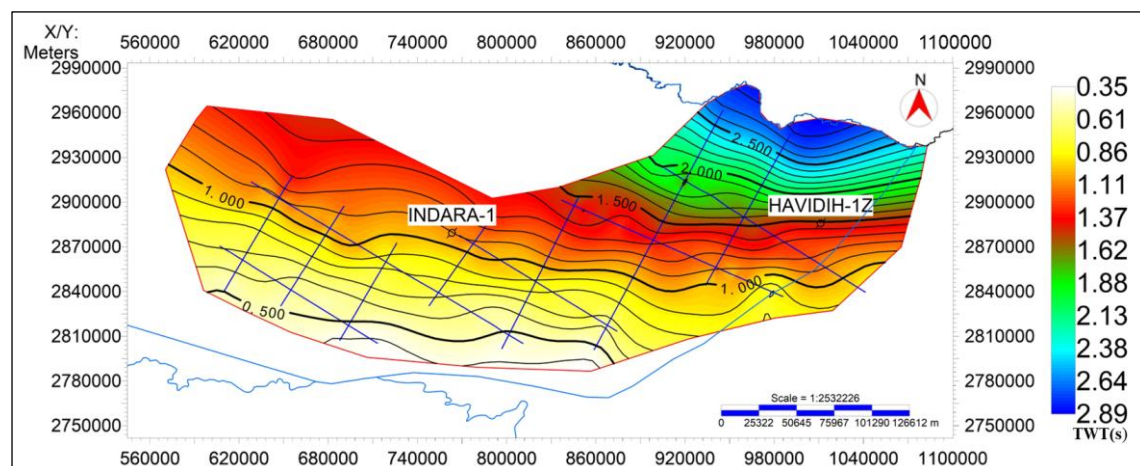


Figure 5.19: Isochore map of Regional Unconformity (RU).

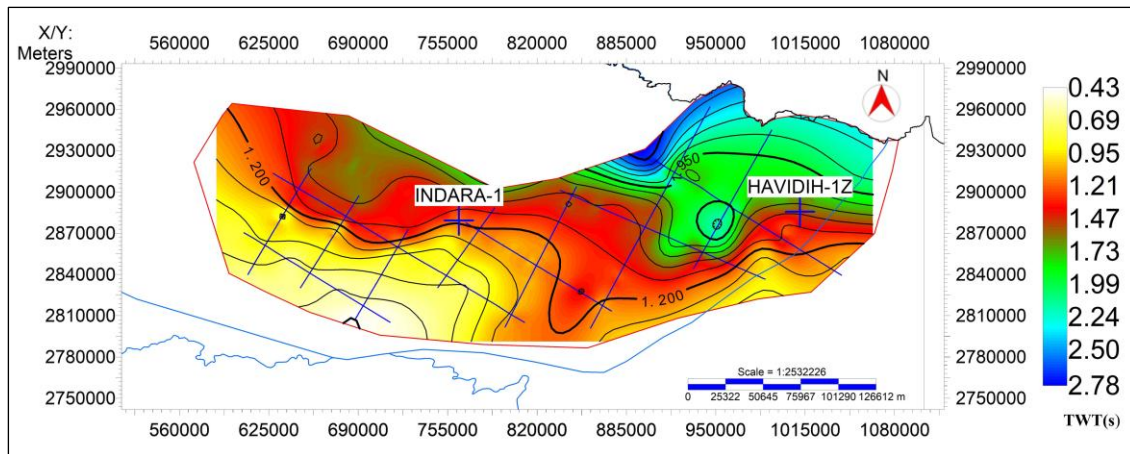


Figure 5.20: Isochore map of Bahraich (BH)

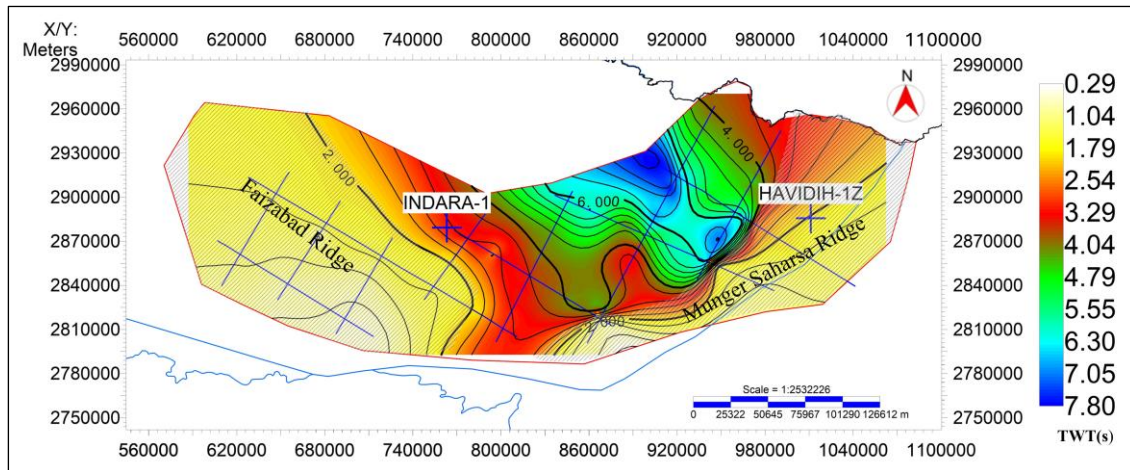


Figure 5.21: Isochore map of Archean Basement (AB)

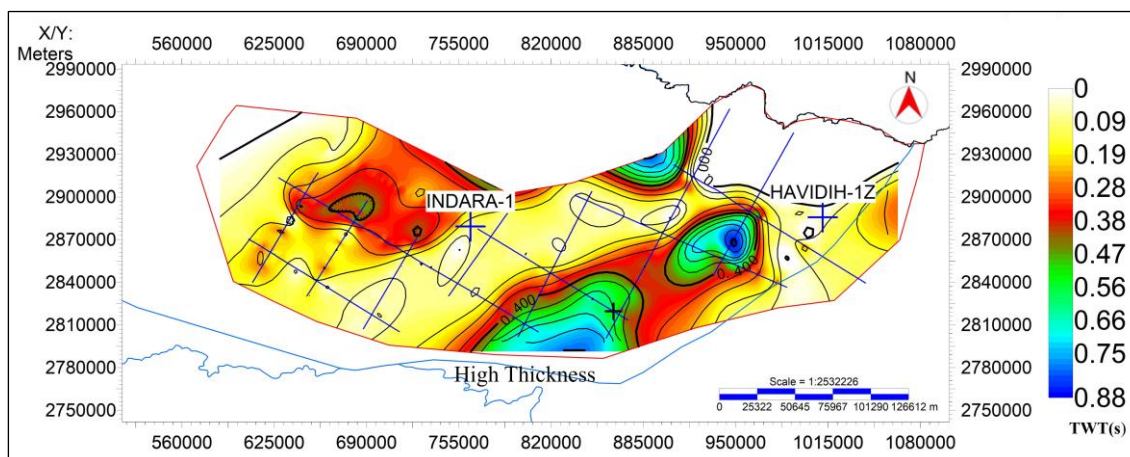


Figure 5.22: The map shows the Proterozoic sediment time thickness between the Bahraich and Regional Unconformity (RU) formations. The higher thickness between these formations is trending in the NE-SW direction.

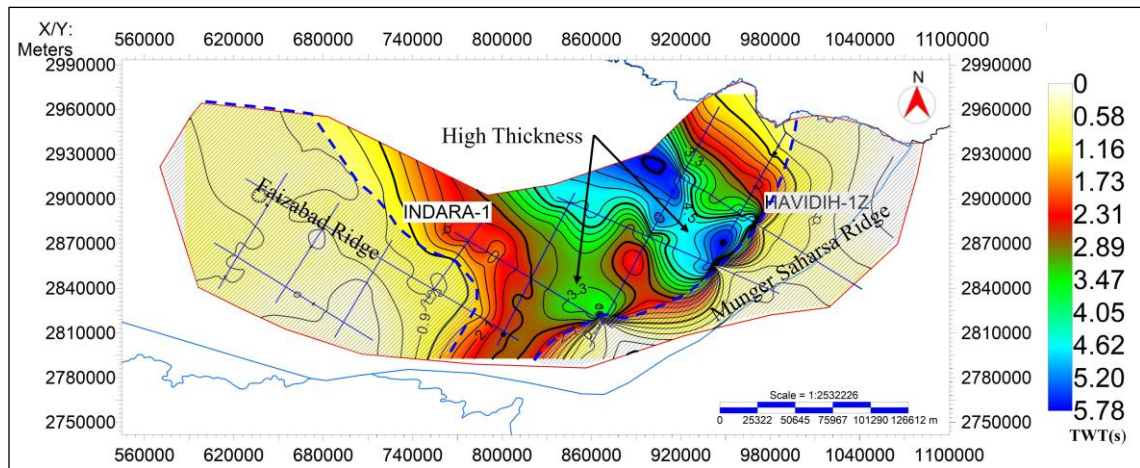


Figure 5.23: The map shows Proterozoic sediment time thickness between Regional Unconformity (RU) and the Archean basement. The higher thickness between these formations is trending in the NW-SE direction.

5.6.2 3D Seismic Data Interpretation

A 3D reflection seismic volume was interpreted to delineate the geometry of a subsurface structure and different types of sedimentary environments, such as fluvial, deltaic, marine, or lacustrine, which produce distinct seismic signatures. The survey has SEG normal polarity, meaning that a peak with black color represents the increasing amplitude (positive amplitudes), while decreasing amplitude (negative amplitudes) is represented by a trough with red color. The 3D seismic data were acquired from 0 to 8 s TWT. However, in this study, the area of interest is located between 0 and 4 s TWT, which covers the Bahraich and Siwalik sediments (Figure 5.25). Five horizons: Upper Siwalik (US), Middle Siwalik (MS), Lower Siwalik (LS), Regional Unconformity (RU), and Bahraich (BH) were identified from the well correlations. Belongs from the Tertiary to the pre-Tertiary age. Regional Unconformity (RU) and the Bahraich (BH) formation could be traced comfortably because of their good lateral continuity. In contrast, horizons within the Siwalik were challenging to trace laterally because of poor lateral continuity, showing fluvial sediment deposition in the Siwalik. However, Tilhar (TLR) and Ujhani (UJH) formations exist between RU and BH formations, but their reflection events are not continuously visible and show a chaotic reflection as well.

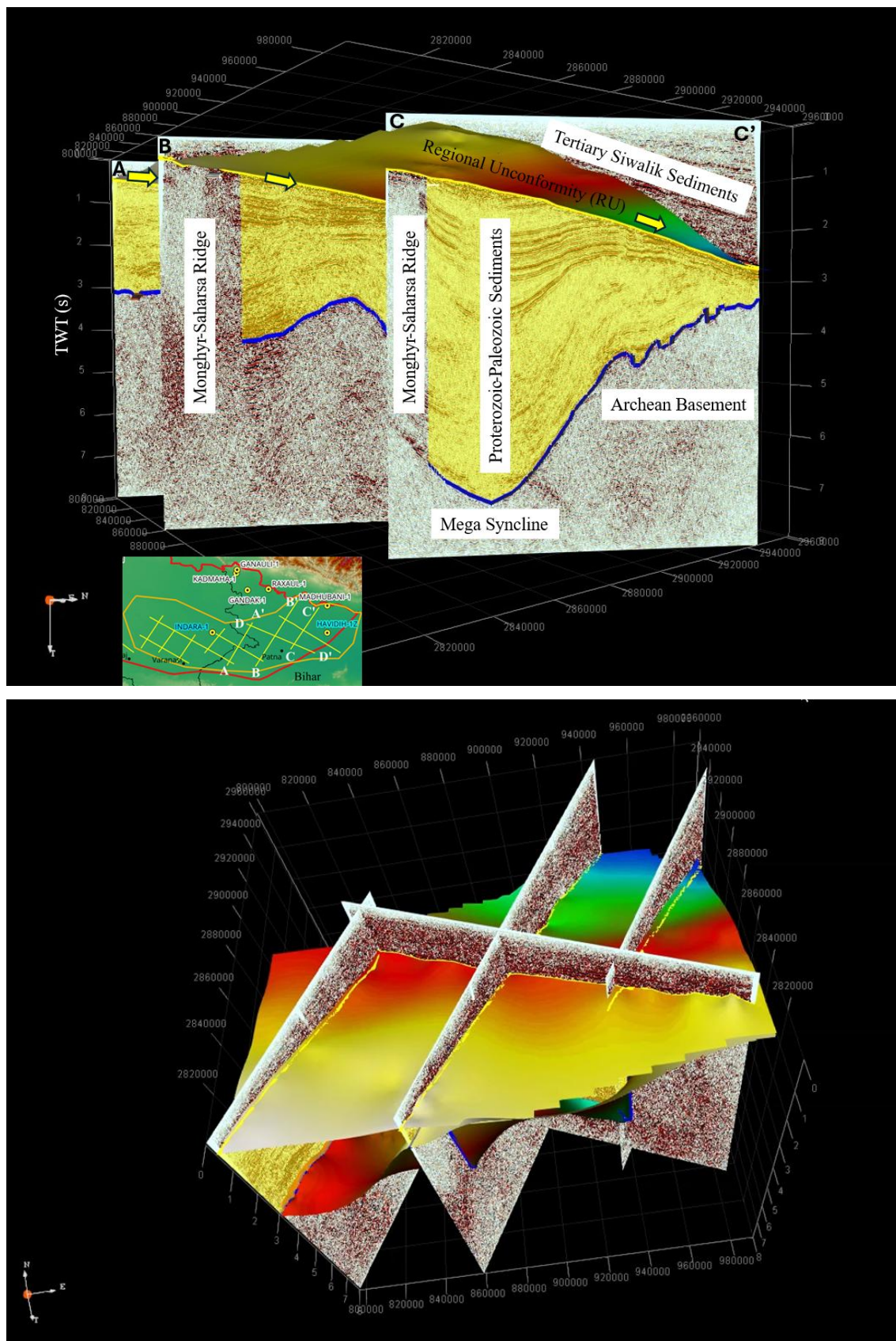


Figure 5.24: The upper 3D diagram represents the time thickness between the Archean basement and the Regional Unconformity (RU). The lower 3D diagram depicts the dipping direction of the Siwalik sediments, which is primarily in the NE.

All selected horizons were mapped, and their TWT isochrone maps are discussed below.

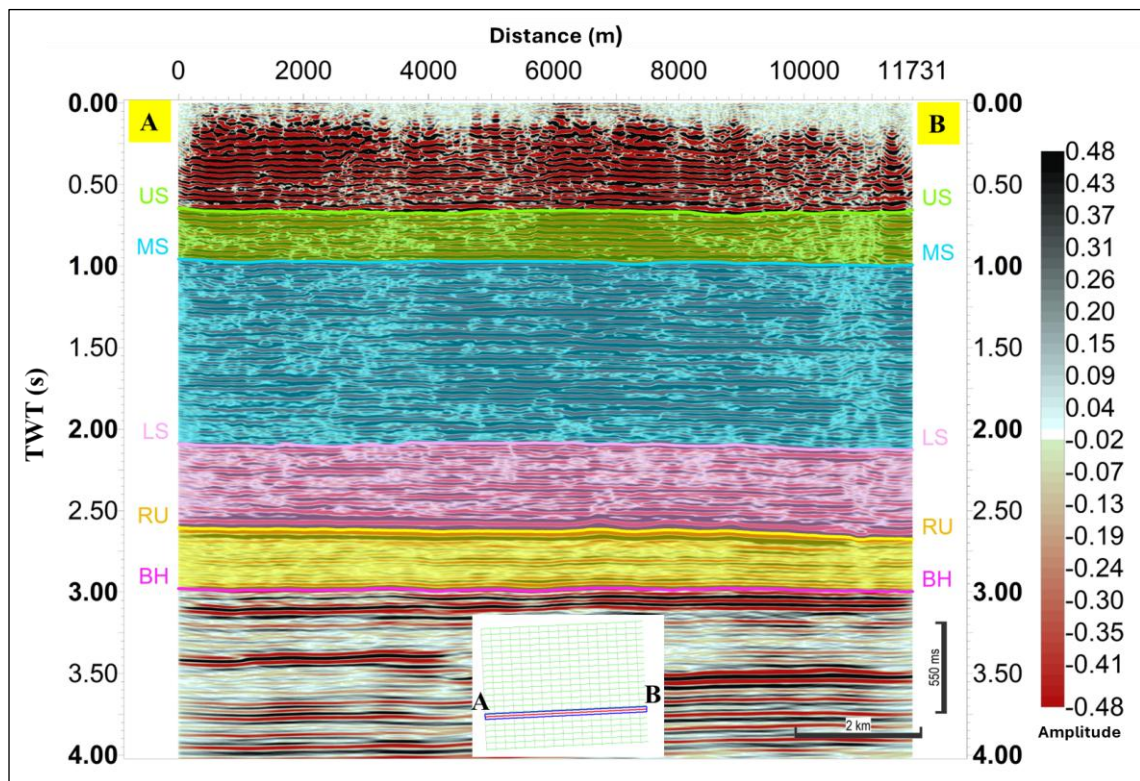


Figure 5.25: This figure illustrates the seismic section of the crossline 370 section with a marked horizon.

5.6.2.1 TWT Structure Maps

Formation tops interpretation requires picking a reflection horizons event across all the seismic survey inlines and crosslines. The horizon Bahraich has been picked up in the 3D seismic volume based on well correlation information. This horizon has a concordant relationship with the reflectors below and above. The TWT contour value varies from 2.96 to 3.07 s for the Bahraich formation. This formation shows linear continuous reflection with marine sediment deposition. There are no faults in the penetrating Bahraich formation observed in the 3D volume. However, below the Bahraich formation, several reverse faults have been identified. Those faults may have developed during the tectonic events in the Proterozoic era. Overall, the contours run NE-SW, indicating the surface has a regional dip towards NE (Figure 5.26E).

The regional unconformity (RU) horizon shows a high-amplitude, continuous, strong seismic reflector range of 2.59 to 2.78 s TWT depth (Figure 5.26D). This is the most prominent marker in the basin. It indicates a long hiatus boundary between Tertiary and pre-Tertiary sediment deposition, which could be identified all over the Ganga basin. The contours in the isochron map run approximately NE-SW, indicating the regional dip of the surface is towards NE. Most of the horizons below this reflector (RU) truncate against it.

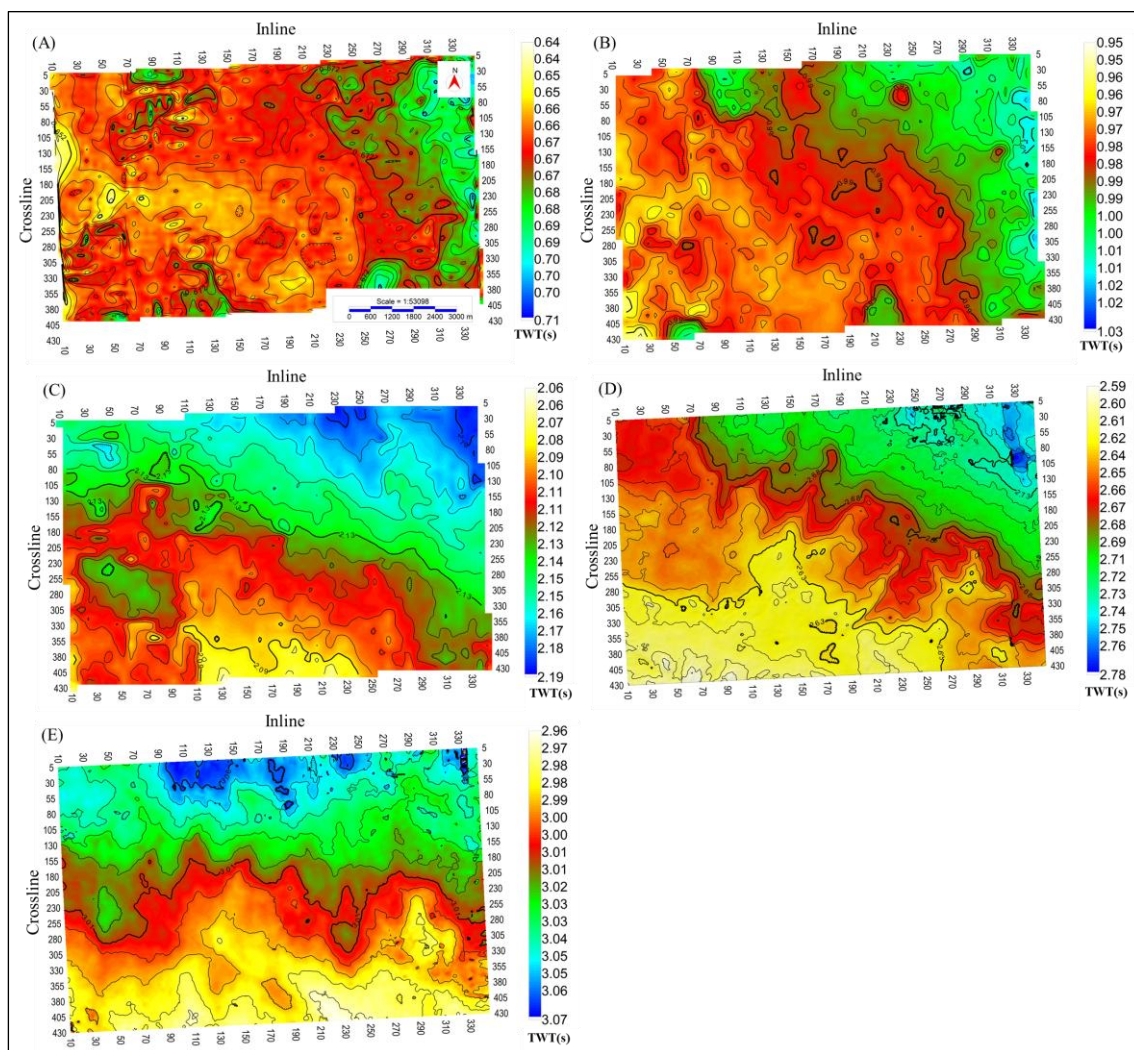


Figure 5.26: The schematic diagram illustrates (A-E) an isochron map of the picked formation tops in 3D seismic data. A (Upper Siwalik), B (Middle Siwalik), C (Lower Siwalik), D (Regional Unconformity), E (Bahraich).

The Lower Siwalik (LS) shows the poor lateral continuity and amplitude contrast of seismic reflectors at this interval; it is relatively problematic to correlate regionally.

Tertiary succession is almost undisturbed except for the northernmost area, which is affected by the Himalayan Frontal Thrust (HFT) and has given rise to fault-related folds. The general trend of the contours is NW-SE, indicating that the surface has a regional dip towards NE. The maximum and minimum TWT contour values are 2.19 s and 2.06 s, respectively (Figure 5.26C).

The formation top for the middle Siwalik and upper Siwalik shows TWT depth ranges of 0.95 to 1.03 s and 0.64 to 0.71 s, respectively. The contours of this formation also dip towards the NE direction and are primarily undisturbed by faults (Figure 5.26B) & Figure 5.26A). All these selected formation tops have also been mapped in a 3D diagram (Figure 5.27).

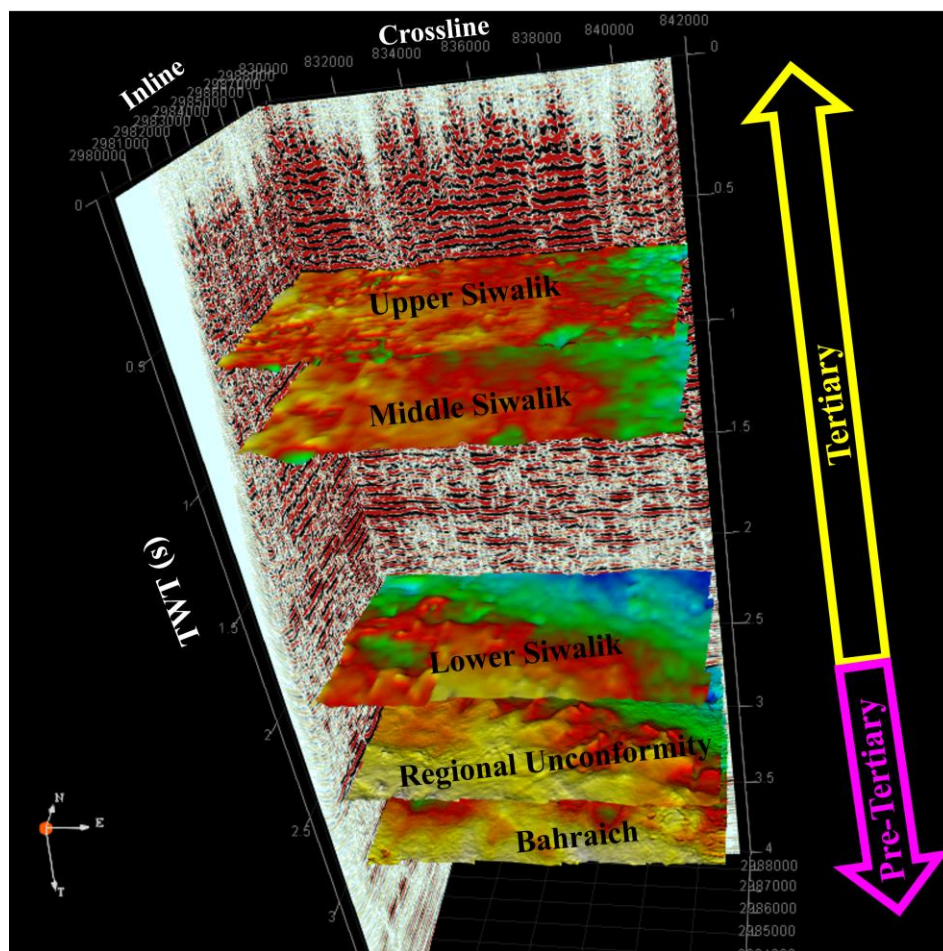


Figure 5.27: 3D seismic data from the Gandak depression showing relative time depth of picked formation tops horizons in the Tertiary and pre-Tertiary sediments.

5.6.2.2 Seismic Facies Analysis

The reflection configurations for the three-dimensional seismic data are displayed in the image below. To achieve accurate identification of depositional habitats, it is necessary to include seismic attribute analysis, which will be covered further in this thesis.

In this study, seismic facies analysis was performed on crossline 370, trending in the W-E direction. The facies were categorized into two mega sedimentary formations, tertiary (Upper Siwalik, Middle Siwalik, and Lower Siwalik) and pre-Tertiary (RU/Karnapur, Tilhar, Ujhani, and Bahraich) (Figure 5.28). Upper Siwalik is composed predominantly of subparallel, semicontinuous, chaotic, thin myrmekitic beds, having high- to low-amplitude reflection. These indicate an environment of varied depositional energy in which loose sand, kankar, gravels, and pebbles were settled. Middle Siwalik is characterized by parallel but discontinuous deposition with high-frequency, thin-bedded strata. The chaotic nature of the facies suggests rapid, uniform sedimentation and fluctuations in fluvial energy conditions. Lower Siwalik is dominated by deltaic channel deposits, displaying parallel to subparallel, chaotic thin bed deposition. Reflections are discontinuous, indicating the influence of deltaic processes. Regional Unconformity (RU)/Karnapur features high-amplitude, concave, strong reflection boundaries. The deposits are continuous, with thick beds, low-frequency wavy-parallel stratification, and an unconformity surface indicating significant tectonic or erosional events, having vertical stacking patterns. Tilhar displays subparallel, low-amplitude reflections with thick beds that are discontinuous, highlighting a relatively stable depositional regime with localized disruptions. In the Ujhani formation, facies are wavy and continuous with subparallel, high-amplitude stratified reflections. These strong reflections suggest well-defined layering, likely due to uniform sedimentation processes. The Bahraich formation exhibits continuous, subparallel reflections at the top and varying amplitudes at the

bottom, which has been a washout indication that this formation is composed of metasediments.

	Amplitude	Seismic character interpretation	Lithology
Tertiary (Post-collisional)		Upper Siwalik- Subparallel, semicontinuous chaotic thin beds, myrmekitic, high to low amplitude reflection	Interbedded Sandstone, Silty Claystone
		Middle Siwalik- Parallel, discontinuous deposition high Frequency, thin beds strata, chaotic	Sandstone, Claystone, and Siltstone
		Lower Siwalik- Deltaic channel dominant, parallel to subparallel, chaotic thin bed deposition, discontinuous reflection, deltaic	Sticky clay, Sandy claystone, and hard siltstone
Pre-Tertiary (Pre-collisional)		RU/Karnapur/Dharmsala- High amplitude, concave strong reflection boundary, Continuous, Thick Beds, Low frequency, Wavy- Parallel, Stratified, unconformity surface	Siltstone, Shale, Sandstone and Limestone/Marl. Dominantly arenaceous with fissile shales, claystone
		Tilhar- Sub parallel, low amplitude, thick beds, discontinuous	Shale, Siltstone, Sandstone Argillaceous Limestone,
		Ujhani- Wavy continuous, subparallel high amplitude, stratified, strong Reflection	Quartzitic Sandstone with Shale and Claystone
		Bahraich- High to low amplitude, continuous, subparallel, thick beds	Quartzitic Sandstone, Limestone Basic rocks, Phyllites, and Schists

Figure 5.28: The above diagram shows different seismic facies along crossline 370, from pre-Tertiary to Tertiary sediment deposits.

Chapter 6 : Evaluation of Proterozoic Sedimentary Sequences Using Seismic Data and Gravity Modelling

6.1 Background

Integration of recently acquired high-resolution regional seismic with gravity and well log information has provided new insights into the tectono-stratigraphic evolution and subsurface architecture of the Ganga Basin. Seismic interpretation reveals that the basin experienced significant tectonic deformation during the Early to Meso-Proterozoic, as evidenced by the presence of folds, faults, periods of uplift, and multiple unconformities. The principal phase of sedimentation occurred within the intracratonic rift system, resulting in the deposition of six distinct stratigraphic sequences newly identified in this study. Two major erosional unconformities formed during the Proterozoic that indicate episodic uplift and erosion not previously recognized in the stratigraphic record. Deposition of the Bahraich Group during the Late Mesoproterozoic, followed by the Ujhani, Tilhar, and Karnapur formations during the Neoproterozoic–Early Paleozoic, established the pre-Tertiary framework of the basin.

Two-dimensional gravity modelling along four select seismic profiles across gravity highs in the southern parts of the Gandak and Madhubani depressions indicates that these gravity anomalies correspond to dense Paleoproterozoic sequences rather than basement uplifts, with the successions extending to basement depths of approximately 6-20 km. The presence of Neoproterozoic to Early Paleozoic sequences in the Ganga Basin equivalent to the Vindhyan Group, which hosts proven hydrocarbon discoveries suggests that potential petroleum prospects could be present in the region. Seismic interpretation further indicates the presence of structural, stratigraphic, and combination traps across the basin. However, extensive erosional hiatuses and the lack of well-developed trapping mechanism may pose challenges to hydrocarbon preservation. This study establishes a

refined tectono-stratigraphic framework for the basin and emphasizes the need for more closely spaced 2D and 3D seismic surveys to delineate structural and stratigraphic traps more precisely, assess the continuity of Proterozoic sequences, and evaluate the hydrocarbon prospectivity of this underexplored region.

6.2 Introduction

The Ganga Basin has been an area of significant interest for hydrocarbon exploration over the past several decades due to its extensive sedimentary cover and complex geological history. The first exploratory well was drilled in 1960, and since then, 26 wells have been drilled in pursuit of oil and gas. Recent commercial gas discoveries within the Proterozoic strata of the Vindhyan Basin to the south (Pandey and Ojha, 2025) have encouraged exploration activities for evaluating analogous plays in the Ganga Basin. In this context, the present study integrates recently acquired deep 2D seismic data with available gravity information and wireline logs to evaluate the observed gravity anomalies for characterization of the Proterozoic sequences within the basin.

Physiographically, the Indian subcontinent is divided into the Himalayan orogenic belt, the Peninsular craton, and the intervening Indo-Gangetic Plain (Khanolkar et al., 2020). The Indo-Gangetic Plain represents a vast foreland system comprising several sub-basins the Indus, Punjab, Ganga, Bengal, and Brahmaputra formed primarily by Neogene–Quaternary sedimentation in response to Himalayan uplift. The Ganga Basin, occupying the central segment of this foreland system, preserves an exceptionally long record of Proterozoic to Recent tectono-sedimentary evolution (Figure 6.1).

The basin initiated as an intracratonic rift in the Early Proterozoic and later transitioned into a pericratonic settings (Sastri et al., 1971). Passive-margin sedimentation during Mesoproterozoic rifting led to deposition of the Bahraich Group directly overlying the

Bundelkhand Granite Complex (BGC) (Srinivas et al., 2014). This rifting event may be associated with the fragmentation of the Columbia supercontinent (Rogers and Santosh, 2002; Li and Zheng, 2008; Santosh, 2012; Meert and Pandit, 2015). Following deposition of the Bahraich Group, the basin experienced its first major depositional hiatus.

During the Neoproterozoic–Paleozoic, renewed pericratonic subsidence facilitated deposition of the Madhubani, Ujhani, Tilhar, and Karnapur formations (Vindhyan equivalent), possibly linked to breakup of Rodinia supercontinent (Meert and Pandit, 2015). Regional uplift triggered by the Pan-African orogeny curtailed sedimentation in large parts of Peninsular India, although localized deposition persisted within restricted depressions in the Ganga Basin. Paleozoic sedimentation, dominated by shallow-marine platformal facies, remained strongly influenced by inherited basement heterogeneities (Valdiya, 1976).

The Neoproterozoic–Paleozoic sequences subsequently underwent inversion, likely associated with Hercynian–Appalachian tectonism (Cawood et al., 2007; Dhamodharan et al., 2020). This compressional regime promoted uplift, dislocation, and erosion across the basin, while concomitant rifting further south initiated the Gondwana basins. Most of the Mesozoic to early Paleogene record is absent due to prolonged peneplanation, represented by the regionally extensive unconformity (RU) that spans approximately 385 million years (Ojha, 2012).

A major shift in the basin's tectonic framework occurred following the breakup of Gondwana and the rapid northward drift of the Indian plate. Collision with Eurasia around 45–50 Ma resulted in crustal shortening, development of the Himalayan orogen, and establishment of a peripheral foreland basin (Dewey and Bird, 1970; Chatterjee et al., 2013). Progressive Himalayan uplift produced a flexural foredeep that was rapidly infilled with molasse sediments derived from the rising orogen to the north and from the

Vindhyan highlands to the south. These Neogene deposits, collectively termed the Siwalik Group, record an extensive history of fluvial aggradation and foreland subsidence (Summons et al., 1988; Sinha et al., 2010; Demudu Babu et al., 2020).

Certain wells in the Ganga Basin have indicated hydrocarbon occurrences, especially gas shows within the Proterozoic intervals (Prasad and Rao, 2006), underscore the basin's untapped resource potential. Commercial gas discoveries in analogous Proterozoic reservoirs of the Vindhyan Basin (Pandey and Ojha, 2025) have further prompted the Government of India to intensify hydrocarbon exploration efforts in the Ganga Basin. Initiatives like the National Seismic Programme (NSP), launched in 2016, have acquired extensive regional 2D seismic surveys across all 26 sedimentary basins of India, including the Ganga Basin, thereby improving subsurface imaging in previously underexplored areas (DGH, 2024).

Earlier geophysical studies have used Bouguer gravity maps and magnetotelluric (MT) data to examine the crustal thickness in the area. Choudhury (1975) determined a crustal thickness of about 36 km north of Lucknow by modelling these data. Ravi Kumar et al. (2013) reported an average crustal thickness of 38 km and a lithospheric thickness of 140 km from spectral analysis of the Bouguer anomalies. Adilakshmi et al. (2021) documented the Moho discontinuity at a depth of 40–45 km in their MT survey conducted in the Bundelkhand region.

The present study synthesizes high-resolution seismic profiles from the NSP, Bouguer gravity maps, and well-log constraints to refine subsurface stratigraphic and structural frameworks in the Ganga Basin. Through integrated gravity–seismic modelling, we aim to improve delineation of Proterozoic sequences, basement configuration, and density variations within key lithostratigraphic units. This combined approach enhances the

reliability of structural and stratigraphic interpretations that are vital for evaluating hydrocarbon prospectivity within deeply buried Proterozoic targets.

6.3 Study Area and Geological Settings

The Indo-Gangetic (IG) Plain covers an area of approximately 304,000 sq. km and includes Ganga Basin (GB) to the east of the Delhi-Haridwar Ridge (DHR) and Punjab Plain (PP) to the west (Figure 6.1). The Ganga Basin extends over 1,000 km in length and 300 km in width, between 77°E - 86°E longitudes and 25°N – 33°N latitudes. The Punjab Plain encompasses an area of roughly 62,000 sq. km, whereas the Ganga Basin covers a larger expanse of about 242,000 sq. km, accounting for more than three-quarters of the total area of the Indo-Gangetic Plain.

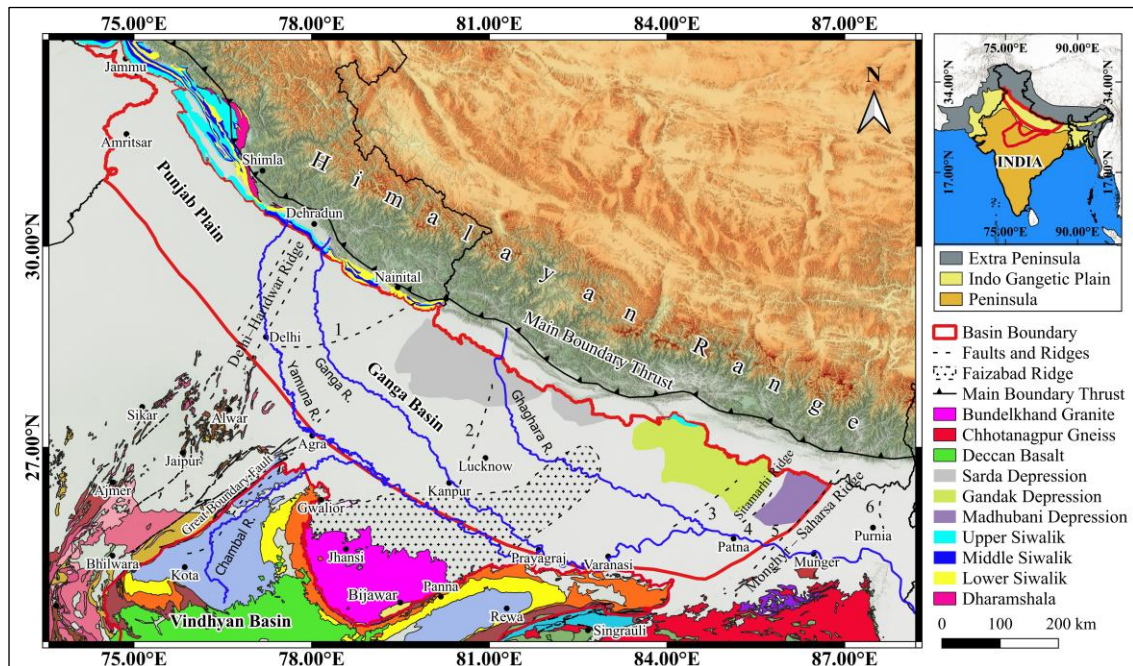


Figure 6.1: The regional map illustrates the lithology and tectonic structures of the Ganga Valley basin, with numbers indicating the significant subsurface faults identified through geophysical methods. 1. Delhi-Moradabad Fault, 2. Lucknow Fault, 3. West Patna Fault, 4. East Patna Fault, 5. Monghyr-Saharsa Ridge Fault, 6. Malda-Kishanganj Fault; R. River. The inset figure on the top-right represents physiographic classification of the Indian subcontinent. The lithological map is modified from GSI map available at <https://bhukosh.gsi.gov.in/Bhukosh/Public>.

The current study examines 2D seismic and gravity data in the eastern region of the Ganga Basin, specifically the southern parts of the Gandak and Madhubani depressions (Figure 6.1).

The basin is bounded by the subsurface Monghyr–Saharsa Ridge to the east and the Delhi-Haridwar Ridge (DHR) to the west (Figure 6.1). To the north, it is delineated by the outermost Siwalik foothills adjacent to the Himalayan Frontal Thrust, a series of reverse faults extending parallel to the Himalayas along the northern perimeter of the basin. The southern boundary of the basin is defined by the exposed Purana sediments (Vindhyan Group) and Bundelkhand granite-gneiss massif. Based on gravity-magnetic, aeromagnetic, and seismic survey analyses, previous researchers have delineated three significant depressions in the Ganga Basin – Sarda, Gandak, and Madhubani (Rao, 1973; Valdiya, 2016). These depressions are said to be separated from one another by intervening basement ridges (Figure 6.1). The Faizabad Ridge divides the Sarda and Gandak depressions, and the Sitamarhi Ridge separates the Gandak and Madhubani depressions. Sastri et al. (1971) provided a comprehensive tectonic and geological classification of the Ganga Basin by categorizing it into seven major structural provinces from east to west: (1) Monghyr-Saharsa Ridge, (2) East Uttar Pradesh Shelf, (3) Gandak Depression, (4) Faizabad Ridge, (5) West Uttar Pradesh Shelf, (6) Sarda Depression, and (7) Delhi-Hardwar Ridge.

The Monghyr-Saharsa Ridge stretches northeast, serving as a natural continuation of the Chotanagpur Plateau. This ridge delineates the boundary between the Purnea and Madhubani depressions. It likely comprises rock formations typical of the Satpura fold belt. The Bundelkhand granites constitute the basement that experienced faulting as a result of tectonic activity. This process resulted in the formation of two intracratonic

basins, referred to as the eastern and western shelves of Uttar Pradesh, with a prominent elevation in the centre known as the Faizabad Ridge.

The eastern limit of the East Uttar Pradesh shelf is delineated by the Monghyr-Saharsa Ridge, while its western limit is marked by the Faizabad Ridge. This zone is bordered to the south by the exposed Vindhyan of the Son Valley and the underlying basement rocks. The East Uttar Pradesh shelf dips northward into the Gandak Depression, which is likely underlain by rocks from the Satpura Fold Belt, overlain successively by Vindhyan, Paleogene, and Neogene sequences (R. Sinha et al., 2005). This shelf area is defined by east-west trending aeromagnetic contours, signifying the existence of numerous highs and lows plunging in an easterly direction (Suresh et al., 2023).

The Faizabad Ridge, an important tectonic feature distinguishing the Ganga Basin, is regarded as a subsurface extension of the Bundelkhand massif into the Ganga Basin (Suresh et al., 2023), extending from southwest to northeast. The region situated to the west of the Faizabad Ridge is designated as the West Uttar Pradesh shelf, confined by the Great Boundary Fault and the Delhi-Moradabad Fault (DMF) to the west of the Ganga Basin. The major faults in this region trend in NE-SW direction, parallel to the Aravalli-Delhi Fold Belt (ADFB) (Duvall et al., 2021; Kashyap et al., 2022; Demudu Babu et al., 2024).

The Sarda depression forms the northern segment of the West Uttar Pradesh shelf, demarcated tectonically by its sedimentary thickness exceeding 6 km and distinguished by a NW-SE trending depocenter axis. The substantial sedimentary accumulation in this depression may encompass Mesozoic and Paleogene layers, in addition to Vindhyan and Neogene deposits (Sastri et al., 1971).

The Delhi-Haridwar Ridge (DHR) extends in a north-northeast direction from the Aravalli-Delhi Fold Belt and defines the western limit of the Ganga Basin. The oldest sedimentary layer in the basin, the Vindhyan succession, may gradually decrease in thickness towards this ridge (Roy and Purohit, 2015; Kashyap et al., 2023).

6.4 General Stratigraphy and Depositional Environment

The accumulation of sedimentary materials within a basin is profoundly influenced by tectonic activity and prevailing environmental conditions. Sedimentological analyses offer valuable insights into the unique depositional environments of various formations within the Ganga Basin. Geologically, the basin comprises an Archean–Paleoproterozoic Bundelkhand Granite Complex basement overlain by a thick succession of Mesoproterozoic to Quaternary sediments. Terrigenous sedimentation within the basin is broadly grouped into three major intervals: i) the Mesoproterozoic Bahraich Group, ii) the Neoproterozoic – Early Paleozoic Ujhani, Tilhar, and Karnapur formations, and iii) the Tertiary Siwalik Group capped by Quaternary Alluvium (Shukla et al., 1994; Gorain et al., 2023).

A generalized stratigraphic framework of the Ganga Basin and its depositional environment is summarized in Table 6.1. The sequence begins with the Bundelkhand Granite, subsequently faulted by tectonic activity. Overlying this is the Bahraich Group, equivalent to the Lower Vindhyan sequence, comprising phyllitic shale, slate, and orthoquartzite. These lithologies indicate a shallow-marine inner-shelf environment, with a prominent regressive trend manifested through systematic coarsening-upward orthoquartzite (Ojha, 2012). The Ujhani, Tilhar, and Karnapur formations correspond to the Upper Vindhyan succession of Neoproterozoic to Early Paleozoic age (Ojha, 2012). The Ujhani Formation reflects a progressive marine transgression from littoral to inner-shelf settings, supported by isotopic signatures indicative of marine conditions and

characterized by alternating layers of shale, sandstone, and limestone (Srinivas et al., 2014). The Tilhar Formation records deposition on a restricted semi-arid carbonate shelf with minimal terrigenous influx, suggesting limited tectonic activity. A subsequent transgressive phase shifted sedimentation to an outer-shelf regime dominated by fine clastics, producing alternating carbonate and pelitic assemblages (Tandon et al., 2008; Khanolkar et al., 2020). The Karnapur Formation, deposited in a shallow marine setting, comprises alternating thick shale and sandstone sedimentary units, indicating diverse depositional facies from littoral-marginal marine to shallow shelf settings (DGH, 2012). The basin was predominantly filled with Tertiary Siwalik sediments and Quaternary alluvium deposited by rivers originating from the Himalayan range (Mishra et al., 2000; Tunini et al., 2016; Singh and Khan, 2021; Manglik et al., 2022). The Tertiary deposits are categorized into five formations, three of which are part of the Siwalik Group. The Siwalik Group represents a fluvial to alluvial-fan depositional system, evolving from low-energy meandering rivers (Lower Siwalik) to high-energy braided and fan systems (Upper Siwalik) as orogenic uplift intensified and sediment supply increased (Nakayama and Ulak, 1999; Goswami and Deopa, 2018). The Siwalik Group is marked by an overall coarsening upward trend with isolated fining upward siliciclastic units and has the thickest accumulation of debris sourced from the Himalayas in the foreland basin (Parkash et al., 1980; Gautam and Rösler, 1999; Kumar et al., 2003; Quick et al., 2020). The Cenozoic sediment thickness in several depressions of the Ganga Basin exceeds 4.5 km, expanding in a northward direction and along the Himalayan foothills (Hetényi et al., 2006; Adilakshmi et al., 2021).

Table 6.1: Generalized stratigraphic sequence of the Ganga basin [modified after (Ojha, 2012; Srinivas et al., 2014)].

Era	Period		Age (Ma)	Group / Formation		Thickness (m)	Lithology	Depositional Environment	Tectonics
Cenozoic	Quaternary		1.5 - Recent	Alluvium		200-426	Loose sand, Kankar, Gravel, and Pebbles	Widespread braided fluvial system	Himalayan Orogeny
	Tertiary	Neogene	6.5-1.5	Upper Siwalik	200-1300	Interbedded Sandstone, Silty Claystone			
			10.8-6.5	Middle Siwalik	250-1970	Sandstone, Claystone, and Siltstone			
			18.3-10.8	Lower Siwalik	130-1540	Sticky clay, Sandy claystone, and hard siltstone			
	Paleogene	35-28	Matera	400	Grey to black silt shale alternation, occasional sandstone	Marine Incursion in Basal Part			
Regional Unconformity									
Neoproterozoic-Lower Paleozoic			635-540	Karnapur		50-450	Dominantly arenaceous with fissile shales and claystone	Outer Shelf	Tianshanian Orogeny
			670-635	Tilhar		210-380	Argillaceous Limestone, Dolomitic at base with Shale	Carbonate Shelf	Extensional Tectonics around Gondwana
			Unconformity						
			700-800	Ujhani		130-850	Quartzitic Sandstone with Shale and Claystone	Shallow Marine	Gondwana Stabilization, Rodinia Breakup
Unconformity									
Mesoproterozoic			1450-1350	Bahraich	Avadh	527+	Quartzitic Sandstone, Limestone	Marginal Marine, Synrift Sediments	Tectonic Subsidence
			1550-1450				Sarda		
Archean Basement (Bundelkhand Granite/Gneiss)									

6.5 Seismic, Wells and Gravity Data Analysis

This study characterizes the subsurface geological structures and depositional stratigraphy of pre-Tertiary sediments in the eastern Ganga Basin (Figure 6.1) through the integration of regional seismic profiles, wireline logs, and gravity anomaly data. High-resolution 2D reflection seismic data covering 3,858-line kilometres (LKM) were

recently acquired under the National Seismic Program (NSP). In the eastern part of the basin, twelve 2D seismic lines totaling 1,508 LKM (Figure 6.2), were acquired in 2017-18 using dynamite as the energy source. The seismic acquisition employed a shot interval of 60 m and a receiver interval of 20 m, producing a nominal fold of 150. Data were recorded at a 2 ms sampling rate with a record length of 8 seconds two-way travel time (TWT). The seismic data follow SEG normal polarity convention, wherein a peak represents a positive reflection coefficient, and a trough corresponds to a negative reflection coefficient. Preliminary mapping of seismic horizons and interpretation of major stratigraphic units were conducted on post-stack time-migrated sections using S&P Global's *Kingdom*TM software.

The Havidih-1Z and Indara-1 wells are essential components of the geological investigation within the Ganga Basin (Figure 6.2). The Havidih-1Z well was drilled in 2009 to a depth of 1,700 m, whereas the Indara-1 well was drilled in 2013, reaching a depth of 1,955 m. The two wells are approximately 250 km apart. Wireline logs, together with mudlog and core data from both wells, were used to construct detailed lithological descriptions and subsurface stratigraphic characteristics.

Satellite Bouguer gravity data were used to identify subsurface anomaly patterns within the Ganga Basin and its adjoining regions, and to delineate basin scale tectonic features for a comprehensive regional analysis. The gravity grids were derived from the Earth Gravitational Model (EGM 2008) provided by the International Gravimetric Bureau (BGI); (<https://bgi.obs-mip.fr/>). The dataset is regional, with a resolution of 2.5' x 2.5' arc minutes and an accuracy of ± 5 mGal (Ravi Kumar et al., 2013).

The integrated interpretation of gravity and seismic datasets provides critical insights into regional tectonic processes and geological architecture. Together, these datasets help

unravel basin evolution, structural history, depositional settings and sedimentary patterns – factors essential for basin modelling and for formulating effective regional exploration strategies.

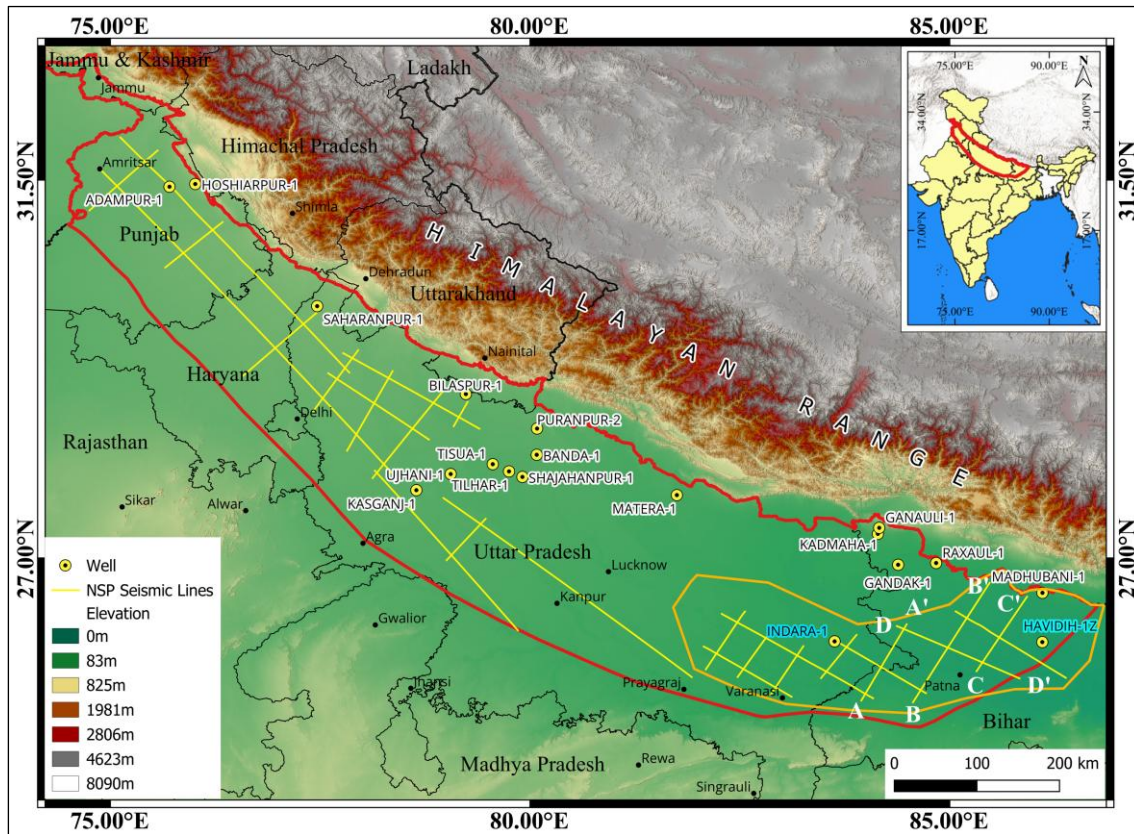


Figure 6.2: This represents an elevation map of the Ganga Basin, with measurements taken relative to mean sea level. The map indicates the locations of NSP seismic lines and wells. The seismic lines AA', BB', CC', and DD' have been interpreted for the present study.

6.5.1 Lithologic description of the Havidih-1Z and Indara-1 wells

Depth-wise lithological details for the Havidih-1Z and Indara-1 wells are presented in Table 6.2 and Table 6.3, respectively. The correlation of wireline logs from these wells is illustrated in Figure 6.3 and has been used to delineate the geological formations, assess hydrocarbon potential, and interpret structural features within the Ganga Basin.

Table 6.2: Lithostratigraphy of the well Havidih-1Z.

Age	Formation	Depth (m)	Lithology
Recent	Alluvium	0-670	Loose sand, Sandstone with Claystone,
Tertiary	Recent and Upper Siwalik	670- 870	Micaceous sandstone interbedded with Claystone, Limestone/Dolomite and minor siltstone, Lignite
	Middle Siwalik	870-950	Interbedded Claystone, Micaceous Sandstone, Limestone and Dolomite
		950-1005	Interbedded Claystone, Limestone and Dolomite with minor Micaceous Sandstone
		1005-1280	Interbedded Claystone and Micaceous sandstone with minor Limestone and Dolomite
		1280-1305	Dominant Claystone and Micaceous Sandstone with intercalations of Siltstone, Limestone and Dolomite
	Lower Siwalik	1305-1325	Dominant Claystone and Micaceous Sandstone with intercalations of Siltstone, Limestone and Dolomite
		1325-1410	Claystone interbedded with Micaceous Sandstone, Limestone and Dolomite.
Post Paleozoic?	Unknown/ Mesozoic?	1410-1510	Claystone with intercalation of Sandstone, Limestone and Dolomite
		1510-1525	Interbedded Claystone and Sandstone with minor siltstone, Limestone and Dolomite
Regional Unconformity (RU)			
Neoproterozoic -Lower Paleozoic	Karnapur	1525-1550	Interbedded Claystone and Sandstone with minor siltstone, Limestone and Dolomite
		1550-1608	Interbedded Claystone and Siltstone with minor Limestone and Dolomite
		1608-1625	Massive claystone with minor Siltstone, Limestone and Dolomite
	Tilhar	1625-1700	Interbedded Claystone, Limestone and Dolomite with minor Sandstone and Siltstone.
		1684-1700	Pelite sands, crystalline limestone

The Havidih-1Z well shows that the Upper Siwalik to recent alluvial deposits strata consist of micaceous sandstone interbedded with claystone, limestone/dolomite, and

minor siltstone, with occasional lignite layers. In the Middle Siwalik formation, the composition varies with depth, comprising interbedded claystone, micaceous sandstone, limestone, and dolomite. The deeper section of the Lower Siwalik has a similar composition, with dominant claystone and micaceous sandstone, interspersed with siltstone, limestone, and dolomite.

Table 6.3: Lithostratigraphy of well Indara-1.

Age	Formation	Depth (m)	Lithology
Quaternary	Alluvium	0-288	Loose sand, sandstone, and claystone
Tertiary	Upper Siwalik	288-500	Light brown, grey, dominantly fine grained, micaceous, calcareous sandstone.
	Middle Siwalik	500-962	Grey, brown, fine to coarse-grained, calcareous sandstone and light brown, soft, sticky, sandy, calcareous claystone. Traces of coal/peat are also present.
	Lower Siwalik	962-1182	Light brown, dominantly fine-grained, calcareous sandstone and ochre, yellow, dirty white, sandy, calcareous claystone.
Regional Unconformity (RU)			
Neoproterozoic - Lower Paleozoic	Karnapur	1182-1512	Consists of reddish-brown-colored hard and compact pebbly sandstone with some iron concretions, iron-rich hard claystone, and oolitic sandstone. Reddish-brown, brown, fine-to-coarse-grained, noncalcareous sandstone.
	Tihar + Ujhani?	1512-1612	Fine- to coarse-grained, non-calcareous sandstone with minor claystone and siltstone.
Mesoproterozoic	Bahraich	1612-1693	Grey, brown, fine-to-coarse-grained, non-calcareous sandstone with minor shale.
Precambrian	Basement?	1693-1955+	Basic Igneous Rock (Gabbro)

Below the Regional Unconformity (RU), the lithology transitions to claystone interspersed with sandstone, limestone, and dolomite. Furthermore, the Karnapur section features interbedded claystone and sandstone, transitioning into a massive claystone unit with minor siltstone and carbonates from depths of 1608 to 1625 m. The Tilhar Formation at the base is characterized by interbedded claystone, limestone, and dolomite, accompanied by minor sandstone and siltstone.

The stratigraphy of the Indara-1 well reveals a slightly different succession. The near-surface Quaternary Alluvium comprises loose sand and clay. The Upper Siwalik formation is made up of dominantly fine-grained micaceous to calcareous sandstones and clay/claystone deposits. The Middle Siwalik features a mix of sandstone, clay, claystone, and siltstone layers. The Lower Siwalik strata consist mainly of claystone, sandstone, and siltstone. Beneath the Regional Unconformity (RU), the Karnapur Formation predominantly consists of sandstone and attains a thickness of about 330 m, compared to 100 m in the Havidih-1Z well. The geological formation beneath Karnapur is believed to be Tilhar + Ujhani (?) and comprises deposits of sandstone, clay, claystone, and siltstone. The Bahraich Formation, characterized by shale, sandstone, claystone, and siltstone layers, overlies the Precambrian basement(?) encountered at 1693 m TVDKB, which consists of basic igneous rock (gabbro).

Furthermore, an electrolog correlation study (Figure 6.3) was conducted between the two wells using gamma-ray, density and sonic logs. These data were used to estimate formation density and velocity – key parameters for gravity modelling along select seismic lines (Table 6.4).

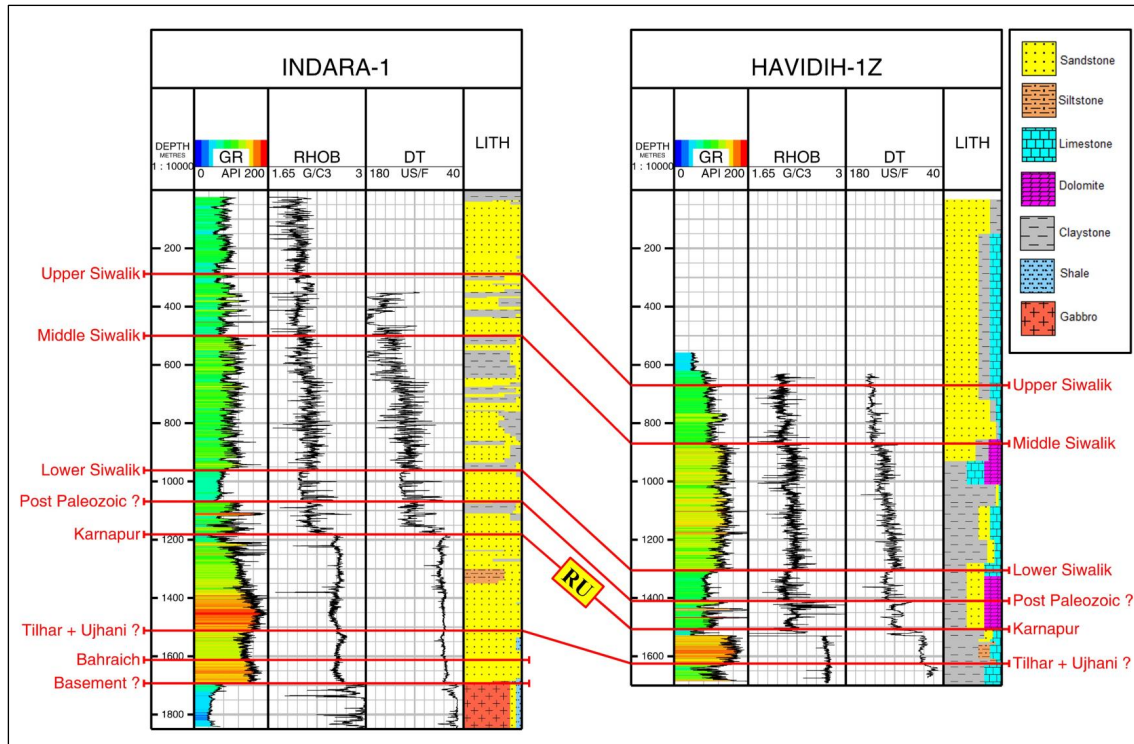


Figure 6.3: Electrolog correlation between Indara-1 and Havidih-1Z wells. The top of the Karnapur Formation is marked as the Regional Unconformity (RU).

6.5.2 Seismic data and its Interpretation

This study includes four select regional 2D seismic lines totaling 575 LKM. Three seismic lines are oriented in the NE-SW direction, while one is oriented in the NW-SE direction, intersecting the other three lines. These seismic lines are labeled on the elevation base map as AA', BB', CC', and DD' (Figure 6.2). The Indara-1 and Havidih-1Z wells within the study area, are utilized for seismic-to-well correlation, lithology identification, and seismic horizon picking.

The reliability of the interpreted seismic horizons and sequence boundaries is enhanced through calibration with the Indara-1 and Havidih-1Z wells using seismic-to-well ties, synthetic seismograms, and formation tops. Regional correlation across the intersecting seismic profiles (AA', BB', CC', and DD') further improves confidence in the continuity

of the interpreted horizons and structural features. However, the deeper Proterozoic sequences are not directly constrained by well data; therefore, their interpretation is based on seismic reflection characteristics, reflector continuity, seismic facies, and integration with gravity modelling. Consequently, the confidence in the interpreted horizons is high within the calibrated intervals and moderate for the deeper pre-Tertiary succession, where interpretations rely primarily on integrated geophysical evidence.

The NSP regional seismic sections provide extensive coverage of the Gandak and Madhubani depressions, offering detailed imaging of the subsurface structures and improved understanding of depositional history and lithostratigraphy relevant to hydrocarbon exploration. The select seismic sections (AA', BB', CC', and DD'; Figure 6.4 - Figure 6.7) illustrate high-frequency, high-amplitude reflectors for the upper, middle, and lower Siwalik fluvial deposits, dipping towards the northeast. A pervasive, strong reflector representing the major Regional Unconformity (RU) is observed beneath the lower Siwalik formation.

Significant Proterozoic sequences, also referred to as pre-Tertiary sequences, were identified below the RU, characterized by high-amplitude, continuous reflectors. The Ujhani, Tilhar, and Karnapur formations of Neoproterozoic to Early Paleozoic age are delineated and highlighted in yellow on the seismic sections. These formations exhibit folding, faulting and truncation against the RU, indicating potential for hydrocarbon entrapment. The Bahraich Formation of Mesoproterozoic age is depicted in magenta. Furthermore, prominent Paleoproterozoic sequences are notable beneath the Bahraich Formation and are designated as S1, S2, S3, S4, S5, and S6.

Potential structural traps in the pre-Tertiary sequences may be confined to local highs or ridges, which are observed in the seismic sections (Figure 6.5–Figure 6.7). Stratigraphic

traps are potentially associated with unconformities and pinch-out zones (Figure 6.4–Figure 6.7), while faults may act as seals and closures. Hydrocarbon prospects could exist in the upper Bahraich deposits in association with fault systems under favourable conditions.

The Tertiary sediments in the foreland basin (Siwaliks) were deposited over a relatively uniform surface with a gentle dip towards the Himalayas. The faults identified in the pre-Tertiary section in this study area do not extend into the Siwalik strata. Thus, seismic evidence indicates that the basin was tectonically active during Late Proterozoic sedimentation, with clear signature of subsidence, folding, and faulting. The Regional Unconformity (RU) signifies a gap in the Mesozoic sedimentary record (Table 6.1). Subsequently, extensive fluvial sediments derived from the Himalayas were deposited to form the Siwalik Formation within the foreland basin. The seismic sections also reveal the hidden basement ridges, such as the Monghyr-Saharsa ridge, which indicate possible magmatic intrusions during the development of the Ganga Basin. The subsequent discussion provides a comprehensive interpretation of each seismic profile.

Seismic section A-A'

The 114 km long seismic section A-A' images the Gandak depression in a NE-SW orientation, with its uninterpreted and interpreted versions shown in Figure 6.4. The seismic section shows a prominent reflector below the Lower Siwalik, designated as the Regional Unconformity (RU), dipping towards the northeast, and is delineated between 0.5 to 1.5 seconds two-way travel time (TWT). This high-amplitude seismic horizon is continuous throughout the Ganga Basin and is interpreted as the boundary surface between the Tertiary (T) and Pre-Tertiary (PT) sequences. Additionally, two other major

unconformity surfaces, designated as UC-1 and UC-2, are identified in the seismic section.

The seismic data also illustrate well-developed sedimentary sequences (S1–S6) within the Pre-Tertiary section below the Bahraich Formation. A series of high-angle reverse faults, associated with compressional tectonics, are observed across the seismic section. The Archean basement complex is identified below 3 s TWT. Overall, the seismic section shows evidence of potential structural and stratigraphic hydrocarbon traps in the Ganga Basin. The Bundelkhand Granite Complex represents the Archean basement (Suresh et al., 2023).

Seismic section BB' & CC'

The seismic sections BB' and CC' (Figure 6.5 and Figure 6.6) are parallel and separated by approximately 46 km. These seismic sections distinctly illustrate intense compressional tectonics resulting in the development of a prominent synclinal fold structure adjacent to the Monghyr–Saharsa Ridge in the southwest. The Regional Unconformity (RU) is dipping in the northeast direction. Since the Bahraich Formation (shown in Magenta), of Mesoproterozoic age, directly overlies the unconformity UC-2, suggesting that the mega-synclinal structure is most likely filled with Meso- to Paleoproterozoic metasediments. Further towards northeast, the Paleoproterozoic sequences are covered by the Lower Siwalik (Figure 6.5).

The Early Paleozoic and Cenozoic sequences were distinguished and separated by the Regional Unconformity (RU) or Tertiary-Pre-Tertiary (T-PT) surface in the sedimentary succession. In both sections, the deepest zone is recorded at around 7.5 seconds TWT. Potential hydrocarbon-bearing zones may include stratigraphic traps or combination traps within the Paleozoic interval bounded by the Regional Unconformity (RU). At

certain locations, these traps may be further controlled by faulting or underlying basement ridges.

Seismic section DD'

This section (Figure 6.7) depicts an anticline where the hinge zones of several Paleo- to Meso- Proterozoic sequences have been eroded, forming the surface marked as UC-2. The erosional surface representing the Neoproterozoic to Early Paleozoic interval is associated with the Regional Unconformity (RU). Structural and stratigraphic traps may be present within the Neoproterozoic-Paleozoic interval abutting the RU surface and the Monghyr-Saharsa ridge.

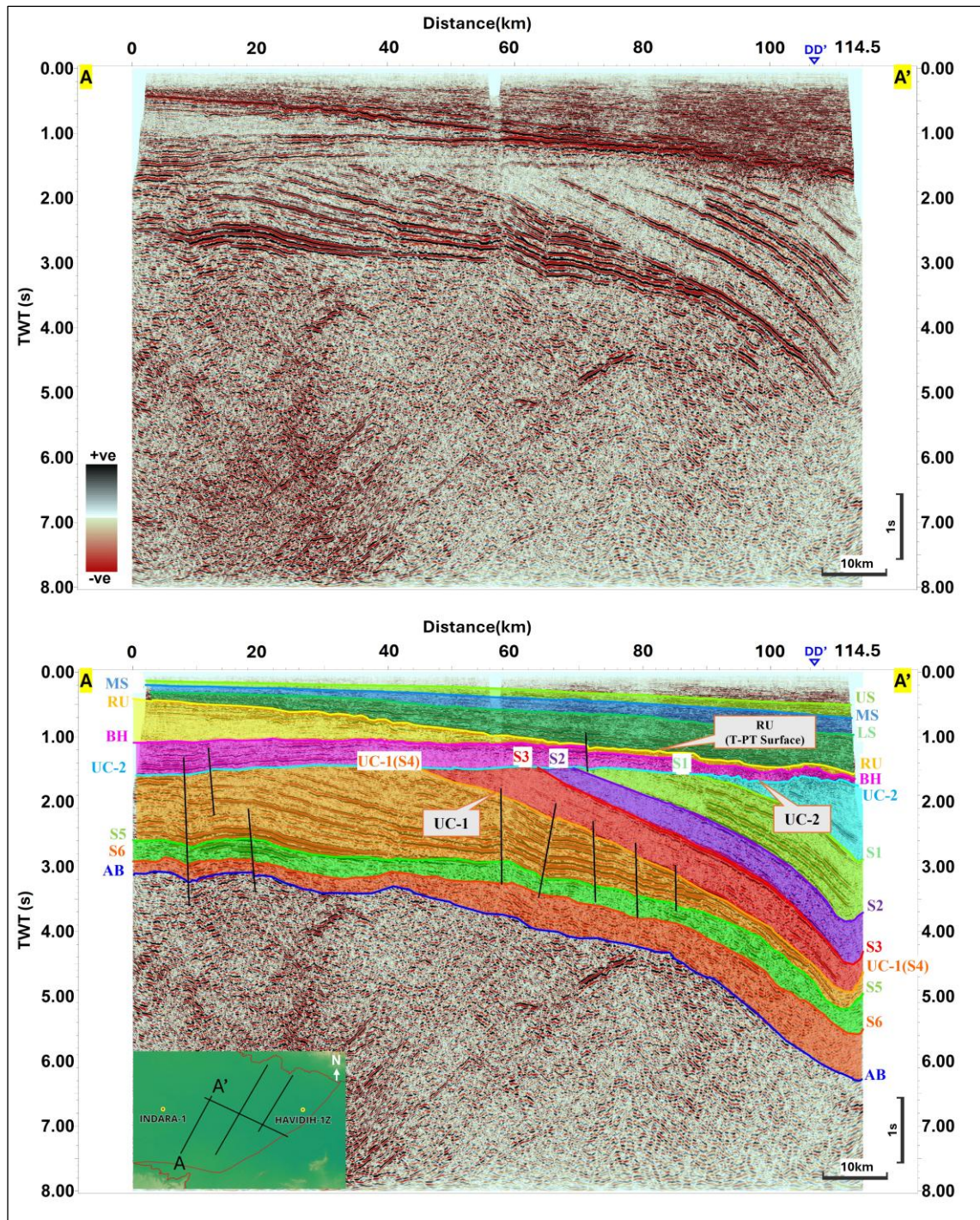


Figure 6.4: The seismic section along line AA' measures 114.5 km in length. The upper image is an uninterpreted section and its interpretation is shown in the lower image. Various formations within the Ganga Basin have been identified, including Upper Siwalik (US), Middle Siwalik (MS), Lower Siwalik (LS), and Bahraich (BH). Unconformities are marked as Regional Unconformity (RU), Proterozoic Unconformity surfaces as UC-1 and UC-2. Proterozoic sequences from S1 to S6, and Archean Basement (AB) are also marked. Vertical to subvertical faults are marked as solid black lines. The inset in the lower image is a part of the base map as shown in Figure 6.10.

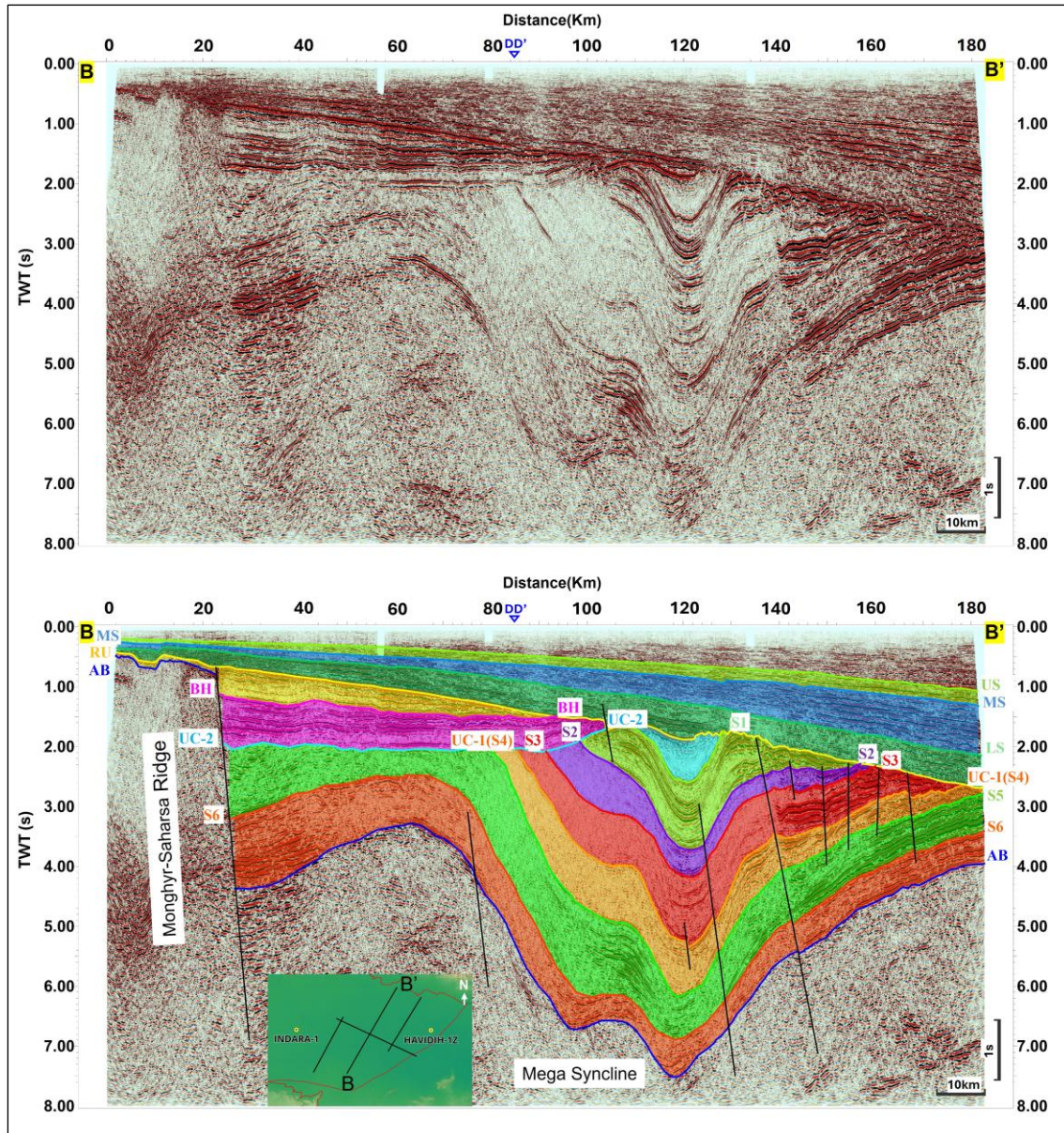


Figure 6.5: The seismic section along line BB' has a length of 182 km. The upper image presents an uninterpreted section, while the lower image provides its interpretation. Various formations within the Ganga Basin have been identified and marked. The abbreviations used are consistent with those in the preceding figure.

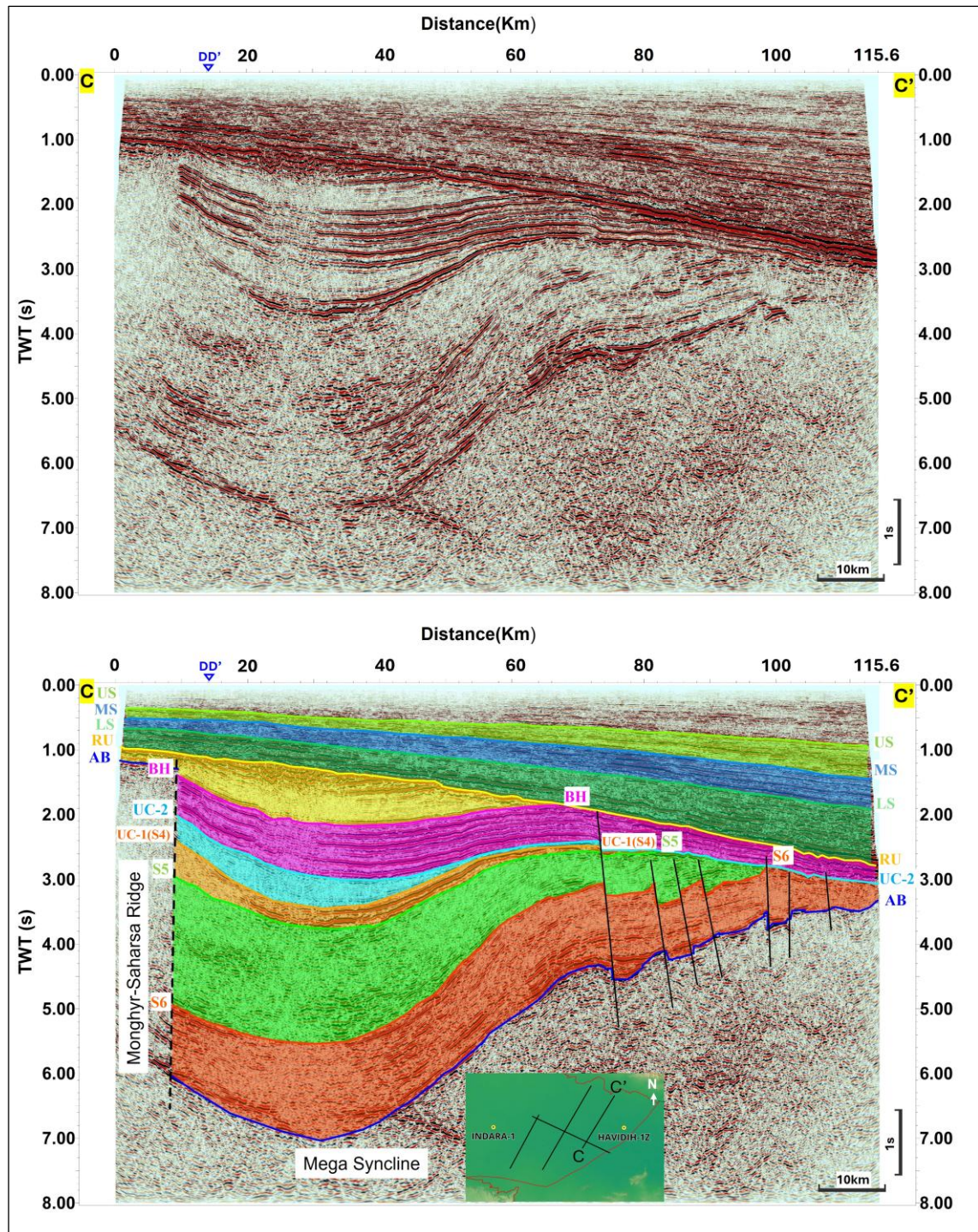


Figure 6.6: The seismic section along line CC' has a length of 115 km. The upper image shows an uninterpreted section and its interpretation is illustrated in the lower image. Various formations have been identified and marked on the section. The abbreviations used are in line with those in the preceding figure.

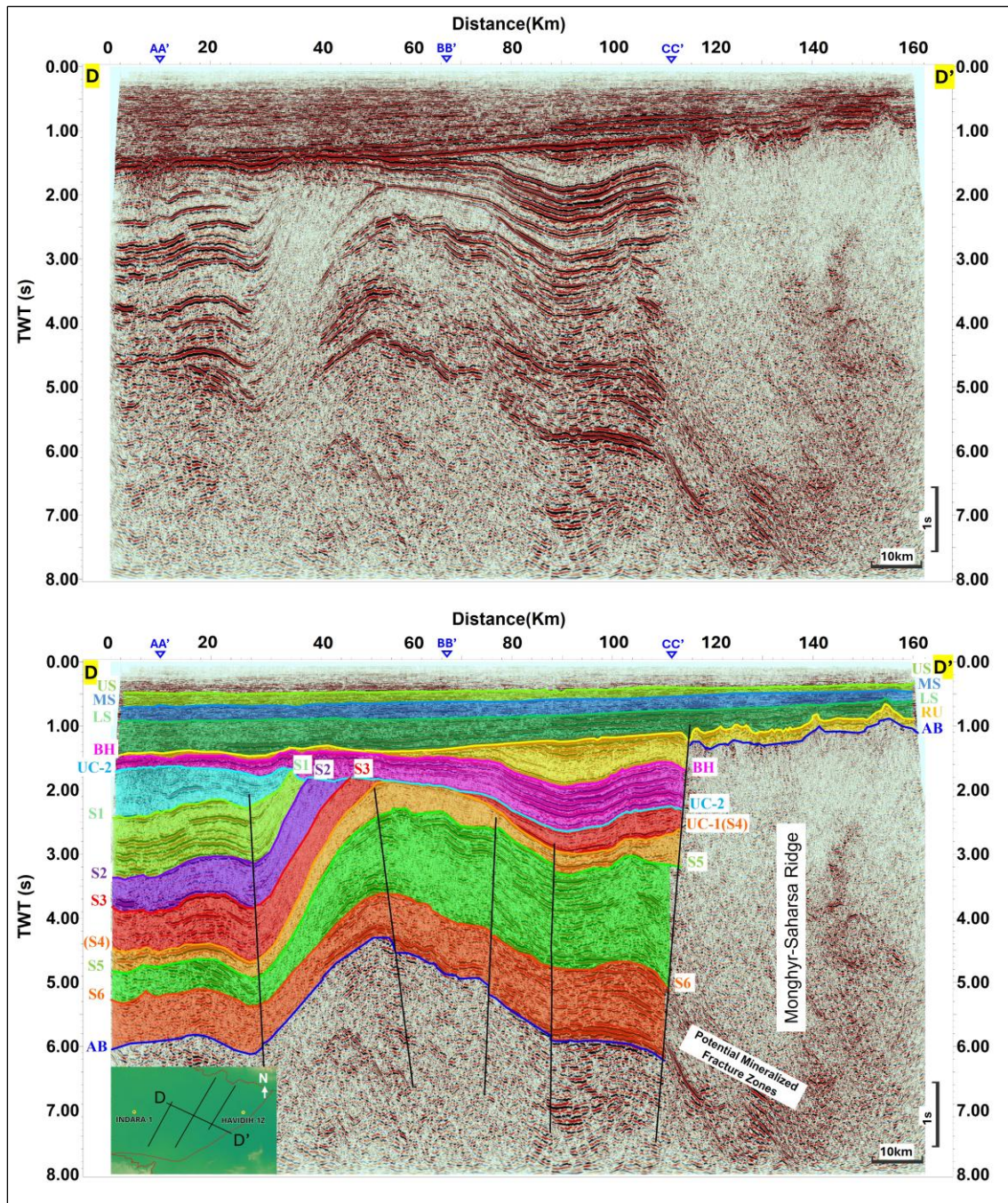


Figure 6.7: The seismic section along line DD' has a length of 162 km and is oriented in the NW-SE direction. The uninterpreted section is displayed in the upper image while its interpretation is depicted in the lower image. Various formations have been identified and labelled on the section. The abbreviations used are in line with those in the preceding figure.

6.5.3 Gravity data

In the preceding section, we have observed from the recently acquired reflection seismic data that there are sedimentary sequences older than the Bahraich Formation in the Ganga Basin, which have not been penetrated by any wells in the region. This study uses gravity measurements (Figure 6.8) and gravity modelling along the seismic sections to investigate the subsurface structures of the Ganga Basin and assess its hydrocarbon prospectivity.

Gravity modelling was employed to complement the seismic interpretation by constraining the geometry of the deeper subsurface units that are not penetrated by the available wells. The gravity models were constrained using the interpreted seismic horizons, interval velocities, and density values derived from well-log analysis. As gravity inversion is inherently non-unique, the interpreted density distribution represents the most geologically consistent solution that satisfies the observed Bouguer gravity anomalies while remaining compatible with the seismic interpretation.

Gravity field characteristics in the Ganga Basin and the Himalayan foothills are influenced by the underlying regional lithospheric depression, which resulted from collisional forces. The regional horizontal gradient of the gravity field varies from north to south, with a low gravity anomaly located in the foredeep trough, while higher values of the provincial component in the southern region correspond to the marginal ridge area (Godin and Harris, 2014). Figure 6.8 highlights several significant gravity anomalies, including lows associated with the Sarda, Gandak and Madhubani depressions along the Siwalik Foothills of the Himalayan Range, and highs along the Bundelkhand craton, the Great Boundary fault, Aravalli-Delhi Fold Belt, and Sargodha Ridge. The Delhi-Haridwar Ridge (D.H.R.) separates the Ganga Basin from the Punjab Plain, while the

eastern boundary of the Ganga Basin is marked by the Monghyr-Saharsa Ridge (M.S.R.) (Ravi Kumar et al., 2013).

Bouguer gravity values in the study area decrease northward from -30 to -210 mGal. Typically, prominent highs and lows on a gravity map reflect basement undulations and/or subsurface density variations. Nonetheless, as explained in the next section, a residual gravity anomaly map is prepared using a high-pass filter to reveal subtle gravity features within the basin. Their probable sources can be identified through modelling of the residual components along the seismic lines.

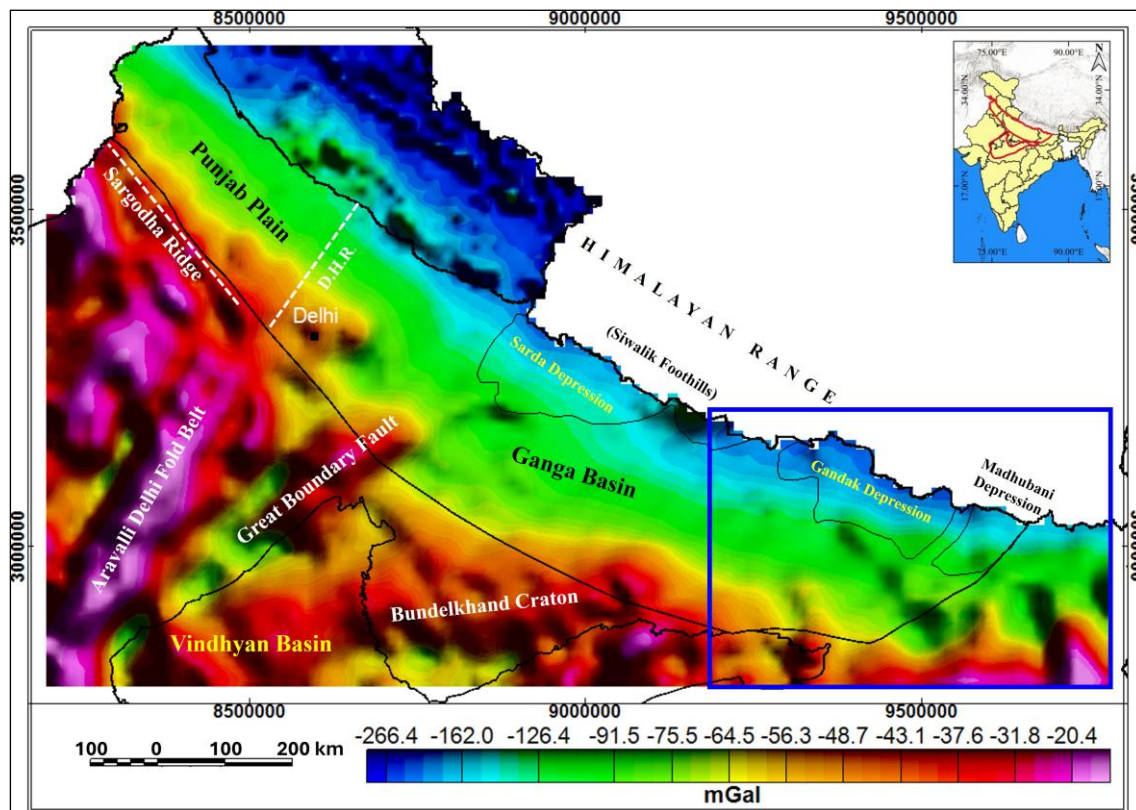


Figure 6.8: The Bouguer gravity anomaly map of the Ganga Basin and its surrounding areas obtained from Earth Gravitational Model (EGM2008). Regional tectonic elements are marked on the map. The residual gravity map for the study area within the blue colour rectangular outline is shown in Figure 6.10.

6.5.3.1 Spectral analysis

The Radial Averaged Power Spectrum (RAPS) is often used for a spectral analysis of Bouguer gravity data, wherein a 2D power spectrum of the gravity map is averaged at each wavenumber such that it is transformed into a 1D spectrum to estimate the depth of subsurface sources contributing to the gravity anomalies. The technique was developed by Spector and Grant (1970). This technique involves transforming the Bouguer map into the spatial frequency (or wavenumber) domain via the 2-D Fast Fourier transform (FFT). A mean power value is calculated for each wavenumber, and the resultant 1D power spectrum is plotted with wavenumber on the x-axis and average power on the y-axis. The slopes of the 1D power spectrum are used to estimate the depths of the anomaly sources. This technique is capable of separating information from different sources at depths (Spector and Grant, 1970).

The observed Bouguer gravity anomaly, denoted as g_o , is comprised of the regional field (g_{reg}), the residual field (g_{res}), and an aggregate noise (g_{noise}), i.e.

$$g_o(r) = g_{reg}(r) + g_{res}(r) + g_{noise}(r), \quad (6.1)$$

where, r denotes the position of the gravitational field.

The radially averaged power spectrum is a function of wavenumber only and is calculated by averaging the energy in all directions for the same wavenumber.

The mathematical expression of the power spectrum $P(\omega)$ is related to depth (D) as

$$P(\omega) = A \exp(-2\omega D), \quad (6.2)$$

In the above equation, A is the constant for a randomly distributed source, ω is the wavenumber, and D is the depth of the source (Yadav et al., 2018).

The logarithm is commonly applied to the magnitude to normalize and decrease the bandwidth of the power spectrum such that

$$\ln(P) = -2\omega D + \ln(A). \quad (6.3)$$

The slope of the power spectrum – wavenumber plot gives the depth of the anomalous source. The depth of a gravity anomaly source can be determined by analysing the gradient of any linear section of the radially averaged power spectrum curve. The depth of the source of the anomaly is determined by the equation given as

$$D = -\frac{S}{4\pi}, \quad (6.4)$$

where D is the depth and S is the slope of the power spectrum log (Ombati et al., 2022).

Spectral analysis and wavenumber guided filtering enable the differentiation of deep and shallow sources responsible for gravity anomalies. This technique is used to separate the gravity data into *regional* and *residual* anomalies with the high-pass and low-pass filters (Jacques Nguimbous-Kouoh et al., 2019). The gravity anomaly associated with a source from shallow depth typically shows high frequency (or short wavelength), while the anomaly from a deeper source exhibits low frequency (or long wavelength) (Ravi Kumar et al., 2013). A filter can be designed using the power spectrum to attenuate low frequencies related to the regional structures and to enhance the higher frequencies associated with the local anomalies (Steffen et al., 2011; Druet et al., 2018; Blaikie and Kunzmann, 2020; Ombati et al., 2022; Mohanty, 2023). Spectral analysis and filtering of the gravitational data were conducted with *Oasis Montaj*TM software from Geosoft Inc.

A spectral analysis of the Bouguer anomaly map (Figure 6.8) was carried out to estimate the depths of the major gravity source ensembles beneath the study area. The RAPS analysis was intentionally performed using the Bouguer gravity anomaly grid shown in Figure 6.8, as it corresponds to the study area adopted for the integrated gravity modelling presented in this chapter. Although larger datasets better preserve regional long-wavelength anomalies, the selected extent was considered appropriate for the objectives of the present study. As shown in Figure 6.9, the slope of the line segments in the power spectrum is associated with the depth of the anomalous sources. Consequently, the estimated average source depths of 140, 25, and 8 km have been determined using Eq (6.4). Various researchers have suggested Lithosphere-Asthenosphere Boundary (LAB) depth in the order of 140 km based on spectral analysis (Ravi Kumar et al., 2013), and seismic tomography (Priestley et al., 2008). Furthermore, the thickness of the foredeep sediments in the basin is estimated to be in the order of 7 km (Powers et al., 1998).

RAPS of the gravity map (Figure 6.9) and associated signals from the first segment suggest a cut-off wavenumber (k) of 0.004 cycle/unit to separate the *regional* and the *residual* fields. The low-pass and high-pass filters have been designed accordingly. Although the Bouguer anomaly map (Figure 6.8) shows very little structure in the area of interest, the residual map (Figure 6.10) shows a well-defined positive residual anomaly of 20 mGal. In the next section, we have modelled the gravity anomaly with selected seismic lines to understand the density distribution in the subsurface.

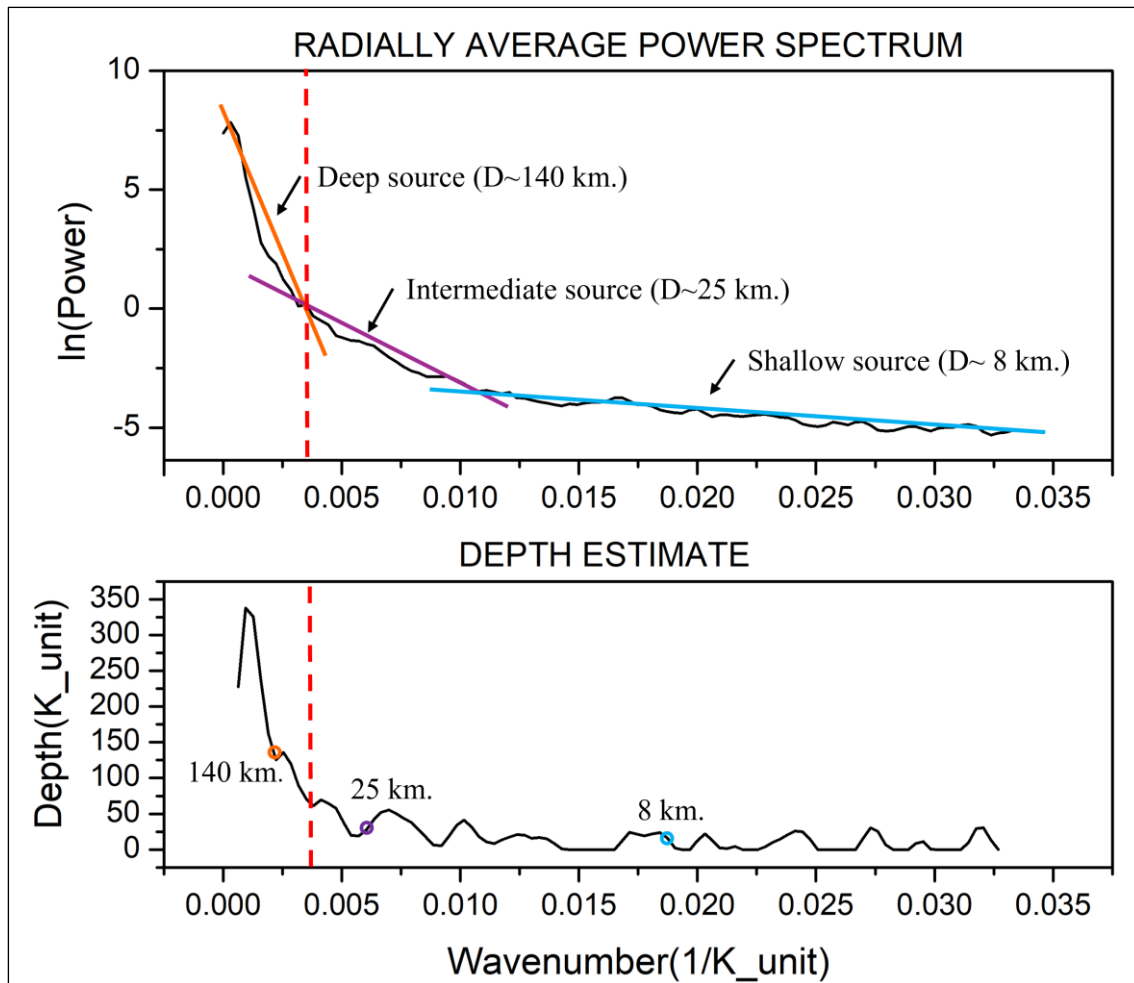


Figure 6.9: The radially averaged power spectrum derived from Bouguer anomaly gravity data illustrates three linear segments of slope equivalent to average depths of 140, 25, and 8 km. The transition indicated by the red dashed line has been used for separating lower frequencies associated with regional anomalies from higher frequencies associated with residual (or local) anomalies.

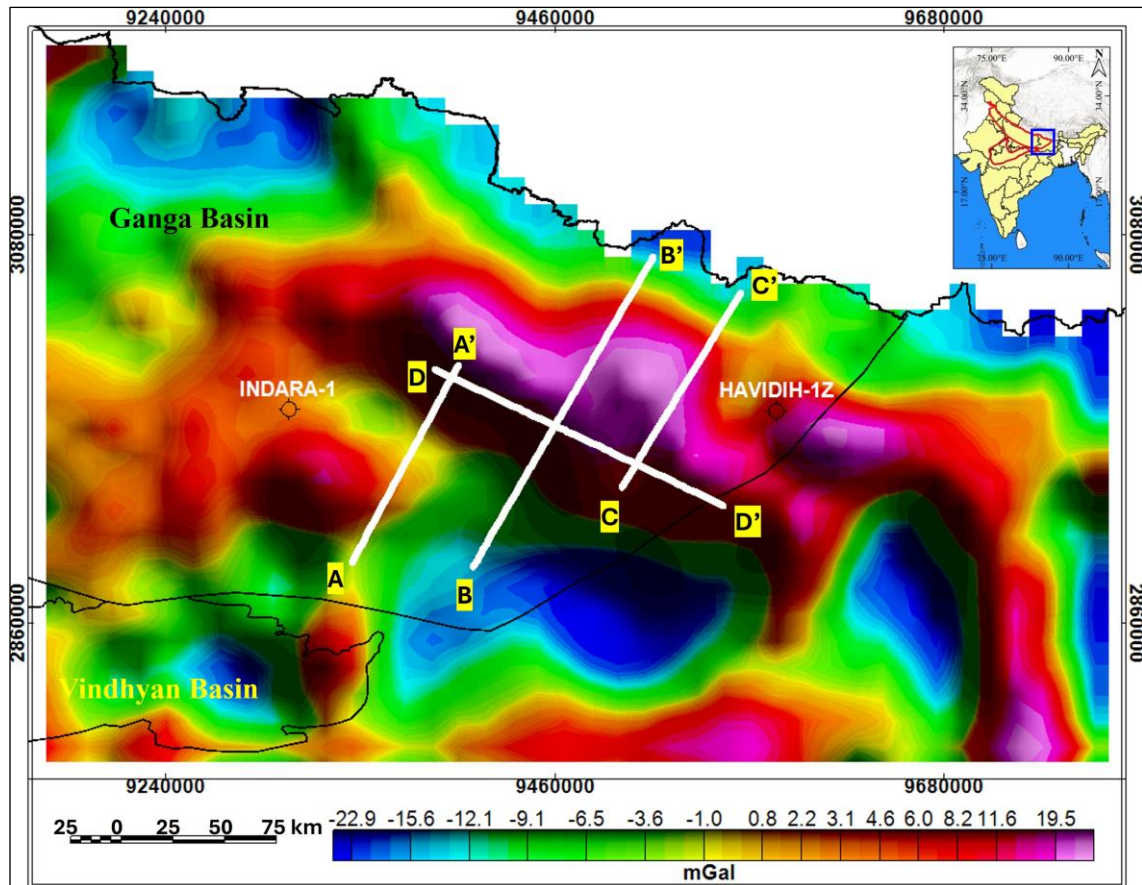


Figure 6.10: A residual gravity anomaly map for the study area in the Ganga Basin is prepared by applying a high pass cut-off filter for wave number > 0.004 . Gravity profiles along AA', BB', CC', and DD' (white-coloured solid lines) were extracted for modelling using the seismic profiles.

6.5.3.2 2D gravity modelling

We performed 2D modelling of the gravitational field to corroborate the crustal boundaries inferred from seismic data interpretation against the gravimetric data depicted on the residual anomaly map (Figure 6.10). We employed the GM-SYSTM software within the Oasis Montaj™ (Geosoft) suite to construct the model in the time domain along the select seismic lines (AA', BB', CC', and DD'). This model classifies the gravity sources of sedimentary sequences overlying the Archean basement according to their deposition periods: Quaternary-Tertiary, Neoproterozoic-Paleozoic, Late Mesoproterozoic, Early Mesoproterozoic, and Paleoproterozoic (Table 6.4).

The 2D gravity modelling process involved several steps, including time to depth conversion in the model using velocity data, calculation of gravimetric anomalies, comparison with observed data, and iterative modification of the density of classified sedimentary layers from various formations within the Ganga Basin.

The input velocities (Table 6.4) were derived from the seismic interval velocities of different layers calibrated with sonic logs from the Indara-1 and Havidih-1Z wells (Figure 6.3). It is pertinent to note that the wells in the region have not penetrated the Proterozoic sedimentary sequences below the Bahraich Formation. Average densities of different layers up to the Bahraich Formation were obtained from the density logs, whereas densities of deeper sequences were estimated from seismic interval velocities using Gardner's equation (Gardner et al., 1974). The computed gravity responses were then compared with observed data, and discrepancies were minimized through iterative adjustment. Initial and inverted densities for each section are presented in Table 6.4.

The gravity profiles traced along the 2D seismic sections AA', BB', and CC' exhibit a sub-parallel SW-NE direction, covering distances of roughly 114 km, 182 km, and 115 km, respectively. Profile DD' traverses in the NW-SE direction intersecting the other three sections and spanning 162 km (Figure 6.10).

The gravity anomaly along profile AA' (Figure 6.11) depicts a steady rise in residual gravity anomaly towards the northeast, with the gravitational field intensifying from -1.8 to 22 mGal. Notably, all horizons, including the lower, middle and upper Siwalik, Tilhar, and the Regional Unconformity (RU), exhibit a dip towards the northeast, mirroring the increasing trend of observed gravity in the same direction. This suggests the presence of concealed deep-seated features or structures beneath the unconformity surface, perhaps possessing higher densities than the surrounding formations. This correlates with the

increasing thickness of the Mesoproterozoic sequences. The modelled basement depth varies from 6 to 13 km along gravity profile AA'.

The residual gravity along BB' exhibits a convex upward profile in the SW-NE direction with minimum and maximum anomalies of -15 mGal and 24 mGal, respectively. Local gravity anomalies reflect the combined influence of depressions in the Archean basement, positive and negative forms of the Proterozoic metasediments, and variable thickness of the Tertiary strata. A significant peak of 24 mGal is observed at 124 km offset along the gravity profile and is attributed to the presence of a mega synclinal structure containing thick Proterozoic sediments beneath the regional unconformity (Figure 6.12). The deepest basement rock is interpreted at 20 km along this gravity profile, indicating the deepest depth to the Archean basement in the Gandak depression.

Profile CC' (Figure 6.13) shows a noticeable decrease in residual gravity from 10 mGal in the southwest to -11 mGal in the northeast. This section also shows a thick sequence of dense Proterozoic sediment (~17 km) at 35 km offset corresponding to a high gravity anomaly of +24 mGal.

The NW-SE oriented line DD' aligns with the trend of high gravity anomaly depicted in Figure 6.10. The residual gravity profile in the top panel of Figure 6.14 shows that the gravitational field has minimum value of +10 mGal and peaks at +22 mGal midway along the line DD'. The uplifted Archean basement in the SE direction indicates the continuity of the Monghyr-Saharsa ridge. Several deep-seated linear features in the basement are discernible in seismic sections, potentially representing mineralized fracture zones.

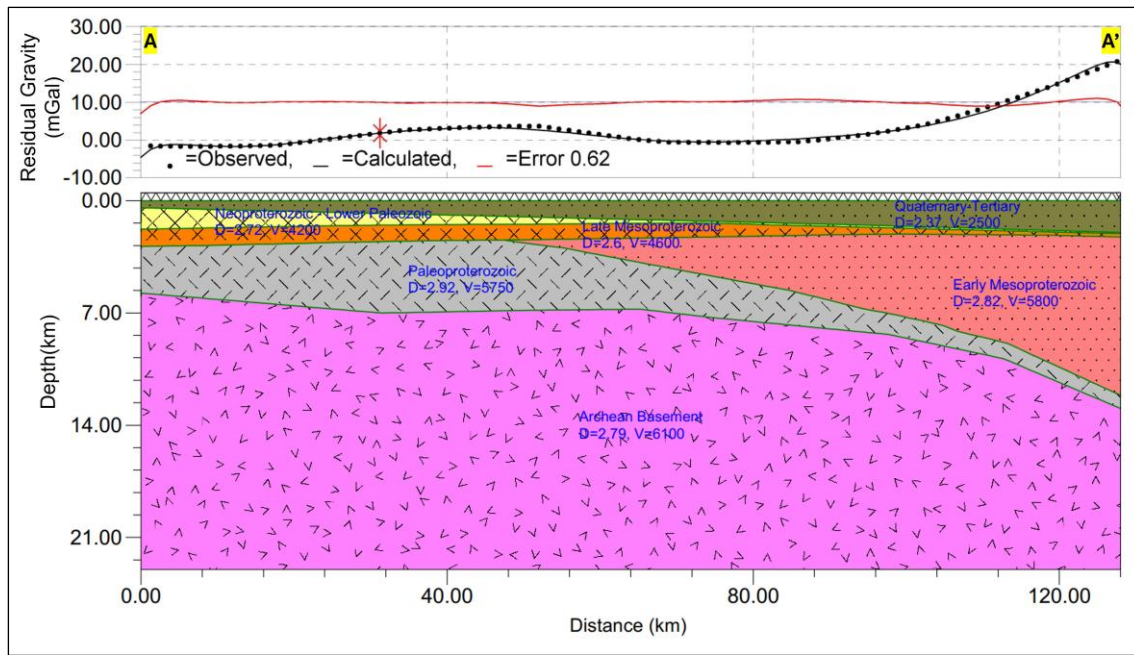


Figure 6.11: Modeled 2D residual gravity profile along the seismic line AA'. Density (D) is in gm/cc and interval velocity (V) is in m/s. The observed and calculated gravity profile are in concordance.

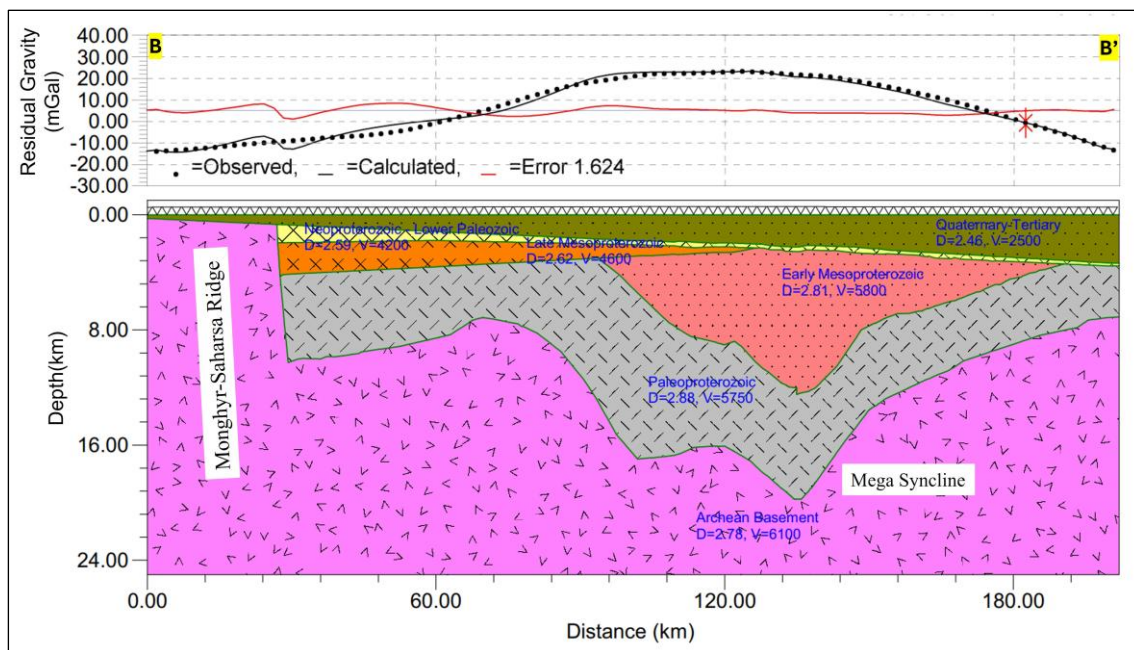


Figure 6.12: Modeled 2D residual gravity profile along the seismic line BB'. Density (D) is in gm/cc, and interval velocity (V) is in m/s. The observed and calculated gravity profile are consistent. Note that the Paleoproterozoic and Early Mesoproterozoic sequences have higher density than the basement.

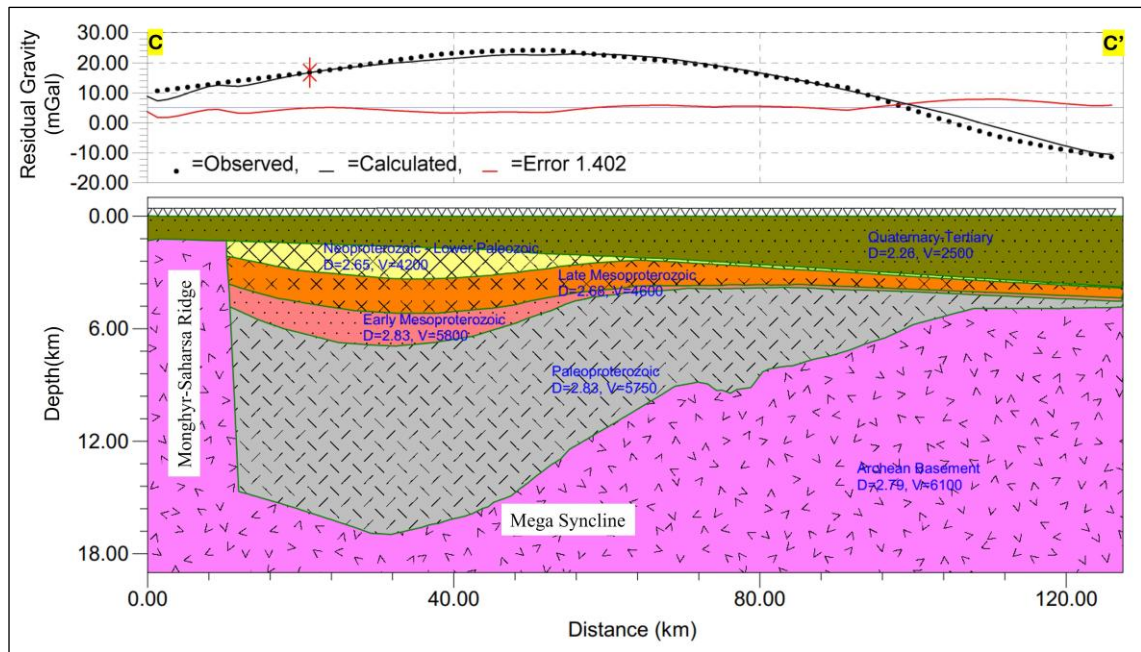


Figure 6.13: Modeled 2D residual gravity profile along the seismic line CC'. Density (D) is in gm/cc, and interval velocity (V) is in m/s. The observed and calculated gravity profile are in concordance.

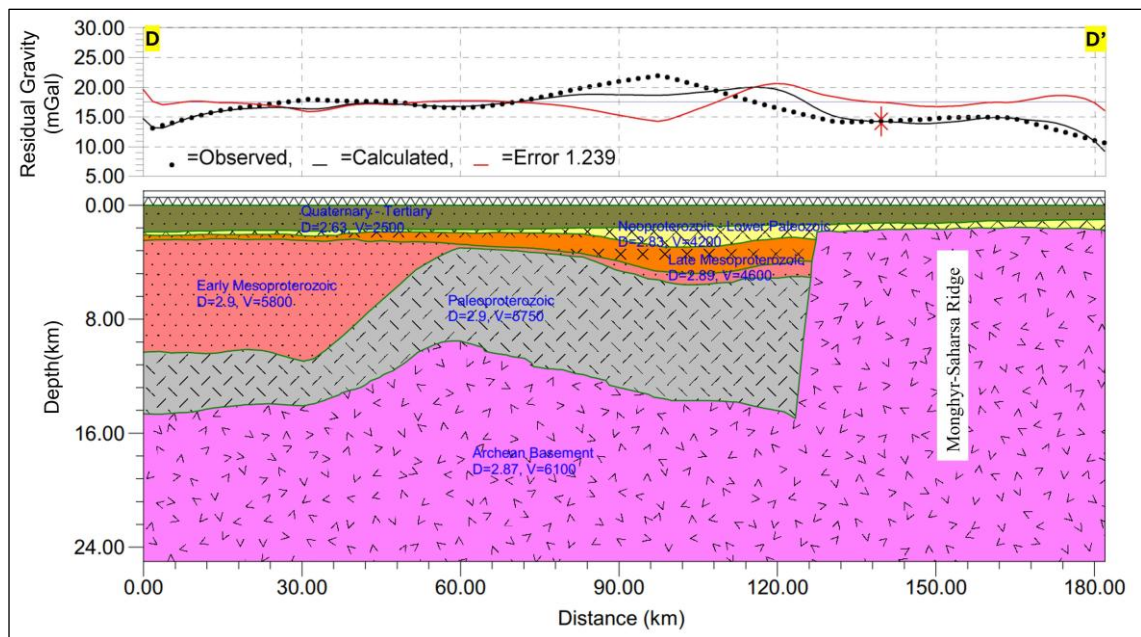


Figure 6.14: Modeled 2D residual gravity profile along the seismic line DD'. Density (D) is in gm/cc and interval velocity (V) is in m/s

Table 6.4: Densities given below are utilized to generate the seismo-gravity model along seismic sections.

Age	Formation	Initial density (g/cm ³)	Inversion density (g/cm ³)	Velocity (m/s)	Section-wise inversion density (g/cm ³)			
					AA'	BB'	CC'	DD'
Quaternary-Tertiary	Alluvium	2.25	2.37-2.63	2500	2.37	2.46	2.26	2.63
	Upper Siwalik							
	Middle Siwalik							
	Lower Siwalik							
Regional Unconformity (RU)								
Neoproterozoic – Lower Palaeozoic	Karnapur	2.62	2.72-2.83	4200	2.72	2.59	2.65	2.83
	Tilhar							
	Ujhani							
Late Mesoproterozoic	Bahraich	2.65	2.6-2.89	4600	2.6	2.62	2.68	2.89
Unconformity Surface -2 (UC-2)								
Early Mesoproterozoic	S1, S2, S3	2.71	2.81-2.92	5800	2.92	2.81	2.83	2.9
Unconformity Surface -1 (UC-1)								
Paleoproterozoic	S4, S5, S6	2.71	2.82-2.9	5750	2.82	2.88	2.83	2.9
Archean	Basement	2.95	2.78-2.9	6100	2.79	2.78	2.79	2.87

6.6 Discussion

Seismic data reveal that the Ganga Basin experienced significant tectonic activity throughout Early to Meso-Proterozoic sedimentation, as evidenced by well-defined folds, faults, uplifts, and unconformities. The principal phase of sedimentation occurred within an intracratonic rift system, resulting in the deposition of six distinct stratigraphic sequences (S1-S6), newly identified from recently acquired high-resolution regional seismic data. These stratigraphic sequences have not been previously recognized in the stratigraphic record of the Ganga Basin. An erosional unconformity (UC-1) is recognized between S3 and S4. Subsequently, during post-compressional tectonism, another erosional surface (UC-2) developed, marking extensive erosion along anticlinal hinge zones and signifying the culmination of compressional deformation. Estimating the magnitude of erosion across UC-2 would require palinspastic reconstruction, which remains an avenue for future investigation.

Following these tectono-sedimentary events, the Bahraich Group was deposited during the Late Mesoproterozoic, succeeded by the Ujhani, Tilhar, and Karnapur formations of Neoproterozoic–Early Paleozoic age, collectively representing Pre-Tertiary sequences of the basin. The Regional Unconformity (T–PT boundary) separates Tertiary from Pre-Tertiary strata and represents a hiatus of approximately 500 Ma (Table 6.1). Overlying this boundary, the basin received voluminous fluvial sediments derived from the Himalaya in the north and the Vindhyan highlands in the south, forming the Siwalik Group.

Seismic sections reveal prominent reflectors corresponding to the Lower, Middle, and Upper Siwalik fluvial deposits, gently dipping northward. Between the Regional Unconformity (RU) and UC-2, Mesoproterozoic to Early Paleozoic sequences are present that correlate with the Vindhyan Group of rocks of the adjoining Vindhyan basin

(Ojha, 2012), where hydrocarbon discoveries have been reported (Pandey and Ojha, 2025). The six delineated Proterozoic sequences (S1–S6) beneath the UC-2 unconformity are highly folded and faulted, suggesting the potential for structural, stratigraphic, and combination traps within the basin.

The presence of pronounced erosional hiatuses has significant implications for the hydrocarbon prospectivity of the basin. These unconformities indicate a complex pattern of uplift and erosion that occurred for an extended period of earth history (Paleoproterozoic to Mesozoic). There are many opportunities for active petroleum systems and the development of structural and stratigraphic traps. At the same time, the presence of major unconformities (UC-1, UC-2, and RU) poses a dual role in basin prospectivity: while they may increase the risk to hydrocarbon entrapment and preservation, they may also contribute to the formation of stratigraphic traps. It would require detailed modelling of petroleum systems with uncertainties around various elements including timings. Of course, deep drilling of stratigraphic wells would be required targeting different sequences and their detailed geological and geochemical studies. Although the widely spaced seismic lines have provided new insights into Proterozoic basin evolution, closely spaced high-resolution 2D and/or 3D seismic surveys are required for detailed structural and stratigraphic mapping.

The newly recognized S1–S6 sequences were further examined using gravity field data over the Ganga Basin. The gravity field reflects regional lithospheric flexure due to the subduction of the Indian plate beneath the Eurasian plate (Ravi Kumar et al., 2013). Negative regional anomalies characterize the foredeep trough, with the horizontal gradient increasing from north to south. Local gravity highs correspond to variations in basement topography, while in the southern Ganga Basin, positive gravity anomalies align with the marginal ridge.

Prominent residual gravity highs occur in the southern part of Gandak and Madhubani depressions, attributable to thick, dense pre-Tertiary sedimentary sequences. Two-dimensional gravity modelling along the four seismic profiles indicates that these high-density Paleoproterozoic successions extend to depths of 6–20 km (Figure 6.11- Figure 6.14). Interval velocities for different sequences were derived from reflection seismic data and calibrated using the Indara-1 and Havidih-1Z wells, where sonic logs were available in the shallower section. Initial density estimates were obtained from density logs and Gardner's equation. Density inversion results from gravity modelling reveal that Paleoproterozoic rocks exhibit higher densities than the underlying Archean basement, a consistent observation across all profiles. Similar density inversion has also been reported in the eastern part of the Vindhyan Basin, where Proterozoic sequences below Lower Vindhyan formation show higher density than the crystalline basement (Rao et al., 2025).

These deep Proterozoic sedimentary rocks may possess inherently low porosities due to compaction, diagenesis, or mineralogical composition, which has a significant impact on petroleum prospectivity in the older, deeper parts of the basin where reservoir quality may be limited. In this study, lateral velocity and density variations within individual sequences were not incorporated, and the current analysis is restricted to two-dimensional modelling, which may account for minor density discrepancies among profiles (Table 6.4).

6.7 Conclusions

The integration of newly acquired NSP seismic data with regional gravity information and wireline logs from existing wells provides a significantly improved understanding of the subsurface architecture and depositional evolution of the Ganga Basin. In particular, the Proterozoic sequences observed in the new high-resolution exploration seismic have been analysed by two-dimensional gravity modelling. The study clearly demonstrates

that the gravity highs are not associated with basement highs; rather, the elevated gravity anomalies are attributable to high-density Paleoproterozoic sequences overlying the Archean basement. Current gravity models use layer-averaged properties. Incorporating laterally varying velocities and densities in 2D/3D modelling will improve the accuracy of subsurface imaging and basement depth estimates.

Seismic interpretation indicates that the Paleoproterozoic sequences have undergone substantial compressional deformation, resulting in well-developed folds and fault systems. The study also identifies two previously unrecognized erosional unconformities (UC-1 and UC-2) within the Paleoproterozoic succession; each associated with considerable temporal gaps. The magnitude and timing of erosion at UC-2, which marks the termination of major compressional activity, remain uncertain. Balanced cross-section modelling will therefore be critical for estimating eroded thicknesses and evaluating trap integrity. The Regional Unconformity (RU) separating Proterozoic and Tertiary units is well established throughout the basin.

The continuity of the Proterozoic Vindhyan Group beneath the southern Ganga Basin combined with confirmed hydrocarbon discoveries in the adjacent Vindhyan Basin highlights comparable exploration potential in the study area. Neoproterozoic–Early Paleozoic formations preserved below the RU may host stratigraphic traps; however, faults identified beneath the unconformity do not propagate upward and appear to have had minimal influence on Siwalik sedimentation. Given the substantial temporal hiatus at the RU, hydrocarbon leakage remains a possibility in the absence of effective trapping configurations.

Although the current regional seismic dataset has enabled recognition of new stratigraphic units and structural features, higher-density seismic acquisition (closely

spaced 2D or 3D surveys) is essential to resolve finer-scale geometries. Key structural elements, including the Monghyr–Saharsa Ridge, require further investigation using complementary datasets such as magnetics and magnetotellurics to refine basin evolution models and evaluate hydrocarbon prospectivity.

Chapter 7 : Depositional Environment Analysis of Tertiary Sediments Using TFCWT Spectral Decomposition

7.1 Background

The Continuous Wavelet Transform (CWT) of a time signal provides a scalogram which was then transformed into a time-frequency spectrum as TFCWT by S. Sinha et al. (2005). A paramount feature of TFCWT is that the inverse Fourier transform of its time summation returns the original signal. There are a number of wavelets to choose from for time-frequency analysis of a signal. In seismic data analysis, the two often used wavelets are: (i) the Mexican Hat \ Ricker wavelet and (ii) the Morlet wavelet. For the TFCWT, however, the Morlet wavelet was used in the study which promises high frequency resolution at low frequencies and high time resolution at high frequencies. In this study, we show that the Paul wavelets of various orders can be used for generating time-frequency spectrum with the TFCWT. The order parameter (m) in the Paul wavelet allows for customization of its time-frequency resolution. The fourth order Paul wavelet closely resembles the Ricker wavelet and much higher order (such as 40th order) approximates the Morlet wavelet. With the help of a synthetic signal having two hyperbolic chirp frequencies, we show that the lower order Paul wavelets have high time resolution and low frequency resolution whereas the higher order Paul wavelets show high frequency resolution at low frequencies and high time resolution at high frequencies which is desired in seismic data analysis. This flexibility makes Paul wavelets suited for analyzing non-stationary signals to delineate complex geologic features like river channels, thin beds, or discontinuous reflectors.

Spectral decomposition with TFCWT using Paul wavelets was performed on 3D seismic data from the Gandak depression of the Ganga Valley basin in India. The study aims to

delineate paleo-river channels within the Siwalik formation of Tertiary age and further understand the paleo-depositional environment along the pre-Tertiary Regional Unconformity. The previous authors have characterized Siwalik sediments based on lithology and paleontology. In this study, we have utilized TFCWT-based spectral analysis with the RGB blending technique for a detailed description of the depositional environments based on the 3D seismic data.

A comparative study is performed for spectral analysis using the 4th-order Paul wavelet and the Morlet wavelet and scrutinized their responses for detecting concealed paleo-river channels and related depositional systems. Corresponding images with RGB color blending of three dominant frequencies (20 Hz, 25 Hz, and 35 Hz) were compared, and it was found that the Morlet wavelet better highlights the variations in the fluvial-deltaic systems of the Lower Siwalik. The Regional Unconformity, which has relatively lower frequencies, is studied with RGB blending of 12 Hz, 20 Hz, and 30 Hz. The study demonstrates that the Morlet wavelet provides enhanced resolution of the shallow marine depositional environment from the pre-Tertiary compared to the Paul wavelet of 4th order. Thus, the Paul wavelets of different orders can be used for spectral analysis of seismic data with associated time-frequency resolution.

7.2 Introduction

Spectral decomposition of a seismic signal, which is non-stationary in nature, has been extensively utilized in the last two decades for seismic feature enhancement as well as an aid in direct hydrocarbon detection (Partyka et al., 1999; Castagna et al., 2003; Farfour et al., 2018). It is now an essential seismic interpretation technique that is widely used in attribute analysis for subsurface mapping and has been included in most of the seismic data interpretation software. Spectral decomposition offers a full perspective of the subsurface paleo-geomorphological depositional study by analyzing spectral seismic

attributes (Ahmad et al., 2014; Ali et al., 2020; Harishidayat et al., 2022; Zhai, 2025). The technique enhances seismic attribute analysis by providing frequency-based attributes that complement traditional time-domain attributes, offering a more comprehensive subsurface picture. Using attributes like amplitude, phase, frequency, coherence, curvature, and spectral components in the time-frequency domain, subsurface features, such as faults, fractures, and stratigraphic boundaries, can be detected, which are critical to identifying the limits of the reservoir and locating potential hydrocarbon traps (Castagna et al., 2003; S. Sinha et al., 2005; Chopra and Marfurt, 2016; Munyithya et al., 2020; Pant et al., 2023; Durogbitan et al., 2023). It enhances the visualization of complex geological structures like channels, reefs, turbidites, and others, which often have unique spectral signatures, thereby facilitating more precise mapping and understanding of depositional environments (Othman et al., 2016; Hossain, 2020; Buist et al., 2021; Li et al., 2023). Moreover, spectral decomposition aids in detecting subtle stratigraphic features, such as thin beds and unconformities, which are crucial for accurate sequence stratigraphy and correlation of stratigraphic units.

Once a seismic trace is spectrally decomposed into its constituent frequencies, individual frequencies can be utilized for enhanced seismic data analysis and interpretation (S. Sinha et al., 2005; Castagna and Sun, 2006; Chenin and Bedle, 2022), or can be mathematically combined for spectral attributes (Sinha et al., 2009; Wang and Gao, 2013), or can be inverted for layer thickness determination (Puryear and Castagna, 2008; Cabrera-Navarrete et al., 2020), or can be denoised and deconvolved dynamically for high resolution (Zhou et al., 2014; Tan et al., 2023). In another innovative approach, three different frequencies were combined in a color composite image using Red (R), Green(G), and Blue(B) blending technique (Marfurt, 2015; Pant et al., 2022; Murat Alyaz et al., 2023) for enhanced visualization and interpretation of spectrally decomposed

seismic data and thus, extracting subsurface details. RGB blending highlights certain hidden subsurface features and reservoir architecture.

The evolution of spectral decomposition in seismic data analysis has developed from traditional time-frequency methods to more adaptive and resolution-efficient algorithms, overcoming the limitations of each preceding approach. The techniques that are utilized to carry out spectral decomposition of seismic data are based on either transforms or optimizations/inversions and include the Short-Term Fourier Transform (STFT), the Continuous Wavelet Transform (CWT), the Matching Pursuit Decomposition (MPD), the Constrained Least Squares Spectral Analysis (CLSSA), etc. (Castagna et al., 2003; Castro de Matos et al., 2010; Puryear et al., 2012; Chopra and Marfurt, 2016; Hossain, 2020; Cubizolle et al., 2022; Pant et al., 2023). Every single one of these approaches comes with its own individual set of benefits and drawbacks (Farfour et al., 2018).

Short-Time Fourier Transform (STFT) was one of the earliest methods introduced by Gabor (1946), which was employed for time-frequency analysis of non-stationary seismic signals. It breaks down a signal into short segments and applies the Fourier transform on each within a fixed-size time window. The time-frequency resolution is fixed because of its predetermined window size, which makes it less efficient for signals with rapidly varying frequency content, as it will not adapt to give high resolution both in the time and frequency domains simultaneously (Mallat, 2009). The type and size of the chosen window decide the information one can obtain regarding the frequency of the event in time. A narrow time window offers good time resolution at the expense of frequency resolution. A broad time window gives good frequency resolution but poor time resolution.

The wavelet transform-based spectral analysis has overcome the problem of fixed time-frequency resolution and is now an integral part of many seismic data interpretation

software for reservoir characterization. The wavelet transform method has an advantage over the STFT method, as it gets rid of the subjective choice of window length; instead, it uses a smart window function that adjusts its support length based on the frequency content in the signal (S. Sinha et al., 2005; Mallat, 2009).

The wavelet transform has evolved over the years, transforming from its early beginnings into a crucial tool for analyzing signals, especially when it comes to non-stationary and multi-scale data. With the pioneering work of Jean Morlet and Alex Grossmann (Grossmann and Morlet, 1984), the Continuous Wavelet Transform (CWT) was established to help us look at signals that have variable frequency components over a moving time window. This approach provides a more localized time-frequency representation compared to the conventional Fourier analysis. CWT uses scalable wavelet functions that dilate and contract to match various signal scales, offering high time resolution for high-frequency components and high-frequency resolution for low-frequency components. A compressed wavelet (small scale) provides a good time resolution for analyzing high-frequency components as it accurately captures the rapid changes in high-frequency signals. At low frequencies the wavelet stretches and provides good frequency resolution as it can distinguish between low-frequency components that are close together in the frequency domain (Mallat, 2009).

This multiscale ability enables more effective analysis of non-stationary seismic signals and enhanced detection of stratigraphic features like thin beds and discontinuities (Ker et al., 2011; Kiani et al., 2016; Ali et al., 2020). Nevertheless, despite its adaptability, CWT provides results in the time-scale domain, also known as scalogram, which can limit its frequency precision. It has limitations in accurately preserving both temporal and frequency information at the same time.

In contrast, the Time-Frequency Continuous Wavelet Transform (TFCWT) developed by S. Sinha et al. (2005) enhances CWT by transforming the signal energy onto a more precise time-frequency domain. This approach provides improved localization in both the time and frequency domains, offering a more detailed and sharper representation of signal characteristics. These advances have rendered TFCWT a useful tool for high-resolution spectral decomposition over the STFT and CWT, especially in complicated geological environments like meandering channels, steep slope fans, discontinuities, stratigraphic boundaries, and small-scale faulting (Sinha et al., 2009; Yari et al., 2011; Li et al., 2024).

Wavelet transforms utilize a variety of wavelet families in spectral decomposition technology, each of which is designed to retrieve various features of signals based on their shape, smoothness, and frequency characteristics. Common wavelet families are Haar, Daubechies, Symlets, Coiflets, Meyer, Paul, Morlet, and Mexican Hat wavelets (Torrence and Compo, 1998; Mallat, 2009). Among them, two commonly used wavelets in seismic data analysis with spectral decomposition techniques are Ricker wavelet (or Mexican Hat) and Morlet wavelet. The Morlet wavelet is especially important for time-frequency analysis because it is complex in nature and has a very good frequency resolution. It is an exponential modulated with a Gaussian function and finds application in the detection of oscillatory behavior in non-stationary signals, such as in geophysics, in seismic data interpretation (S. Sinha et al., 2005; Chopra and Marfurt, 2015). On the other hand, the Ricker wavelet, or the Mexican hat wavelet, is the second derivative of a Gaussian function and is widely utilized for seismic data analysis because it closely resembles the shape of seismic pulses. Its zero-phase and symmetric nature is simple to interpret subsurface reflectivity and renders it highly effective in wave propagation modeling in exploration geophysics (Wang, 2015; Singh et al., 2022). Therefore, the

selection of an appropriate wavelet family is crucial, since it has a direct impact on the accuracy and resolution of the signal representation in time-frequency space.

The Paul Wavelet offers a unique advantage, as its time-frequency resolution can be varied by changing the order of the wavelet. Lower-order Paul wavelets have higher time resolution at low frequencies compared to those of higher-order Paul wavelets. The 4th-order Paul wavelet closely resembles the Ricker wavelet (or Mexican Hat), and the 40th-order Paul wavelet is similar to the Morlet wavelet. This feature of the Paul wavelet makes it suitable for identifying stratigraphic features, thin-bed reservoirs, and faulted formations. From the previous studies, it was suggested that the Paul wavelet, if tuned appropriately, is a good tool for geophysicists in pursuit of enhanced seismic interpretation methods (Luan et al., 2020).

Thus, this study highlights the theoretical foundation of Time-Frequency Continuous Wavelet Transform (TFCWT) with the Paul wavelet and its implementation in seismic signal processing. Furthermore, the study explores its implementation in 3D seismic data from the Ganga Valley basin in India for different depositional sequences using the RGB blending technique. The study compares the results from the 4th-order Paul wavelet (resembling the Ricker wavelet) to those with the 40th-order Paul wavelet (resembling the Morlet wavelet)-based spectral analysis of seismic data.

7.3 Wavelet Theory

A wavelet function $\psi(t) \in L^2(\mathbb{R})$ is localized both in time and frequency domain such that its integral is zero in $(-\infty, \infty)$. It can be scaled and translated to produce a family of wavelet

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right), \quad (7.1)$$

where $a, b \in \mathbb{R}$ and a is not zero. The scaling or dilation parameter a is responsible for frequency localization and b is a translation parameter determining the time location of the wavelet. The time-scale spectrum, also known as the *scalogram*, of a signal $f(t)$ is obtained with Continuous Wavelet Transform (CWT) by taking the inner product of the family of wavelets $\psi_{a,b}(t)$ with the signal and is given as (Mallat, 2009):

$$S_W(a, b) = \langle f(t), \psi_{a,b}(t) \rangle = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \bar{\psi}\left(\frac{t-b}{a}\right) dt, \quad (7.2)$$

where $\bar{\psi}$ is the complex conjugate of the wavelet function ψ , and $S_W(a, b)$ is the time-scale spectrum.

Understanding of a scale in terms of frequency is not very intuitive, and therefore, various researchers use the inverse of scales to represent frequencies. Since each scale has a bandwidth, the amplitude/energy in the time-frequency spectrum is affected by the overlapping scales. Therefore, attributes derived from such a time-frequency spectrum may influence analysis of seismic signals. Satish Sinha et al. (2005) transformed the scalogram into a time-frequency map (i.e. TFCWT) by taking the Fourier transform of the inverse CWT and is given as:

$$F_{TFCWT}(\omega, b) = \frac{1}{C_\psi} \int_{-\infty}^{\infty} S_W(a, b) e^{-i \omega b} \hat{\psi}(a\omega) \frac{da}{a^{3/2}}, \quad (7.3)$$

where $\hat{\psi}(\omega)$ is the Fourier transform of the mother wavelet, C_ψ is a wavelet dependent constant and $F_{TFCWT}(\omega, b)$ is the time-frequency spectrum.

7.4 Comparisons of TFCWT with commonly used wavelet functions

In spectral decomposition technique for seismic data analysis, the frequently used wavelet functions are Ricker wavelet, similar to Mexican Hat wavelet, (Liu et al., 2004; Wang, 2015; Singh et al., 2022) and Morlet wavelet (S. Sinha et al., 2005; Wang, 2012).

The Ricker wavelet in the time domain $R(t)$ is defined in terms of peak frequency (ω_p) as:

$$R(t) = \left(1 - \frac{1}{2} \omega_p^2 t^2\right) \exp\left(-\frac{\omega_p^2 t^2}{4}\right), \quad (7.4)$$

It is a symmetric real wavelet and has a zero mean. Further, the Ricker wavelet in the frequency domain $R(\omega)$ is expressed as:

$$R(\omega) = \frac{2\omega^2}{\sqrt{\pi}\omega_p^3} \exp\left(-\frac{\omega^2}{\omega_p^2}\right). \quad (7.5)$$

The Mexican Hat wavelet, similar to the Ricker wavelet, is often used in applied mathematics and digital signal processing for wavelet transform (Singh et al., 2022). It is obtained by differentiating the Gaussian function twice as:

$$\psi^{MH}(t) = \frac{2}{\sqrt{3}} \pi^{-\frac{1}{4}} (1 - t^2) \exp\left(-\frac{t^2}{2}\right). \quad (7.6)$$

In the frequency domain, a scaled Mexican Hat wavelet can be written as:

$$\hat{\psi}^{MH}(a\omega) = \frac{2\sqrt{2}}{\sqrt{3}} \pi^{-\frac{1}{4}} (a\omega)^2 \exp\left(-\frac{(a\omega)^2}{2}\right). \quad (7.7)$$

The superscript MH for the Mexican Hat wavelet is used to differentiate the function ψ from other wavelets. It can be seen by comparing equation (7.4) and equation (7.6) as well as equation (7.5) and equation (7.7) that the Ricker wavelet and the Mexican wavelet are similar and the scale parameter a is the inverse of the peak frequency ω_p . The Ricker wavelet is a real-valued function and is extensively used in seismic data modeling and analysis. However, a complex version of the Mexican hat function is easily constructed by zeroing the negative part of its Fourier spectrum (i.e. $\hat{\psi}^{MH}(a\omega) = 0$ when $\omega \leq 0$). Another commonly used wavelet in CWT is the Morlet wavelet, which is essentially a plane wave modulated by a Gaussian and it is given as:

$$\psi^{MRL}(t) = \pi^{-\frac{1}{4}} \exp(i\omega_0 t) \exp\left(-\frac{t^2}{2}\right) \quad (7.8)$$

in the time-domain, where ω_0 is a nondimensional frequency to satisfy the admissibility condition (Torrence and Compo, 1998). The superscript *MRL* is used for the Morlet wavelet function. The Morlet wavelet in the frequency domain is written as:

$$\hat{\psi}^{MRL}(a\omega) = \pi^{-\frac{1}{4}} H(\omega) \exp\left(-\frac{(a\omega - \omega_0)^2}{2}\right), \quad (7.9)$$

where $H(\omega)$ is the Heaviside step function. $H(\omega) = 1$ if $\omega > 0$ and $H(\omega) = 0$ otherwise.

Furthermore, in this study, we have used Paul wavelets of various orders and compared it with the Ricker / Mexican Hat wavelet and Morlet wavelet. It is defined in the time domain as (Torrence and Compo, 1998):

$$\psi_m^{PL}(t) = \frac{2^m i^m m!}{\sqrt{\pi(2m)!}} (1 - it)^{-(m+1)}, \quad (7.10)$$

and in the frequency domain with the scaled Paul wavelet, it is given as:

$$\psi_m^{PL}(a\omega) = \frac{2^m}{\sqrt{m(2m-1)!}} H(\omega) (a\omega)^m \exp(-a\omega), \quad (7.11)$$

where m is the order of the wavelet. The parameter m determines the shape of the wavelet, affecting its resolution in time-frequency space. The superscript *PL* is used for the Paul wavelet function. The Paul wavelet can mimic the behaviour of the Ricker and the Morlet wavelets by suitably modifying its order parameter (m) and adjusting scales. A higher value of m corresponds to higher frequency resolution and lower time resolution, and therefore, it is essential to optimize the choice of parameters depending on the seismic dataset and the objectives of the analysis. The Paul wavelet of order 4 is very similar to the Ricker wavelet or the Mexican Hat wavelet (Luan et al., 2020). A sample Ricker wavelet of 20 Hz peak frequency is shown in Figure 7.1 and plotted along with the Mexican Hat wavelet. The shape of the Ricker wavelet and the Mexican Hat exactly match each other, as they are the second derivative of a Gaussian function, the difference only being in the scaling amplitude. The Paul wavelet ($m=4$) at a scale closely

matching with the Ricker wavelet in the time domain is extracted and shown in Figure 7.1a overlaying the Ricker/Mexican Hat wavelet, and their corresponding Fourier spectra are shown in Figure 7.1b. A slight shift in the peak frequency is attributed to the mismatch in the sidelobes of the wavelets in the time domain.

Furthermore, the Paul Wavelet of 40th order is comparable with the Morlet Wavelet, as shown in Figure 7.2. Only the real part of the wavelet in the time domain is plotted and shown in Figure 7.2a, whereas its frequency domain plot (Figure 7.2b) is showing 30 Hz peak frequency.

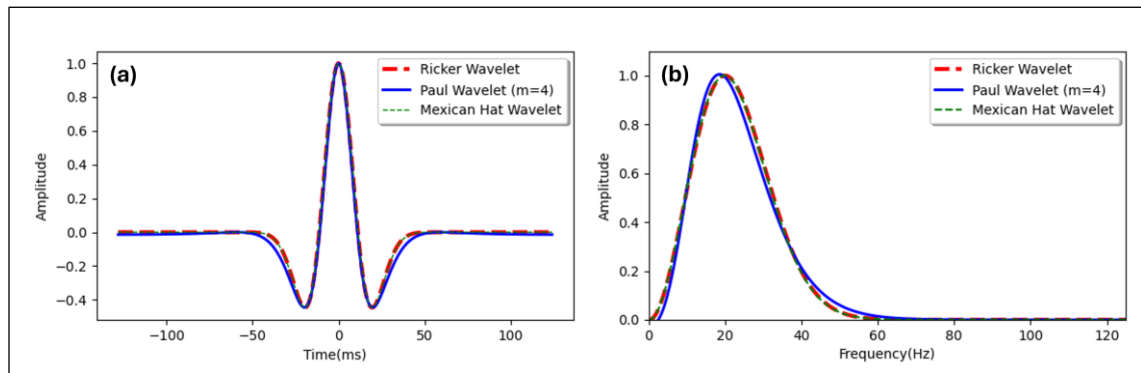


Figure 7.1: The Ricker wavelet having peak frequency of 20 Hz is compared with the Paul wavelet of order 4 and the Mexican Hat wavelet at corresponding scales for best fit. (a) Time domain representation of the Ricker wavelet (red dashed line), the Paul wavelet (solid blue line) and the Mexican Hat wavelet (green dashed line). (b) Frequency domain representation of the three wavelets.

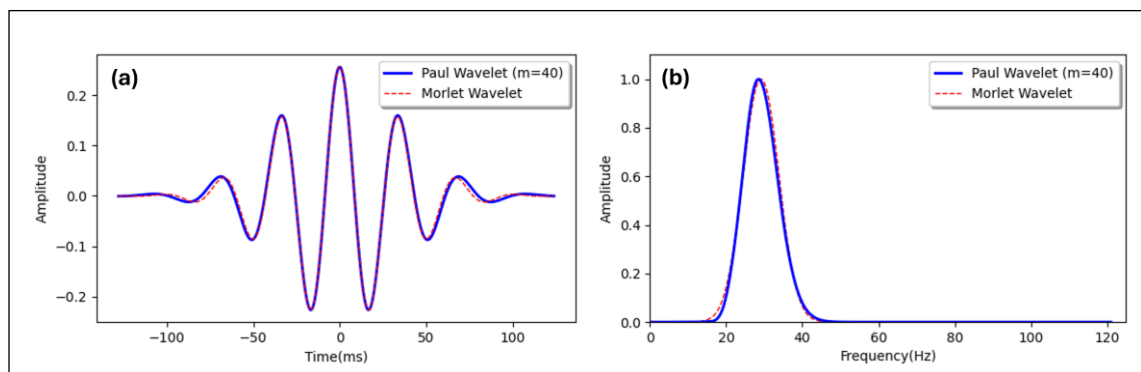


Figure 7.2: The Morlet wavelet is compared with the Paul wavelet of order 40 at corresponding scales for peak frequency of 30 Hz. (a) Time domain representation of the Paul wavelet of order 40 (solid blue line) and the Morlet wavelet (red dashed line). (b) Frequency domain representation of the two wavelets.

7.4.1 Synthetic Example for Time-Frequency resolution with TFCWT

The synthetic signal used for this study is the same as published in the paper by S. Sinha et al. (2005). It consists of two hyperbolic chirp frequencies of constant amplitude separated in time and having a time length of 1.368 sec with a sampling rate of 4 ms (Figure 7.3a). Time-Frequency spectrum with TFCWT using the Morlet wavelet is reproduced in Figure 7.3b. Moreover, we have used a real-valued Mexican Hat wavelet and a complex valued Mexican Hat wavelet [Equation.(7.7)] to generate TFCWT maps for the synthetic chirp signal (Figure 7.3a) and are presented in Figure 7.4a and Figure 7.4b, respectively. Clearly, the Mexican Hat wavelet was not able to detect the two hyperbolic sweep frequencies as it has low frequency resolution and high time resolution. Furthermore, we have experimented with the Paul wavelet of different orders between the 4th-order and the 40th-order. As observed from Figure 7.1 and Figure 7.2, the Paul wavelet of order 4 resembles the frequency response of the Mexican Hat / Ricker wavelet, while the Paul wavelet of order 40 mimics the Morlet wavelet. Therefore, a series of TFCWT map for the synthetic signal was generated using the Paul wavelet of order 4, 10, 15, 20, 30 and 40, and are shown in Figure 7.5a, b, c, d, e and f, respectively. Evidently, the Paul wavelet of order 4 has higher time and frequency resolution compared to the Mexican Hat wavelet [compare Figure 7.4 with Figure 7.5a] while the Paul wavelet of order 40 shows similar time-frequency resolution compared to the Morlet wavelet [compare Figure 7.3b with Figure 7.5f]. Moreover, increasing frequency resolution with increasing order of the Paul wavelet is easily discernible from Figure 7.5. The Paul Wavelet of higher order has high frequency resolution at lower frequencies and high time resolution at higher frequencies, which is desirable in seismic data analysis.

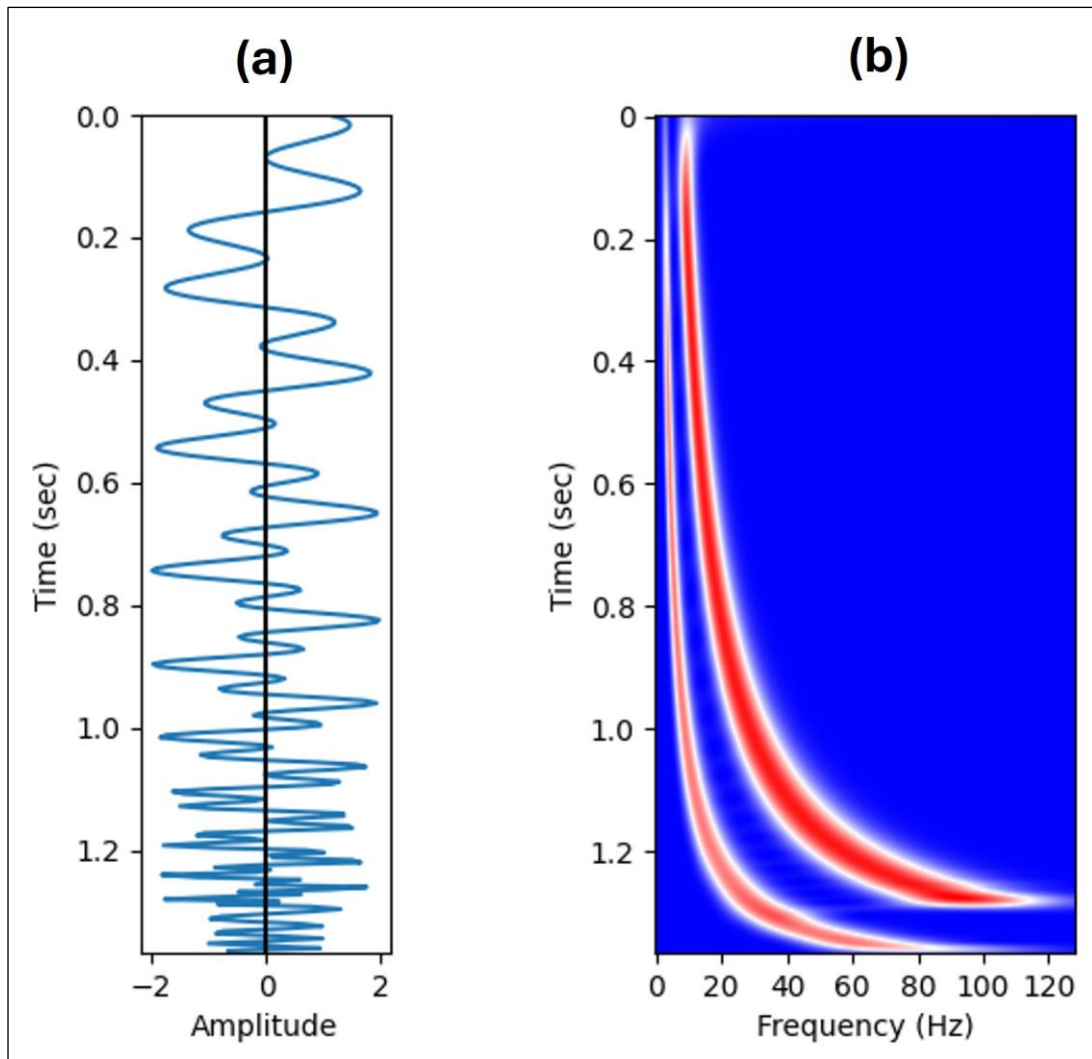


Figure 7.3: (a) A synthetic chirp signal with two hyperbolic sweep frequencies (reproduced from (S. Sinha et al., 2005)). (b) Time frequency map TFCWT obtained for the chirp signal in (a) using complex Morlet wavelet function.

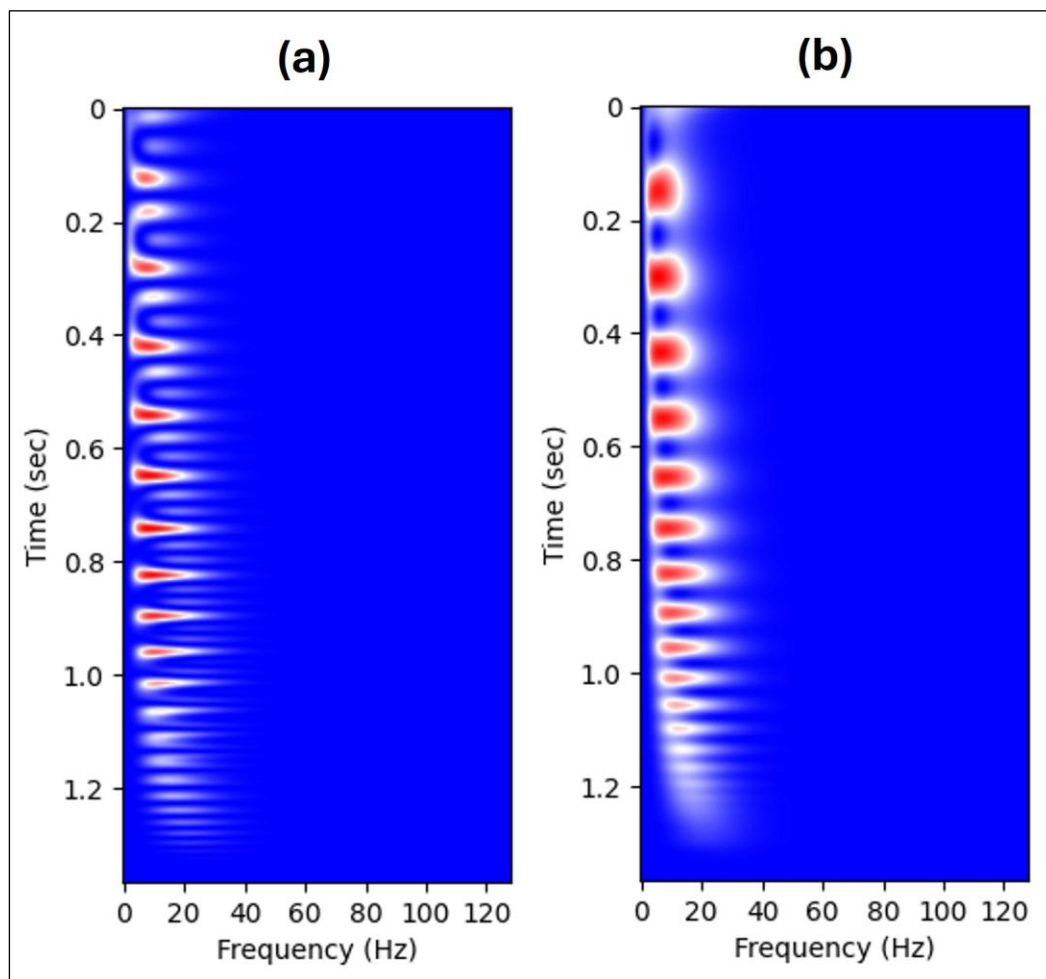


Figure 7.4: Subfigure (a) shows the time-frequency map of the synthetic chirp signal [refer to Figure 7.3(a)] with TFCWT constructed with the real-valued Mexican Hat wavelet and the same constructed with the Complex Mexican Hat wavelet is shown in subfigure (b).

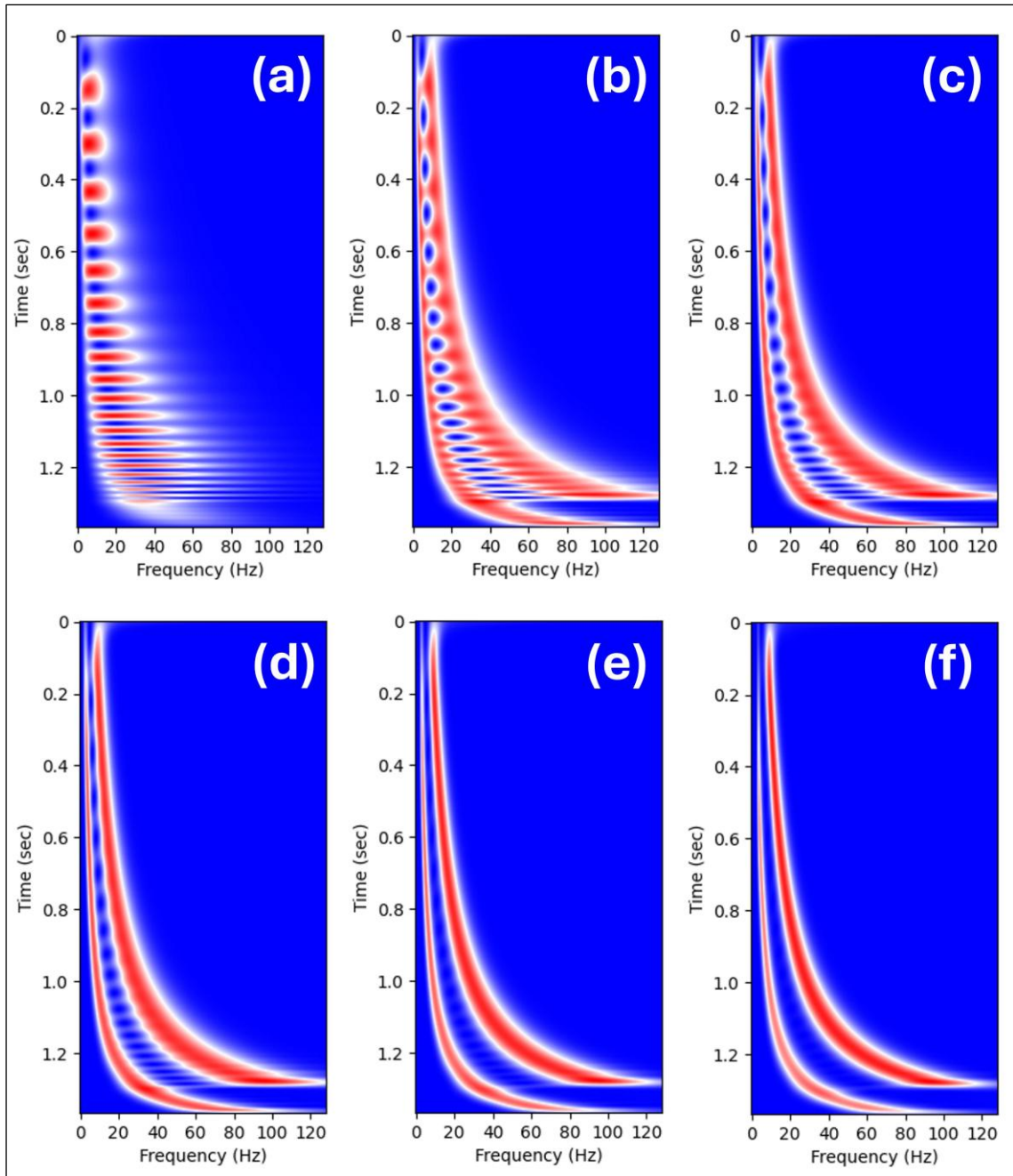


Figure 7.5: Paul wavelets of different order have been used to generate TFCWT map of the synthetic chirp signal [refer to Figure 7.3(a)]. Subfigures (a), (b), (c), (d), (e), and (f) have been produced using the Paul wavelet of order $m = 4, 10, 15, 20, 30$, and 40 , respectively.

7.5 Application of TFCWT with Paul Wavelets to Field Data

7.5.1 Study area and its geological settings

The study area falls in the Indo-Gangetic Basin (IGB) located in the northern part of India and south of the Himalayan foothills. The elongated basinal area extends over 2,000 km in length and 450 km in width, located within Longitude of 77°E to 88°E and Latitude of 24°N to 30°N (Figure 7.6) (DGH, 2024). There are two sub-basins of IGB, namely Ganga Basin and Punjab Plain. The present study accounts for the seismic delineation of the depositional environment in the east Ganga basin (Gandak Depression) using TFCWT derived spectral attribute analysis. The Gandak depression is a prominent tectonic feature within the Ganga basin, located in the eastern part of the basin between the Sarda and Madhubani depression, which is demarcated by the Faizabad ridge in the west and the Sitamarhi ridge in the East. The tectonic evolution of the Gandak depression is closely tied to the Himalayan orogeny influencing sedimentation patterns and structural features in the region (Gorain et al., 2023). The depressions deepen towards northeast (NE) along the Himalayan range front. The Gandak depression hosts the largest sediment thickness among all the depressions of the Ganga Basin having a sedimentary fill exceeding 6-7 km, comprising sequences from the pre-Tertiary Proterozoic sediments which include the Vindhya to the Tertiary Siwalik deposits, brought down by rivers flowing from the Himalaya (T. Dutta et al., 2023).

The Gandak Depression is characterized by favorable tectonic and depositional conditions, making it significant for hydrocarbon exploration (Argal et al., 2024). A seismic section showing Regional Unconformity (RU), pre-Tertiary sequence below and Tertiary sequence above in the area is presented in Figure 7.7. The near-surface sediments are characterized by Quaternary deposits (1.5 Ma to Recent) comprising loose sand, calcareous nodules, gravels, and pebbles. The Neogene sediments beneath include

the Siwalik formations: the Upper Siwalik (5.5–1.5 Ma) with interbedded sandstone and silty claystone, the Middle Siwalik (10.8–5.5 Ma) featuring sandstone, claystone, and siltstone, and the Lower Siwalik (18.3–10.8 Ma) consisting of sticky clay, sandy claystone, and hard siltstone. The prominent Regional Unconformity (RU) is readily recognized on seismic sections throughout the basin below which Lower Paleozoic to Neoproterozoic formations have been identified in exploratory wells in the basin. Such formations include the Karnapur composed of siltstone, shale, sandstone, and limestone/marl, followed by the Tilhar and Ujhani formations, which consist of shale, siltstone, sandstone, and quartzitic sandstone with shale and claystone (T. Dutta et al., 2023; Gorain et al., 2023; Argal et al., 2024).

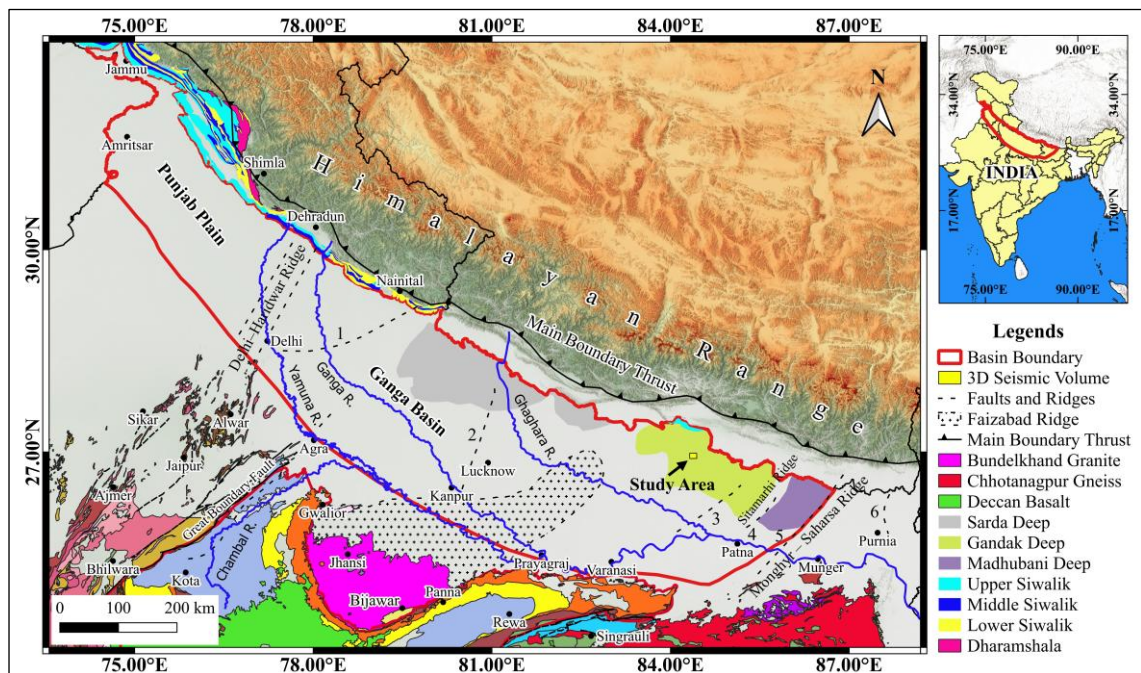


Figure 7.6: The lithostratigraphic map depicts the lithology and tectonic structures of the Ganga Valley basin. The yellow color box represents the 3D seismic volume used in this study and is in the Gandak depression. The numbers represent the major subsurface faults identified using different geophysical methods. 1. Delhi Moradabad Fault, 2. Lucknow Fault, 3. West Patna Fault, 4. East Patna Fault, 5. Monghyr-Saharsa Ridge Fault, 7. Malda-Kishanganj Fault; R. River

7.5.2 Data and Methods

Ganga Basin is mostly covered with 2D seismic lines of different vintages at regional and local scales (DGH, 2024). This study employs a post-stack time-migrated 3D seismic reflection data. The data was acquired and processed by the Oil and Natural Gas Corporation Limited (ONGC) and was made available to Rajiv Gandhi Institute of Petroleum Technology (RGPT) from the Directorate General of Hydrocarbons (DGH). This data offers a spatial view of the subsurface horizons encompassing an area of roughly 104.65 sq km. The survey area has 336 inlines at 35 m spacing and 508 crosslines at 17.5 m spacing. The reflection seismic was recorded up to 8 seconds two-way travel time (TWT). SEG normal polarity convention has been followed, i.e. a peak represents positive reflection coefficient, and a trough represents negative reflection coefficient.

The zone of interest lies between 1.5 sec and 3 sec TWT, which covers from Tertiary (Lower Siwalik) to pre-Tertiary (Neoproterozoic), Regional Unconformity (RU) / Karnapur sedimentary sequences (Figure 7.7). 3D seismic data is significant in understanding depositional environments, offering a detailed and comprehensive view of subsurface geological formations. This advanced imaging technology enables geoscientists to analyze the spatial distribution and characteristics of buried sedimentary layers with high precision, significantly enhancing the interpretation of paleo-depositional processes and environments (Sarkar et al., 2010; Zhu et al., 2016). It helps in the identification and mapping of sedimentary facies and their geometries and visualization of complex depositional features such as channels, point bars, deltas, reefs, and turbidite systems (Bitrus et al., 2016). These features often have distinct seismic signatures that can be used to infer the depositional architecture, sediment transport mechanisms, and paleogeomorphology. For instance, fluvial systems may be identified

by their meandering or braided channel patterns, while deltaic environments exhibit progradation clinoforms (Reijenstein et al., 2011).

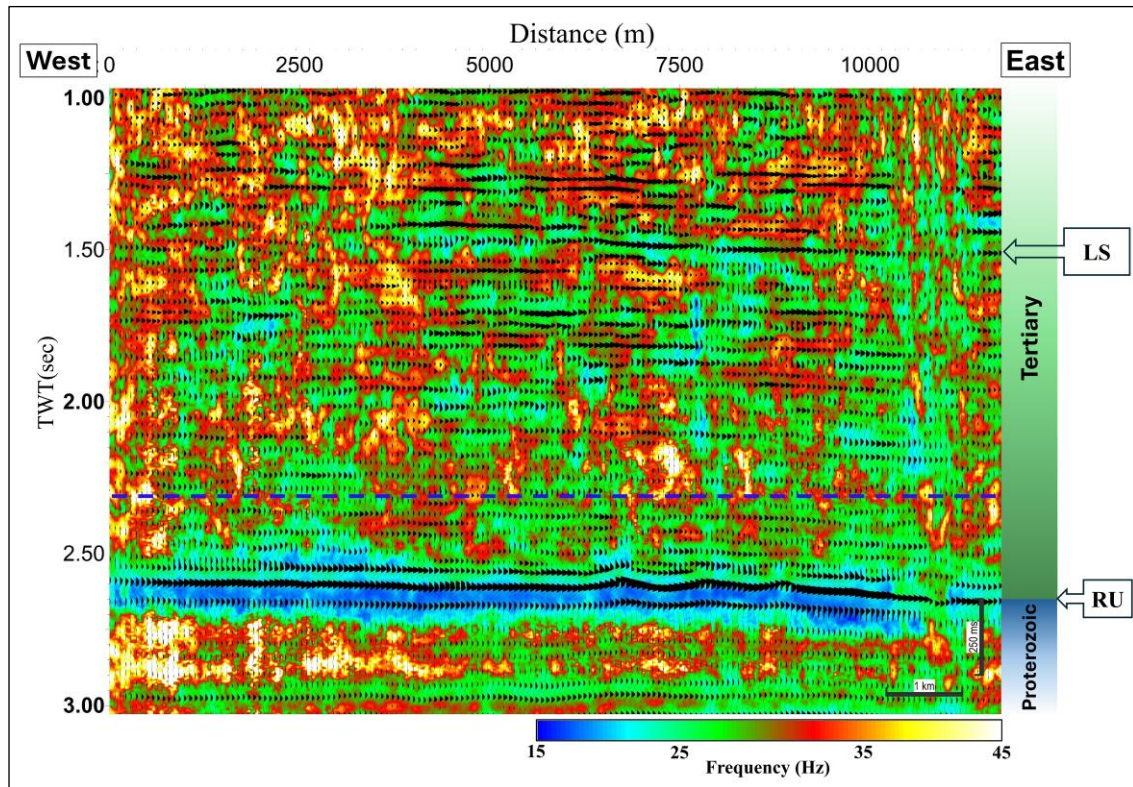


Figure 7.7: An east-west section from the 3D seismic volume showing the Regional Unconformity (RU) and the top of Lower Siwalik formation (LS). The background colour display represents the dominant frequency content. Spectral decomposition attribute shown in the subsequent figures for the Lower Siwalik formation are for the stratal slice along the blue dashed line (~2.3 sec).

The 3-D seismic interpretation of the Ganga basin in the Gandak depression is primarily used for the elaborate depositional environment from the Pre-Tertiary to Tertiary era with the help of TFCWT attribute seismic analysis. This work primarily focuses on identifying the depositional environment along with the sequence of stratigraphic correlation in the Gandak depression. The corresponding seismic reflection events that show reasonable amplitude and continuity along the marked horizon were selected. Formations near the regional unconformity could be traced comfortably because of their good lateral continuity, in contrast to the horizons within the Siwalik formations, which were

challenging to trace laterally because of their poor lateral continuity, showing fluvial sedimentary deposits in the Siwaliks.

7.5.3 Spectral Analysis with RGB blending using Paul Wavelets

In the RGB blending technique, typically three frequencies are chosen: the lowest of the three is colored red (R), the middle frequency is colored green (G), and the highest frequency is represented by the blue (B) color. Thin formations tune at higher frequencies and therefore would appear bluish, whereas thick formations would appear reddish as they tune at lower frequencies.

In this study, spectral decomposition of the 3D seismic data is achieved with the TFCWT where the Paul Wavelet of different orders have been used. From the synthetic signal study above, we have noticed that the Paul wavelet of order 40, which is equivalent to the Morlet wavelet (Figure 7.2) produced higher frequency resolution compared to the Paul wavelet of order 4, which mimics the Mexican Hat or Ricker wavelet (Figure 7.1). Therefore, the Paul wavelet of order 4 and 40 both were used on the real data and the results have been compared. Two different depositional environments from the 3D seismic data have been studied with RGB blending technique on spectrally decomposed data: 1) A stratal slice from the Lower Siwalik formation (along the dashed line at ~2.3 sec in Figure 7.7) is showing fluvial channels, and 2) the Regional Unconformity (RU) surface demarcating Tertiary and Pre-Tertiary formations (along the marked surface RU in Figure 7.7).

The Siwaliks, characterized by clastic units with a shallow offshore shoal to fluvial nature, presents a fining upwards sequence indicative of a braided fluvial system (Nakayama and Ulak, 1999; Kundu et al., 2012). The Lower Siwalik sediments consist of fine sandstones, siltstones, and mudstones, indicating deposition in a more distal setting with increased sediment supply within a low-energy floodplain-lacustrine

environment (Goswami and Deopa, 2018). There are several thin and meandering channels apparent from the energy map in the Lower Siwalik formation (Figure 7.8), however, their continuity is not so obvious. RGB spectral blending technique was used to enhance the channel features on this stratal slice. Three dominant frequencies, viz. 20 Hz, 25 Hz, and 35 Hz, were selected and colored by 'R', 'G', and 'B', respectively. The one with the Paul wavelet of order $m=4$ is presented in Figure 7.9, and the other with the Morlet wavelet is shown in Figure 7.10. Spectral decomposition with the TFCWT has clearly enhanced the depositional system by showing several subsurface details in the area (Figure 7.9 and Figure 7.10). The RGB color blending has proved very useful in visualizing sand-filled sinuous river channels is trending in the NNW-SSE direction, showing lacustrine-deltaic floodplain characteristics, including paleo-meandered river channels and ox-bow lakes within the Tertiary sediments of Lower Siwalik. Although spectral enhancements using the Morlet and the Paul wavelet ($m=4$) are showing very similar features, there are subtle differences where the Morlet wavelet is showing more granularity along the channel features indicating thinner and thicker part of the channels. The Pre-Tertiary Regional Unconformity/Karnapur Formation is characterized as composed of siltstone, shale, sandstone, and limestone/marl deposited in shallow sea environments (Decelles et al., 2001; Ojha, 2012). These sediments were deposited in a marine shelf-dominated environment and subsequently buried under a thick pile of Tertiary sediments. The energy map (Figure 7.11) does not explicitly show the features of this depositional environment. However, spectral decomposition with TFCWT and RGB blending technique has significantly enhanced the interpretation of the depositional system by revealing several subsurface features.

In comparison to Siwalik sediments, the Regional Unconformity (RU) / Karnapur formation of Pre-Tertiary has continuous lateral seismic events, which can be traced

easily throughout the basin, shows characteristic low frequency (Figure 7.7). Therefore, RGB blending is done in the lower frequency range. Three dominant frequencies, viz. 12 Hz, 20 Hz, and 30 Hz were selected and colored by 'R', 'G', and 'B', respectively. Figure 7.12 shows the RGB blended spectral image of RU with the Paul wavelet of order 4, whereas Figure 7.13 shows the same using Morlet wavelet. The RGB color blended outcomes indicate a very different depositional environment when compared with the Lower Siwalik. This stratal slice indicates a shallow shelf marine environment having a paleo-coastal to paleo-sea interface (shoreline trending in the NW-SE direction) at the unconformity marker. Previous researchers (Decelles et al., 2001; Ojha, 2012; Goswami and Deopa, 2018), based on their geological studies, discussed similar depositional environments for the Tertiary and the pre-Tertiary sequences.

Several paleo submarine canyons were also observed in the NE direction. Although Figure 7.12 and Figure 7.13 are showing almost similar geomorphic features, there are more details in the colors of Figure 7.13. Therefore, the TFCWT with Morlet wavelet better depicts the geology in comparison with the Paul wavelet of order 4.

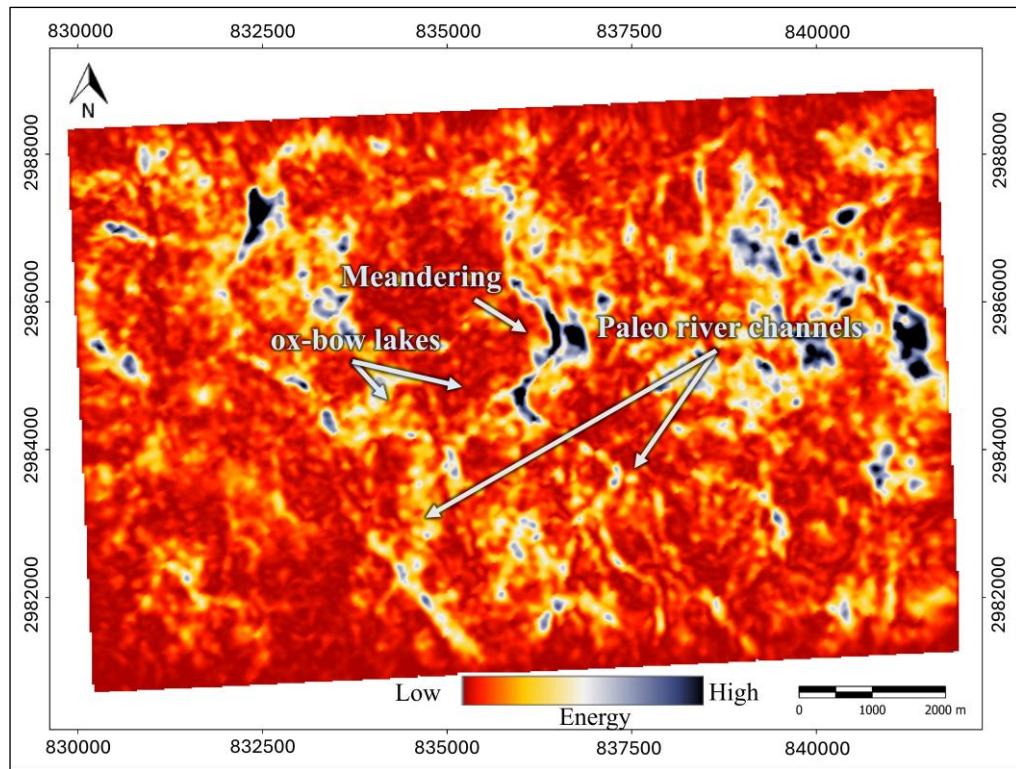


Figure 7.8: The stratal slice of energy volume along the blue dashed line shown in Figure 7.7. It is essentially an amplitude-squared attribute of the original seismic data. Note that the formation has NNW-SSE-trending paleo-channels.

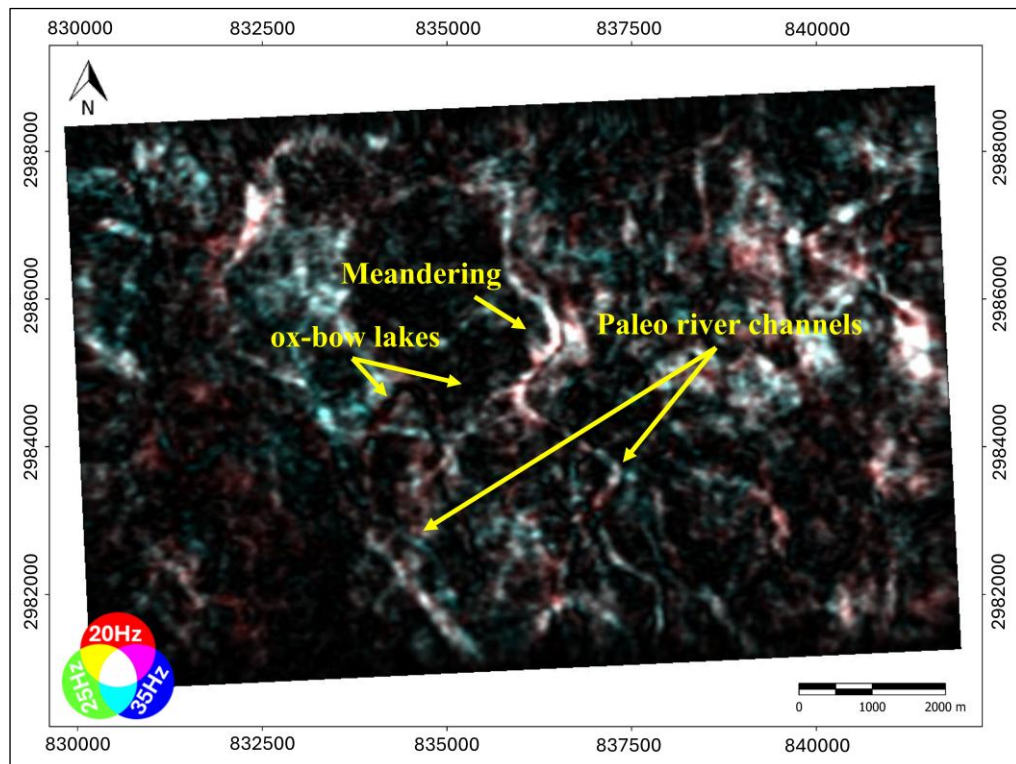


Figure 7.9: RGB blending of 20 Hz, 25 Hz and 35 Hz spectrally decomposed data with TFCWT using the *Paul wavelet of order 4*. The stratal slice is extracted from the Lower Siwalik formation, the same along which Figure 7.8 has been presented.

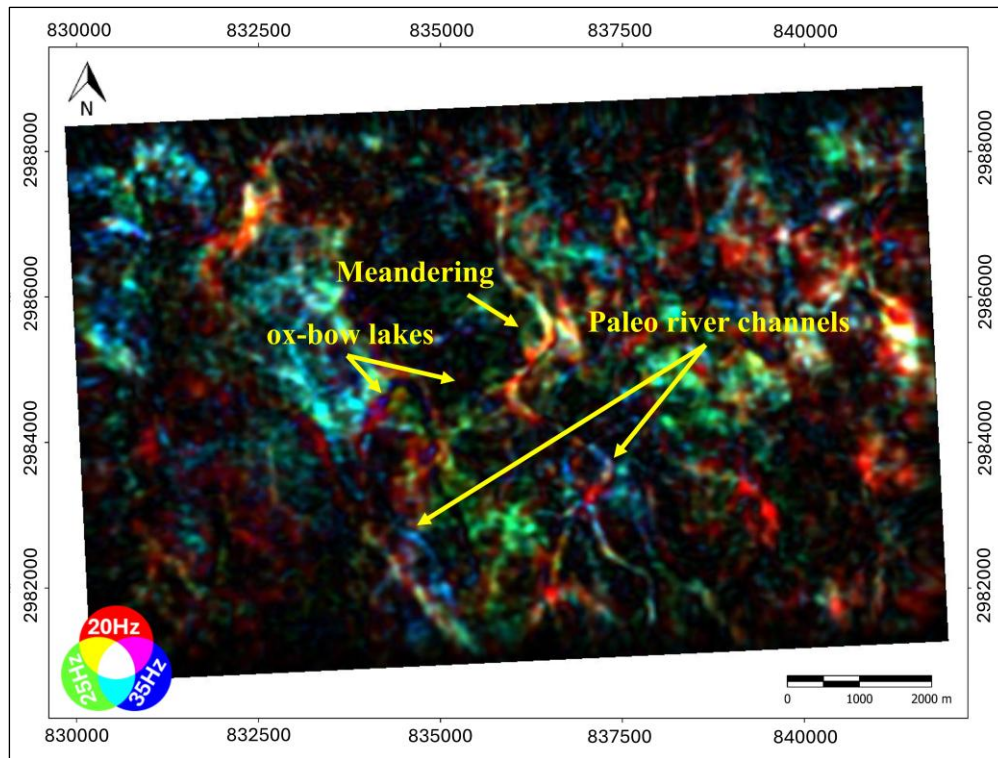


Figure 7.10: RGB blending of 20 Hz, 25 Hz and 35 Hz spectrally decomposed data with TFCWT using the *Morlet wavelet*. The stratal slice is extracted from the Lower Siwalik formation, the same along which Figure 7.8 has been presented. Notice the increased details of the fluvial channels in the form of colours.

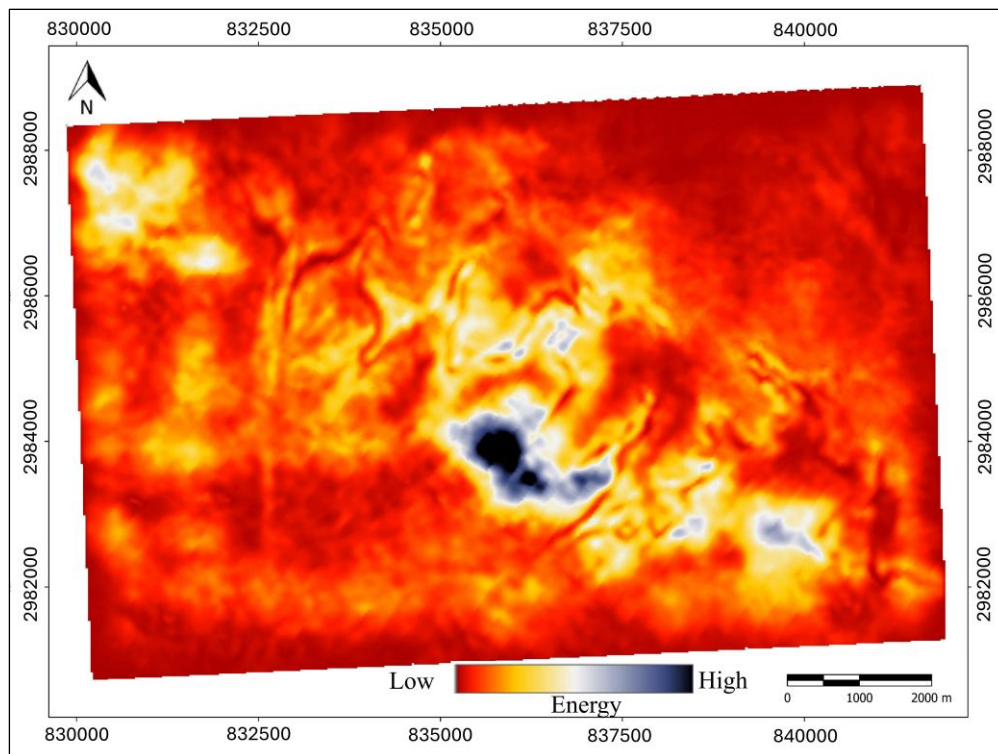


Figure 7.11: Map view of energy attribute along the Regional Unconformity (RU) shown in Figure 7.7.

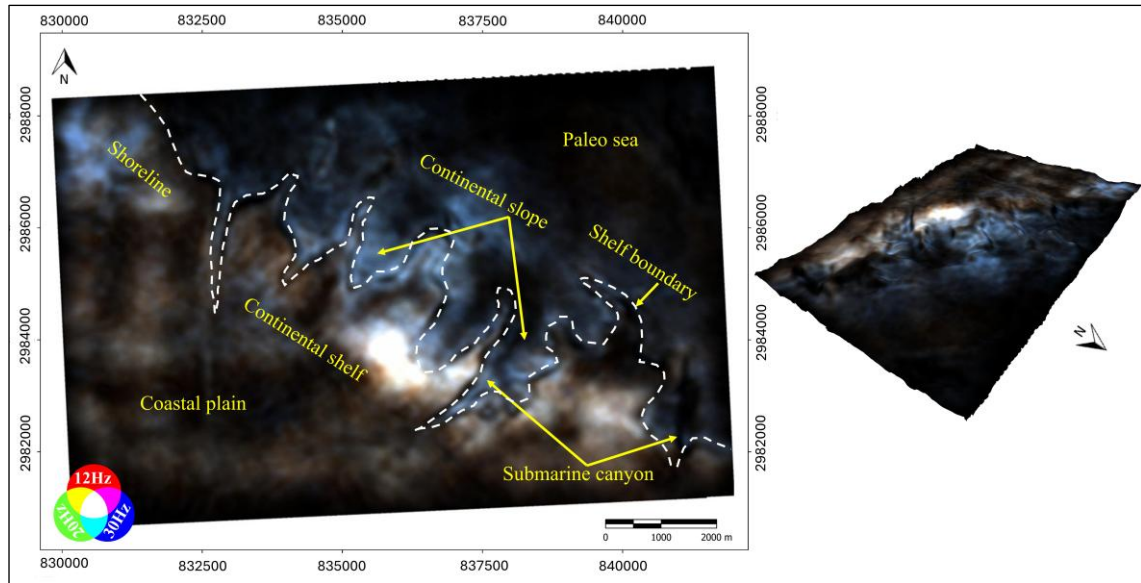


Figure 7.12: RGB blending of 12 HZ, 20 Hz and 30 Hz spectrally decomposed data with TFCWT using the *Paul wavelet of order 4*. Different depositional sites along the RU have been differentiated. The coastal line trends in the NW-SE direction. A 3D representation of the map view is shown on the right with the coastal plain away from the viewer and paleo sea towards the viewer.

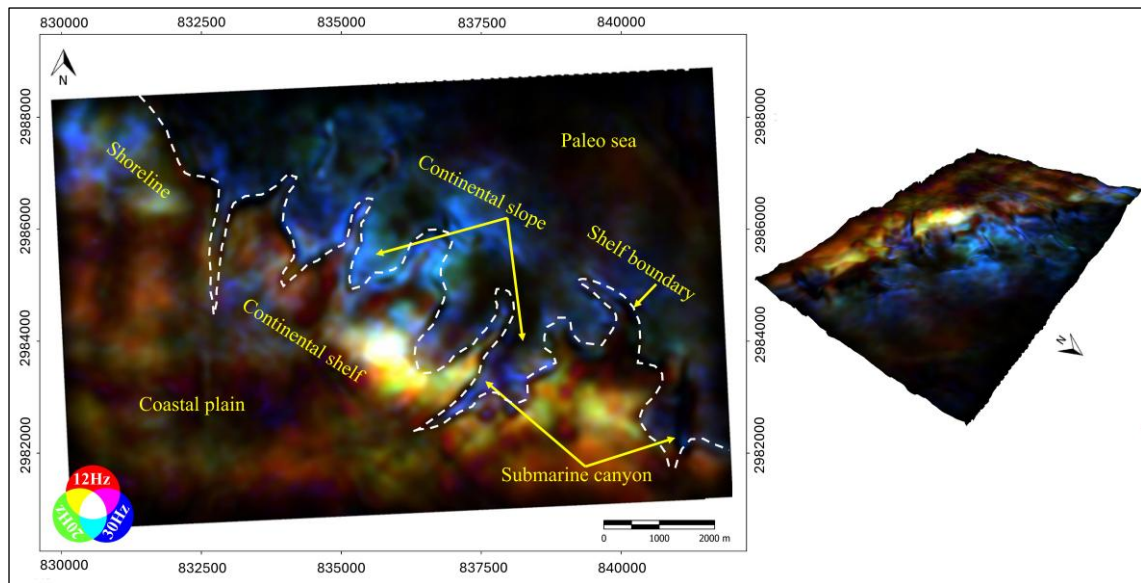


Figure 7.13: RGB blending of 12 HZ, 20 Hz and 30 Hz spectrally decomposed data with TFCWT using the *Morlet Wavelet*. Different depositional sites along the RU have been differentiated with higher granularity. The coastal line trends in the NW-SE direction. A 3D representation of the map view is shown on the right with the coastal plain away from the viewer and paleo sea towards the viewer.

7.6 Conclusions

Unlike other spectral decomposition techniques, which are based on optimization algorithms, the TFCWT transforms the time signal into time-frequency space in such a way that the inverse Fourier transform of the time summation of the time-frequency map recreates the original signal, thus keeping all the information intact in the time-frequency space. The Paul wavelet used in this study is especially suited for spectral decomposition, as its time-frequency resolution can be adjusted by changing the order of the wavelet. While the Paul wavelet of order 4 mimics the Mexican Hat / Ricker wavelet, its fortieth-order wavelet approximates the Morlet wavelet. The lower-order Paul wavelet has enhanced temporal resolution with TFCWT, while the higher-order Paul wavelet demonstrates improved frequency resolution. Consequently, for the need of superior time resolution, one can use the 4th -order Paul wavelet, which may be considered as a pseudo-Ricker wavelet. The 40th -order Paul wavelet provides high-frequency resolution in the lower frequency regime, which can potentially be used in the identification of low-frequency gas shadow zones.

Spectral decomposition based on TFCWT combined with the RGB spectral blending technique has been able to enhance two diverse depositional environments: Tertiary paleo-channels in the Lower Siwaliks and the pre-Tertiary shallow marine depositional system associated with the Regional Unconformity/ Karnapur Formation in the Ganga basin. This can also be used for delineation of depositional environment and seismic stratigraphy in the region. The spectral interpretation of these two separate depositional environments from pre-Tertiary to Tertiary uncovers the sea level fluctuation from RU to Lower Siwalik, in which riverine sediments thickened towards the northeast from the pre-Tertiary to the Tertiary period.

Chapter 8 : Sequence Stratigraphic Evaluation of Proterozoic Depositional Architecture

8.1 Background

This study integrates seismic reflection data, gravity modelling, and well-log information to reconstruct the geological evolution and deep crustal architecture of the Ganga Basin. Newly analysed 2D seismic profiles acquired under the National Seismic Programme (NSP), together with gravity data and information from the Indara-1 well, reveal four major stages of basin development from the Paleoproterozoic to the Cenozoic. Beneath the established Bahraich Formation, six previously unrecognized Proterozoic sequences (S1–S6) have been identified. The lower sequences (S1–S3) are interpreted as extensions of the Paleoproterozoic Gwalior Formation and are characterized by high-density lithologies, including quartzites and banded iron formations. The overlying sequences (S4–S6) display affinities with the Mesoproterozoic Bijawar Group, comprising shallow-marine carbonate and phosphorite-bearing units that account for gravity highs in the study area.

After a prolonged depositional hiatus, Neoproterozoic sedimentation was dominated by shallow-marine clastic and carbonate facies represented by the Ujhani, Tilhar, and Karnapur formations. Limestone development within the Tilhar Formation indicates the establishment of a stable carbonate platform and highlights potential targets for future hydrocarbon exploration. This phase ended with formation of a basin-wide Regional Unconformity (RU). During the Cenozoic, Himalayan uplift-controlled foreland basin development, resulting in rapid accumulation of Siwalik molasse in fluvial to deltaic settings and subsequent burial by Quaternary alluvium.

The results indicate that the Ganga Basin preserves a significantly older and more complex stratigraphic framework than previously recognized. The refined geological model improves understanding of basin evolution and provides new insights into its tectonostratigraphic significance and resource potential within the northern Indian shield.

8.2 Introduction

The Ganga Basin, situated immediately south of the Himalayan orogenic belt, represents one of the most extensive peripheral foreland basins of the Indian subcontinent. Elongated predominantly along an east–west axis, this basin owes its present geometry and internal architecture to the protracted tectonostratigraphic evolution associated with the Himalayan orogeny (Figure 8.1). As the Indian Plate collided with and continued to indent into the Eurasian Plate, significant crustal shortening and flexural subsidence resulted in the formation of a foredeep south of the rising Himalaya. This tectonic configuration facilitated the accumulation of a remarkably thick sedimentary pile comprising primarily Tertiary and Quaternary successions that progressively overlie the much older Proterozoic substratum. While the Cenozoic sedimentary evolution of the Ganga Basin has been extensively addressed in earlier works, the nature, distribution, and tectonic significance of the underlying Proterozoic sequences remain among the least understood aspects of the basin.

In contrast to the poorly exposed interior of the basin, the southern fringes adjoining the Bundelkhand craton display well-exposed Proterozoic successions that have been the subject of detailed geological investigations (Mohanty, 2023). These exposures, along with their counterparts in the adjoining Gwalior, Bijawar, and Vindhyan basins, underscore the presence of a complex Proterozoic framework beneath the younger alluvial cover. However, due to the masking effect of several kilometres of Cenozoic sedimentation, direct observation of these units in the subsurface remains challenging.

This knowledge gap becomes particularly critical given that the Directorate General of Hydrocarbons (DGH, 2024) has classified the Ganga Basin as a Category-3 basin from a hydrocarbon exploration perspective. Such a classification implies that although the basin is under-explored, it holds substantial prospects for hydrocarbon generation and entrapment. Realizing this potential necessitates an integrated and systematic basin analysis that combines geological, geophysical, and stratigraphic approaches supplemented by exploratory drilling.

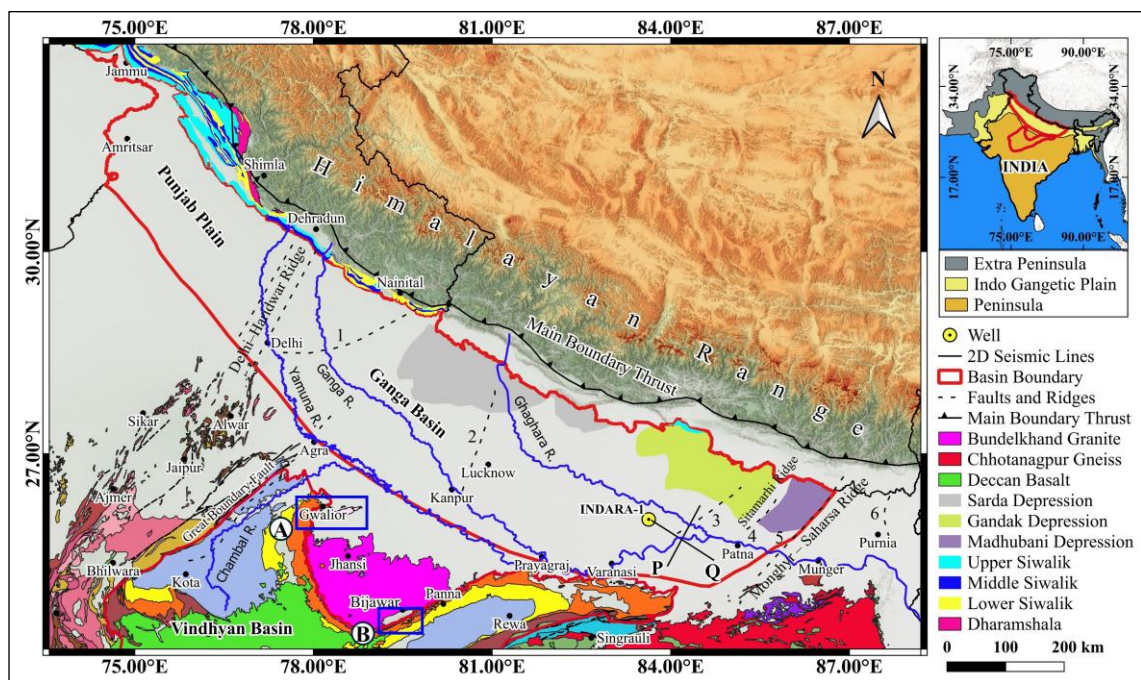


Figure 8.1: Regional map depicts the lithology and tectonic structures of the Ganga Valley basin along with the selected 2D seismic lines (P, and Q) and exploratory well Indara-1. River is abbreviated as R. Numbers represent the major subsurface faults and ridges identified by previous researchers. 1. Delhi-Moradabad Fault, 2. Lucknow Fault, 3. West Patna Fault, 4. East Patna Fault, 5. Monghyr-Saharsa Ridge, 6. Malda-Kishanganj Fault. Blue boxes A, and B, represent locations of the Gwalior and Bijawar Basin, respectively, which are expanded in Figure 8.2A and Figure 8.2B.

A major advancement in this direction has been the acquisition of regional scale 2D seismic data under the National Seismic Program (NSP), which has revealed the presence of hitherto unrecognized deeper seismic sequences interpreted to be of Proterozoic affinity. The identification and characterization of these deeper units offer a unique

opportunity to reassess the basin architecture, pre-Tertiary tectonic history, and its implications for resource exploration.

The depositional evolution of the Ganga Basin is intricately linked with the Himalayan tectonics. Earlier studies by Valdiya (1976), Raiverman et al. (1984), and later by Kumar et al. (2004) have delineated how episodic tectonic uplift, subsidence, and migration of depocenters influenced sedimentation patterns across the basin. The Siwalik Group, representing a thick accumulation of Tertiary molasse-type sediments, is prominently exposed along the Himalayan foothills (Duvall et al., 2021). These lithologies, encountered in numerous wells drilled within the basin (Misra, 2009), attest to the strong provenance control exerted by the rising Himalaya. The Tertiary succession is further overlain by extensive Quaternary alluvium (Sinha et al., 2010), which blankets much of the basin and complicates direct geological observations.

South of the basin, the geological landscape changes markedly with the exposure of several Proterozoic basins, including the Gwalior, Bijawar, and the vast Vindhyan basins. These units rest unconformably on the Archean Bundelkhand craton and collectively define a mosaic of Paleoproterozoic to Neoproterozoic sedimentary basins with distinct lithostratigraphic attributes. Stratigraphically, the Vindhyan Group overlies both the Bijawar and Gwalior groups (Rao et al., 2005; Azmi et al., 2008). The Gwalior Basin occurs along the northwestern margin of the Vindhyan Basin, whereas the Bijawar Basin forms part of the southeastern periphery (Figure 8.1). Although both Gwalior and Bijawar sequences are Paleoproterozoic in age, isotopic and stratigraphic evidence suggests that the former predates the latter (Chakraborty et al., 2020).

The Vindhyan Basin itself represents one of the largest and best-preserved Mesoproterozoic to Neoproterozoic intracratonic basins worldwide, with sedimentation spanning nearly 1.2 billion years (~1791–625 Ma) (Mandal et al., 2019; Mohanty, 2023).

The Bundelkhand granitoid massif structurally bifurcates the basin into two major sectors the eastern Son Valley sector and the western Rajasthan/Chambal Valley sector each possessing distinct but correlatable stratigraphic successions. Broadly, the Vindhyan Supergroup is subdivided into the Lower Vindhyan (Semri Group) and the Upper Vindhyan succession comprising the Kaimur, Rewa, and Bhandar Groups. Age assignments based on radiometric dating place the Lower Vindhyan between ~1700–1400 Ma and the Upper Vindhyan between ~1200–800 Ma (Meert and Pandit, 2015; Chakraborty et al., 2020). Significant contributions to refining Vindhyan chronology include Rb–Sr dating of glauconites (Kumar, 2001), U–Pb zircon ages from the Porcellanite Formation (Ray et al., 2002), Pb–Pb isochron ages (Gopalan et al., 2013), and fossil-based interpretations that have controversially suggested much younger Ediacaran–Cambrian ages for parts of the Lower Vindhyan (Azmi et al., 2008; Prasad and Asher, 2016). These varied interpretations underscore the complexity of Proterozoic chronostratigraphy in central India.

The Bijawar Basin preserves important lithological markers of early Paleoproterozoic tectonism and sedimentation. Radiometric dates from the Dargawan sill (1789 ± 21 Ma) and Kurat lava (1691 ± 180 Ma) (Haldar and Ghosh, 2000) provide constraints on its volcanic and sedimentary evolution. In contrast, the Gwalior Basin, considered older, is constrained temporally by multiple isotopic datasets including $^{40}\text{Ar}/^{39}\text{Ar}$ ages (Rao et al., 2005), Rb–Sr isochron ages (Chakraborty et al., 2020), and U–Pb zircon concordia ages (Deb et al., 2002). Absar et al. (2009) placed the period of Gwalior Basin sedimentation between 2000 Ma and 1791 Ma. Despite their shared tectonic backdrop and provenance from the Bundelkhand craton, the Gwalior and Bijawar basins differ markedly in depositional style. The Gwalior Basin shows a dominance of clastic sedimentation representing environments ranging from alluvial-fan to proximal shelf, whereas the

Bijawar Basin exhibits strong chemical sedimentation in its basal units including dolomite, chert breccia, and phosphorite along with volcanoclastic inputs. The basin evolution diverges further, with the Gwalior Basin hosting significant Banded Iron Formations (BIFs) and the Bijawar Basin containing phosphorite-rich intervals (Absar et al., 2009; Chakraborty et al., 2015). These contrasts provide valuable analogues for interpreting the seismic expressions of buried Proterozoic sequences within the Ganga Basin.

Subsurface studies of the Ganga Basin have evolved steadily over time. Early works by Sastri et al. (1971) and Rao (1973) offered foundational interpretations of the basin's tectonic framework and subsurface stratigraphy using limited seismic and well-log datasets. More recent approaches have expanded the scope of investigation by incorporating geochemical evidence, as demonstrated by Srinivas et al. (2014), who highlighted the potential for hydrocarbon generation based on soil geochemical anomalies. Yet, despite these contributions, the deeper stratigraphic framework, particularly the Proterozoic sequences, remain insufficiently resolved at the basin scale. In the present study, we address this gap by applying a sequence stratigraphic approach to newly acquired deep penetration 2D seismic data from the eastern Ganga Basin under the National Seismic Program (NSP). These data, combined with existing gravity maps and well logs including those from the Indara-1 exploratory well enable an integrated analysis of lateral and vertical variations in seismic facies. Well-to-seismic tying provides the lithological control necessary for reliable interpretation, while gravity information offers constraints on density variations of deep-seated units and its structural configuration revealed by seismic.

This integrated approach allows reconstruction of the deeper continental margin within the Ganga Basin and facilitates new insights into its evolution over an expansive

Proterozoic substrate. The broader implications extend beyond regional geology; understanding these concealed continental margins can improve analog-based interpretations of similar foreland systems worldwide. Ultimately, by resolving the internal seismic architecture, stratigraphic stacking patterns, and tectonic controls operating during early basin evolution, this study contributes to both academic understanding and the practical assessment of subsurface resources in one of India's most important sedimentary basins.

8.3 Study Area

The Indo-Gangetic Plain represents one of the largest and most laterally extensive alluvial landscapes in the world, spanning northern India across an area of nearly 304,000 sq. km. Within this physiographic expanse, the Punjab Plain occupies approximately 62,000 sq. km to the west of the Delhi–Haridwar Ridge, while the Ganga Basin dominates the eastern sector with an areal extent of about 242,000 sq. km (Figure 8.1). The Ganga Basin forms an elongated east–west–trending depression, extending over 1,000 km in length and nearly 300 km in width between longitudes 77°E–86°E and latitudes 25°N–30°N.

The present study focuses on the eastern part of the Ganga Basin, with particular emphasis on delineating its depositional history in a sequence stratigraphic framework. The study area encompasses the southern segments of the Gandak and Madhubani depressions structural lows that play a key role in sediment accommodation and basin evolution. This sector of the basin contains some of the thickest and most widespread Quaternary alluvial deposits in the Indian subcontinent, derived predominantly from rivers draining the rapidly uplifting Himalayan hinterland (Mishra et al., 2000; Tunini et al., 2016; Singh and Khan, 2021; Manglik et al., 2022).

Geomorphologically and tectonically, the Ganga Basin represents an active peripheral foreland basin, where the interplay between Himalayan tectonics and flexural subsidence controls basin configuration and sediment distribution (Sahu and Saha, 2014). Sediment thickness varies significantly across the region, reaching nearly 4.5 km in several depressions and increasing northward toward the Himalayan foothills (Hetényi et al., 2006; Adilakshmi et al., 2021). Earlier studies, such as those by Sastri et al. (1971), have indicated that sediment accumulation may exceed 6 km along the northern basin margin.

8.4 Tectonic Framework

The subsurface architecture of the Ganga Basin is highly heterogeneous, characterized by a complex Proterozoic basement surface dissected by buried faults and ridges. These basement features exert considerable influence on sediment dispersal patterns, subsurface stratigraphic development, and the overall tectono-sedimentary evolution of the east Ganga Basin. The basin is bounded on its eastern margin by the subsurface Monghyr–Saharsa Ridge and on its western margin by the Delhi–Haridwar Ridge, both of which act as major structural divides. The Delhi–Haridwar Ridge is interpreted as a northward continuation of the Aravalli structural trend, and the Faizabad and Munger–Saharsa ridges, which represent extensions of the Bundelkhand and Satpura massifs, respectively (Valdiya, 1976; Gahalaut and Kundu, 2012; Godin and Harris, 2014; Godin et al., 2019; Suresh et al., 2023). To the north, the basin terminates against the outermost Siwalik foothills of the Himalayas, where the Himalayan Frontal Thrust (HFT) a major active fault zone running parallel to the mountain front forms a well-defined tectonic boundary. The southern margin is delineated by exposures of Proterozoic sedimentary rocks of the Vindhyan Supergroup and the Bundelkhand granitic–gneissic massif (Figure 8.1).

Within these boundaries, the basin incorporates three major depressions: the Sarda, Gandak, and Madhubani depressions, each separated by intervening basement ridges (Sastri et al., 1971; Rao, 1973; Valdiya, 2016). The Faizabad Ridge separates the Sarda and Gandak depressions. Further east, the Sitamarhi Ridge demarcates the boundary between the Gandak and Madhubani depressions. The Monghyr–Saharsa Ridge, marking the eastern limit of the basin, is regarded as a structural continuation of the Chotanagpur Plateau and segregates the Madhubani Depression from the adjoining Purnea Basin (Godin and Harris, 2014).

Among the three depressions, the Sarda Depression is the largest, extending east–west with sediment thicknesses exceeding 6 km. The Gandak Depression, lying immediately east of Sarda, contains even greater sediment accumulation, ranging from 7 to 8 km (Ojha, 2012). The Madhubani Depression, situated further east, represents a narrow Mesoproterozoic graben formed around 1400 Ma through transtensional rifting, and is inferred to hold more than 7 km of sediment fill (Ojha, 2012).

8.5 Stratigraphy

The stratigraphy of the Ganga Basin has been documented by numerous researchers, each providing distinct interpretations based on available geological, geophysical, and paleontological evidence. This section presents an integrated overview of the comparative and generalized stratigraphic framework across the basin, summarized in (Table 8.1).

One of the earliest systematic stratigraphic classifications was proposed by Shukla et al. (1994), who identified five major formations within the pre-Tertiary sedimentary record, distinguished primarily by their lithological variations. According to their interpretation, the Bahraich Group dated to the Palaeoproterozoic–Mesoproterozoic forms the

lowermost sedimentary package and directly overlies the granitic basement. Above this lies the Madhubani Formation of the Lower Vindhyan Group, followed by three formations of the Upper Vindhyan sequence: the Ujhani, Tilhar, and Karnapur formations. Collectively, these units comprise the Vindhyan Supergroup within the subsurface of the Ganga Basin. A major regional unconformity of approximately 454 million years separates the Vindhyan successions from the overlying Tertiary deposits, beginning with the Matera Formation. The younger stratigraphy continues with the deposition of the Lower Siwalik during the Early to Middle Miocene, the Upper Siwalik during the Pleistocene, and finally the extensive Holocene alluvium.

Fuloria (1996) proposed a more detailed subdivision, classifying the entire basin succession into nine formations. In this scheme, the granitic basement constitutes Formation IX, overlain by the Proterozoic Bijawar Formation (Formation VIII). The Ujhani Formation equivalent to the Lower Vindhyan and assigned an Upper Proterozoic to Lower Cambrian age is designated as Formation VII. This is unconformably overlain by the Badaun Formation (Formation VI), considered equivalent to the Upper Vindhyan and assigned a Cambrian age. Overlying these is the Raxaul Formation (Formation V), dated to the Upper Jurassic–Lower Cretaceous. The Tilhar Formation is placed stratigraphically higher and categorized as Formation IV of Cretaceous age. Formations III, II, and I represent the Puranpur, Siwalik, and Alluvium units, respectively, collectively spanning the Early Eocene to Holocene.

A major contribution to understanding the Pre-Tertiary successions comes from Prasad and Asher (2001), who reported an extensive assemblage of acritarch microfossils from various subsurface intervals. Their work distinguished two major groups within the Ganga Basin Supergroup: the Bahraich Group of Paleoproterozoic age and the younger Madhubani Group ranging into the Paleozoic. They also recognized the Matera

Formation as part of the Cenozoic stratigraphy, although the Siwalik and younger deposits were not incorporated into their formal stratigraphic scheme.

For the present study, a refined stratigraphic framework has been adopted from Ojha (2012) and Srinivas et al. (2014), further modified to develop a generalized stratigraphic model (Table 8.1). The oldest recognized sedimentary sequence is the Bahraich Group of Mesoproterozoic age, subdivided into the Avadh and Sarda formations, which rest directly upon the Bundelkhand Granite Complex (BGC). A significant hiatus of nearly 550 million years (1350–800 Ma) separates these Mesoproterozoic deposits from the overlying Neoproterozoic to Early Paleozoic platformal sediments.

These younger sequences, largely confined to the Sarda, Gandak, and Madhubani depressions, consist predominantly of siliciclastic units with intermittent carbonate horizons, indicative of deposition within a passive-margin environment. They appear in drill cores as the Ujhani, Tilhar, and Karnapur formations. Their accumulation reflects sustained platformal sedimentation, though locally influenced by pre-existing basement ridges and fault-controlled subsidence.

A prolonged depositional break spanning from ~540 to 35 Ma precedes the deposition of the Matera Formation (Eocene–Oligocene), which is restricted to the Sarda Depression. In contrast, the Siwalik sediments of Tertiary age are widespread across the basin, forming one of its most extensive stratigraphic components and transitioning upward into the basin-wide Holocene alluvium.

Table 8.1: Comparative chrono-stratigraphy of the Indo-Gangetic Basin by various authors [after (Prasad et al., 2002; Ram, 2005; Ojha, 2012; Srinivas et al., 2014)].

Age			Ma	Comparative Stratigraphy					Generalized Stratigraphy										
				(Shukla et al., 1994)			(Fuloria, 1996)				(Prasad and Asher, 2001)								
Cenozoic	Quaternary	Holocene	0.011	Alluvium			Formation-I (Alluvium)				Alluvium								
		Pleistocene	2.4	Siwalik Group	Upper Siwalik (Badaun fm.)	Upper Siwalik													
						Middle Siwalik													
	Neogene	Pliocene	5.3		Middle Siwalik Lower Siwalik	Formation-II (Siwalik fm.)		Middle Siwalik											
		Miocene	23	Formation-III (Puranpur fm.)		Lower Siwalik													
	Paleogene	Oligocene	34	Matera fm.			Matera fm.		Matera										
		Eocene	55.8																
		Palaeocene	65.5																
	Mesozoic	Cretaceous		145	Regional Unconformity (Major Upliftment)			Formation-IV (Tilhar fm) Formation-V (Raxaul fm)		Regional Unconformity (Major Upliftment)									
Jurassic		199																	
Triassic		251																	
Paleozoic	Permian		299	Regional Unconformity (Major Upliftment)					Regional Unconformity (Major Upliftment)										
	Carboniferous		359																
	Devonian		416																
	Silurian		443																
	Ordovician		488																
	Cambrian	Late	542								Vindhyan Super Group	Upper Vindhyan	Karnapur fm.	Upper Vindhyan	Formation-VI (Badaun fm.)	Madhubani Group	Karnapur fm.		
		Middle															Tilhar fm.		Tilhar fm.
		Early																	
Ujhani fm.																			
Neo-Proterozoic	Vendian		1000	Vindhyan Super Group	Upper Vindhyan		Lower Vindhyan	Formation-VII (Ujhani fm.)	Ganga Supergroup	Karnapur Tilhar Ujhani									
	Late	Ujhani fm.																	
Riparian	Middle	1600	Lower Vindhyan			Madhubani fm.													
					Early														
Paleo-Proterozoic					2500		Bahraich group (Metamorphics)			Formation-VIII (Bijawar fm.)									
Archean			Granitic Basement			Formation-IX (Basement)		Bundelkhand Granitic Gneiss		Archean Basement (Bundelkhand Granite/Gneiss)									

8.6 Depositional Environment

Tectonics and depositional environment are the two principal factors governing the character, geometry, and evolution of sedimentary successions within any basin. The Ganga Basin is no exception. Earlier studies suggest that sedimentation within this basin was initiated under a rift-controlled regime during the Mesoproterozoic, when the Bahraich Group was deposited directly over the granitic Archean basement. This initial phase of basin development provided the foundational stratigraphic framework upon which subsequent sedimentary sequences accumulated.

The Bahraich Group is divided into two distinct units: the lower Sarda Formation and the overlying Avadh Formation. The Sarda unit comprises basic volcanic rocks, phyllites, and schists, indicative of an active tectonic setting marked by significant crustal reworking. In contrast, the Avadh unit is dominantly composed of orthoquartzites interbedded with limestone and subordinate shale horizons (Shukla et al., 1994; Prasad and Asher, 2001). These lithologies, combined with the observed sedimentary structures, point to deposition within a shallow-water, tidally influenced inner-shelf environment. The orthoquartzite succession reflects a regressive depositional trend (Ojha, 2012), consistent with a coarsening-upward pattern that characterizes much of the Bahraich Group. Notably, these sediments experienced low-grade metamorphism, reflecting later tectonothermal influences.

Overlying the Mesoproterozoic sequence is the Neoproterozoic–Paleozoic succession comprising the Ujhani, Tilhar, and Karnapur formations, deposited under passive-margin, shallow-marine conditions. This interval represents an extended phase of relatively uninterrupted platform sedimentation. However, notable lithological variability exists among the formations. The Ujhani and Karnapur units are predominantly siliciclastic, while the Tilhar Formation is distinguished by its carbonate-

rich composition with limited clastic input (Gorain et al., 2023), reflecting differences in depositional energy and terrigenous supply.

The Ujhani Formation consists of alternating shale, sandstone, and limestone beds forming a thick, unmetamorphosed sedimentary sequence. Seismic data reveal a weak reflection pattern that corresponds to these fine to medium-grained clastics. The succession records a progressive marine transgression, transitioning from intertidal conditions to a shallow inner-shelf setting (Ojha, 2012; Srinivas et al., 2014).

In contrast, the Tilhar Formation represents the widespread development of semi-arid carbonate platforms, characteristic of a middle- to outer-shelf environment with diminished clastic influx. The relative tectonic quiescence during this period promoted extensive carbonate deposition. Subsequent marine transgression led to the retreat of the carbonate shelf and the establishment of a fine-grained outer-shelf system (Tandon et al., 2008; Khanolkar et al., 2020).

The Karnapur Formation, dominated by alternating shale and sandstone, was deposited in a shallow-marine setting with facies ranging from littoral to middle-shelf environments (DGH, 2012). These lithologies indicate fluctuating energy conditions and episodic clastic supply.

Following the deposition of the Karnapur sequence, the basin experienced a prolonged episode of regression and erosion during much of the Mesozoic and early Palaeogene, resulting in a prominent Regional Unconformity (RU). Sedimentation resumed during the Tertiary, triggered by the Indian–Eurasian collision (45–50 Ma), which transformed the tectonic regime from extensional to compressional and initiated the development of the Himalayan orogen and its peripheral foreland basin.

The ensuing Neogene molasse, collectively termed the Siwalik Group, records deposition in lacustrine to fluvial systems. Lower Siwalik sediments reflect lacustrine conditions influenced by episodic marine incursions, while the Middle and Upper Siwalik formations document the transition to high-energy braided and meandering fluvial environments. These Tertiary and Quaternary clastic sequences represent a typical foreland basin fill dominated by fluvial–lacustrine processes. The Siwalik sediments are ultimately overlain by the extensive Gangetic alluvium, comprising loose sand, kankar, gravel, pebbles, and sandy clays.

8.7 Proterozoic basins

8.7.1 Gwalior Basin

The east–west trending Gwalior Basin, encompassing an area of approximately 2,400 sq. km, occupies a strategic position along the northwestern margin of the Bundelkhand Craton. The basin is composed predominantly of a volcano-sedimentary succession interpreted to have formed within a continental rift or passive-margin setting (Figure 8.2A). Structural observations indicate that bedding planes generally exhibit an ENE–WSW strike with a gentle dip of about 5° towards the north, reflecting a relatively stable and mildly deformed sedimentary regime (Absar et al., 2009). The basin succession rests unconformably upon the Bundelkhand Granite Complex (BGC), which forms the crystalline basement (Absar et al., 2009; Chakraborty et al., 2020). Mesoproterozoic Lower Vindhyan strata occur in contact along the western margin, while Quaternary Gangetic alluvium defines the northeastern boundary, highlighting the basin’s transitional geological setting.

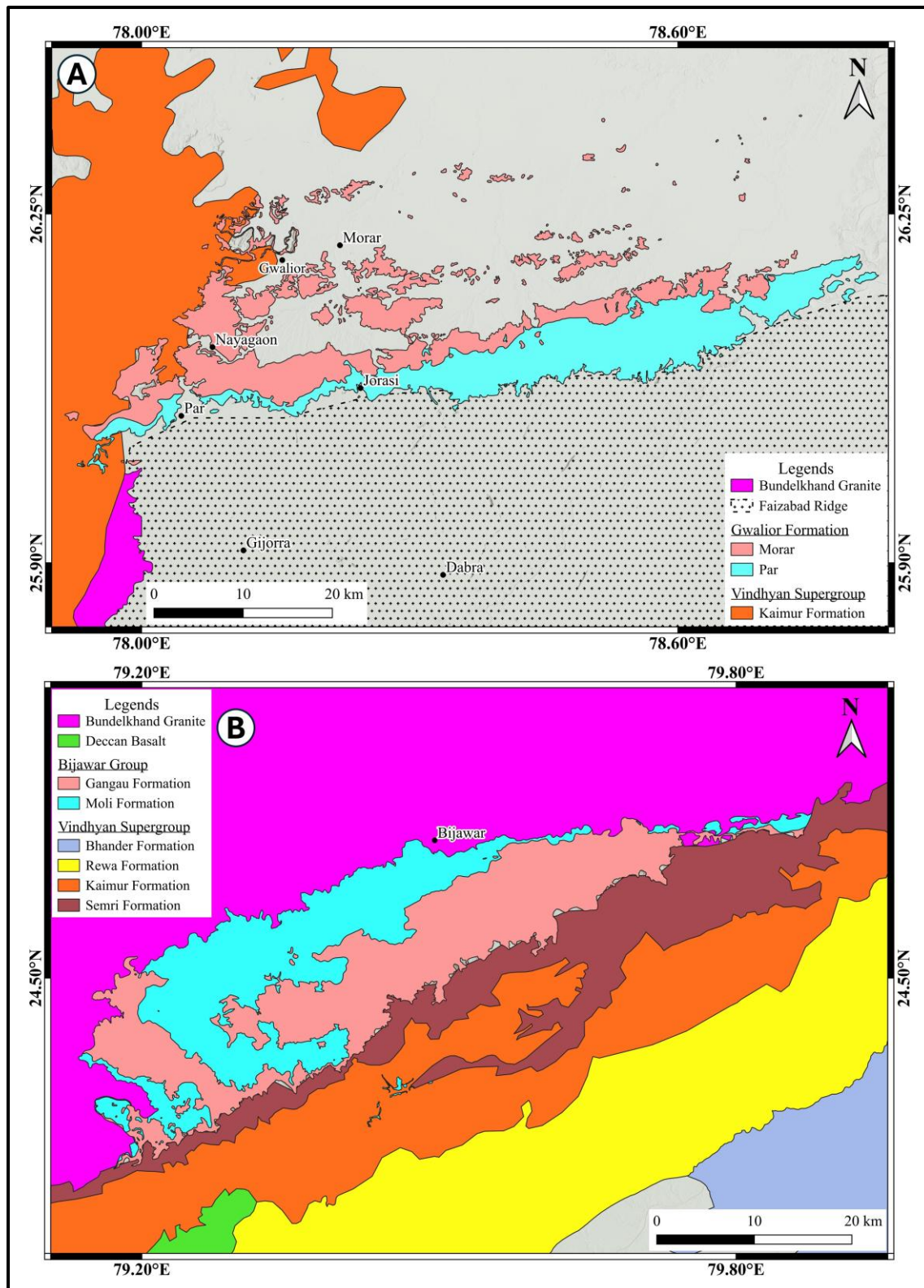


Figure 8.2: Geological maps of Gwalior Basin (A), and Bijawar Basin (B) are presented showing various formations.

Table 8.2: Geochronological units from various stratigraphic sequences within the Gwalior, Bijawar, and Vindhyan Groups of rocks after (Chakraborty et al., 2015). The geochronological age derived from: BIF (Absar et al., 2009), Mafic intrusive (Crawford and Compston, 1969), Tuff and limestone (Absar et al., 2009), Dargawan intrusive (Haldar and Ghosh, 2000), Rohtas limestone & Rampur shale (Rasmussen et al., 2002; Ray et al., 2002; Sarangi et al., 2004; Chakrabarti et al., 2007) Porcellanite (Rasmussen et al., 2002; Ray et al., 2002), Arangi shale (Sarangi et al., 2004). Note, thickness of stratigraphic column is not to scale.

Gwalior Basin				Bijawar Basin				Vindhyan Basin			
Morar Formation	Banded Iron Formation (BIF)		1866 ± 250 Ma [Pb-Pb]	Gangau Formation	Karri ferruginous sandstone		1691± 180 Ma [Rb-Sr]	Upper Vindhyan	Bhandar Group	Maihar sandstone	
	Tuffaceous shale		Hirapur phosphorite			Bhandar limestone				866 ± 90 Ma [Pb-Pb]	
	Mafic intrusive		1830 ± 200 Ma [Rb-Sr]	Moli Formation	Dargawan intrusive				Reva Group	Jhiri shale	
	Alternation between mafic intrusive, tuff and limestone		1914 ± 120 Ma [Pb-Pb]		Bajno dolomite					Panna shale	893 ± 12 [U-Pb]
Par Formation	Sandstone-shale alternation				Malehra chert breccia		Lower Vindhyan	Kaimur Group	Bijaigarh shale	1074 ± 14 Ma [⁴⁰ Ar/ ³⁹ Ar]	
	Medium grained sandstone				Kawar Volcanics					1210 ± 52 Ma [Re-Os]	
	Conglomerate/ Coarse granular sandstone			Bundelkhand Granite Complex (BGC)							
Bundelkhand Granite Complex (BGC)									Rohtas	Rohtas limestone	1601 ±130 Ma [Pb-Pb] 1599 ± 48 Ma [Pb-Pb]
										Rampur shale	1514 ± 120 Ma [Pb-Pb] 1599 ± 8 Ma [U-Pb]
									Semri Group	Chorhat sandstone	
										Koldaha shale	1631 ± 1 Ma [U-Pb] 1628 ± 8 Ma [U-Pb]
										Porcellanite	
										Kajrahat limestone	
									Kajrahat	Kajrahat limestone	
								Arangi shale		1791 ± 90 Ma [Pb-Pb]	
								Deoland sandstone			
								Gwalior / Bijawar Basins			
								Bundelkhand Granite Complex (BGC)			

Sedimentological and facies analyses suggest that the Gwalior Group was deposited on a stable clastic shelf influenced by tidal processes, wave reworking, and intermittent storm activity (Absar et al., 2009). These processes collectively reflect a dynamic but shallow depositional environment that alternated between high-energy and quieter conditions.

Lithostratigraphically, the Gwalior Group is subdivided into two major formations: the Par and Morar formations, arranged in ascending order. The basal Par Formation, roughly 200 m thick, is dominantly arenaceous and comprises conglomerates, coarse-grained to granular sandstones, and alternating sandstone–shale units. These lithologies point to deposition within continental to shallow marine transitional environments, consistent with early rift-related sedimentation.

The overlying Morar Formation, with an estimated thickness of ~800 m, marks a shift towards chemogenic sedimentation. It includes tuffaceous sandstone, ferruginous shale, limestone, and significant occurrences of Banded Iron Formation (BIF). Additionally, the lower portion of this formation contains intercalations of mafic intrusive bodies and volcanic tuffs, indicating episodic volcanic activity during its evolution (Table 8.2) (Absar et al., 2009; Chakraborty et al., 2015; Mohanty, 2023). The chemical and ferruginous nature of these deposits suggests deposition in an oxidizing marine environment with periodic hydrothermal or volcanic influence.

Although no direct geochronological constraints exist for the Par Formation, multiple Pb–Pb whole-rock dating efforts have yielded ages for various units of the Morar Formation. The basal Morar section has been dated at 1866 ± 250 Ma, while limestone associated with BIF records an age of 1914 ± 120 Ma. A tuffaceous shale layer within the intermediate BIF horizon provides a more precise age of 1801 ± 21 Ma (Absar et al., 2010; Colleps et al., 2021; Srivastava et al., 2022). These dates collectively attest to prolonged and multi-phase sedimentation during the Paleoproterozoic.

The abundant mafic sills and intrusive volcanics within the basin, dated between 1790 and 2110 Ma, further constrain the maximum and minimum age limits of the Gwalior Group (Crawford and Compston, 1969; Rao et al., 2005; Absar et al., 2009; Chakraborty

and Paul, 2014). Although the precise onset of sedimentation remains uncertain, the maximum age is broadly inferred from its unconformable relationship with the underlying ~2.5 Ga Bundelkhand Granite Complex (Colleps et al., 2021; Srivastava et al., 2022).

8.7.2 Bijawar Basin

The Paleoproterozoic Bijawar Basin constitutes an important geological province within the Indian Peninsular Shield and forms part of a chain of Proterozoic metasedimentary basins that rest unconformably upon the Bundelkhand basement. The basin trends predominantly ENE–WSW and tapers markedly toward its eastern extremity. It extends for nearly 85 km in length, with its width varying significantly from 1 to 20 km (Figure 8.2B). The preserved strata exhibit gentle to moderate dips ranging between 12° and 40°, directed both northward and southward, reflecting mild post-depositional deformation. Geologically, the basin is flanked by the Bundelkhand Granite Complex to the north and the Vindhyan sedimentary succession to the south, positioning it within a transitional structural corridor between these major crustal blocks.

Stratigraphically, the Bijawar Basin is subdivided into two major subgroups—the Moli and the Gangau with a cumulative thickness of approximately 3.5 km. The Moli Subgroup comprises four formations in ascending order: the Kavar Volcanics, Malhera Chert Breccia, Bajno Dolomite, and Dargawan Gabbro. Overlying this is the Gangau Subgroup, which includes the Hirapur Phosphorite and the Karri Ferruginous Sandstone formations (Table 8.2) (Mohanty, 2023). Around one-fourth of the exposed basin area is occupied by lithologies of the Moli Subgroup, while the remaining expanse is dominated by the younger Gangau Subgroup (Chakraborty et al., 2015).

Depositional conditions within the Bijawar Basin point to a stable shallow-marine to nearshore carbonate platform environment periodically influenced by volcanism. The lithological assemblage characterized by stromatolitic dolomites, cherty limestones, ferruginous shales, and phosphorite indicates sedimentation under predominantly calm, shallow-water settings with intermittent pulses of chemical precipitation. The significant phosphorite enrichment in the Hirapur Formation is interpreted to have formed under upwelling conditions that enhanced organic productivity (Chakraborty et al., 2020). Locally, basal conglomerates record a transgressive surface over the Bundelkhand granite-gneiss basement.

In comparison, while the Gwalior Basin reflects clastic-dominated sedimentation with a strong volcanic imprint, the Bijawar Group is comparatively richer in chemically precipitated and carbonate lithologies. Both basins, however, possess considerable economic value: the Gwalior Group hosts iron ore deposits, whereas the Bijawar succession is well known for its phosphorite resources.

Chronologically, the Bijawar Group is considered younger than the Gwalior Group, with a significant depositional hiatus separating the two successions. Age constraints derived from Rb-Sr dating of mafic intrusive bodies indicate that the Dargawan Gabbro has a minimum age of 1789 ± 21 Ma, while the Kurat lava suggests that basin formation predates 1691 ± 180 Ma (Chakraborty et al., 2020). These dates collectively provide a broad timeframe for the evolution of the Bijawar Basin during the Paleoproterozoic.

8.7.3 Vindhyan Basin

The Proterozoic rocks of the Vindhyan Basin form one of the most extensive sedimentary successions in central India. They rest unconformably on the Archean Bundelkhand Granite Complex (BGC) in several areas, while in other regions they overlie the

Paleoproterozoic Gwalior and Bijawar sequences. Stratigraphically, the Vindhyan Supergroup is divided into two major units: the Lower Vindhyan (Semri Group) and the Upper Vindhyan (comprising the Kaimur, Rewa, and Bhandar Groups). These two successions are separated by a distinct intra-Vindhyan unconformity, reflecting a major break in sedimentation. Collectively, the Vindhyan strata record a long-lived history of marine to continental sedimentation along a stable cratonic margin, punctuated by repeated transgressive–regressive cycles (Chakraborty et al., 2020).

The Lower Vindhyan succession predominantly consists of marine deposits, including shales, argillites, and dolomites, which reflect deposition in shallow-marine to intertidal settings. In contrast, the Upper Vindhyan succession represents a gradual shift to continental environments, consisting mainly of red and buff-colored sandstones, interbedded shales, and subordinate limestones that were laid down in fluvial, deltaic, and shallow-marine systems. The Vindhyan sediments are notably unmetamorphosed, generally undeformed, and characteristically display horizontal or gently dipping strata. Their remarkable lateral continuity makes them one of the best-preserved Proterozoic sedimentary archives in the region.

The age of Vindhyan sedimentation has long been debated. Early constraints were provided by Rb–Sr dating of glauconites from the Semri Group near Chitrakoot, which suggested a maximum age of around 1650 Ma for the onset of deposition (Chakraborty et al., 2020). More precise U–Pb zircon ages from the Porcellanite Formation of the Lower Vindhyan yielded values of 1631.2 ± 5.4 Ma and 1630.7 ± 0.8 Ma, offering robust confirmation of early Mesoproterozoic sedimentation (Table 8.2) (Ray et al., 2002). Conversely, Azmi et al. (2008) proposed a much younger Vendian to Early Cambrian age (~650–520 Ma) based on paleontological evidence. This younger interpretation

aligns with regional correlations that link basal Vindhyan glacial deposits with the Marinoan (“Snowball Earth”) glaciation.

8.8 Data and Methodology

A comprehensive basin-scale understanding of the Ganga Basin has been developed through the interpretation of regional-scale reflection seismic data, which serves as a critical tool for deciphering subsurface structural configurations, stratigraphic disposition, depositional patterns, and variations in sedimentary thickness. In this study, we analyse post-stack time-migrated 2D seismic reflection data and correlate it with the nearest exploratory well, Indara-1. To further augment the geological understanding, satellite-derived gravity data are integrated with the seismic interpretations, enabling improved delineation of deeper stratigraphic sequences and structural trends. The synthesis of basin-scale sedimentary processes and stratigraphic architecture derived from seismic stratigraphy significantly improves our understanding of its potential and structural plays relevant to hydrocarbon exploration.

The regional 2D seismic data utilised in this work were acquired by the Oil and Natural Gas Corporation Limited (ONGC) during 2017–2018 as part of the National Seismic Programme (NSP). These data provide high-resolution two-dimensional subsurface images, with seismic reflections recorded up to 8 seconds of two-way travel time (TWT) at a sampling interval of 2 milliseconds. Such acquisition parameters contribute to reliable imaging of both shallow and deep crustal features across the basin.

Two key 2D reflection profiles Line-P and Line-Q (Figure 8.1) form the primary dataset for sequence stratigraphic interpretation. Line-P extends approximately 114.43 km in a NE–SW orientation, while Line-Q covers nearly 123.44 km in a NW–SE direction, intersecting Line-P near its midpoint. The Indara-1 well, located in proximity to the

seismic grid, provides essential lithological and petrophysical information for seismic-to-well correlation. Sonic and density logs from the well were employed to generate a synthetic seismogram, thereby refining the interpretation of seismic horizons and enhancing confidence in horizon picking.

All seismic and well datasets were imported into the S&P Global Kingdom™ platform and visualised within the WGS84/UTM Zone 44N coordinate system. This integrated workflow of seismic interpretation, synthetic seismogram calibration, and gravity correlation establishes a robust framework for reconstructing system tracts and deciphering the depositional history of Proterozoic sequences within the Ganga Basin.

8.9 Results

8.9.1 Interpretation of wireline logs

The subsurface stratigraphy interpreted from the Indara-1 well (total drilled depth: 1955 m) provides valuable insights into the geological framework of the Ganga Basin (Figure 8.3). A concise summary of the lithostratigraphic units encountered in the well is presented in Table 8.3. The wireline log signatures, in conjunction with lithological descriptions, enable the identification of distinct stratigraphic intervals and their corresponding depositional characteristics.

The basal section of the well, below 1693 m, comprises thick melanocratic, medium- to coarse-grained crystalline plutonic basic igneous rock, petrographically classified as gabbro. This basement unit is characterised by calcium-rich plagioclase laths locally altered along with clinopyroxenes, ferruginous olivine, and disseminated magnetite. Immediately overlying the crystalline basement is the Mesoproterozoic Bahraich Formation, encountered between 1612 and 1693 m. This unit predominantly consists of non-calcareous sandstones interbedded with subordinate shale, claystone, and siltstone.

In most wells across the basin, the Bahraich interval is recognised as a metasedimentary succession with limited hydrocarbon prospectivity.

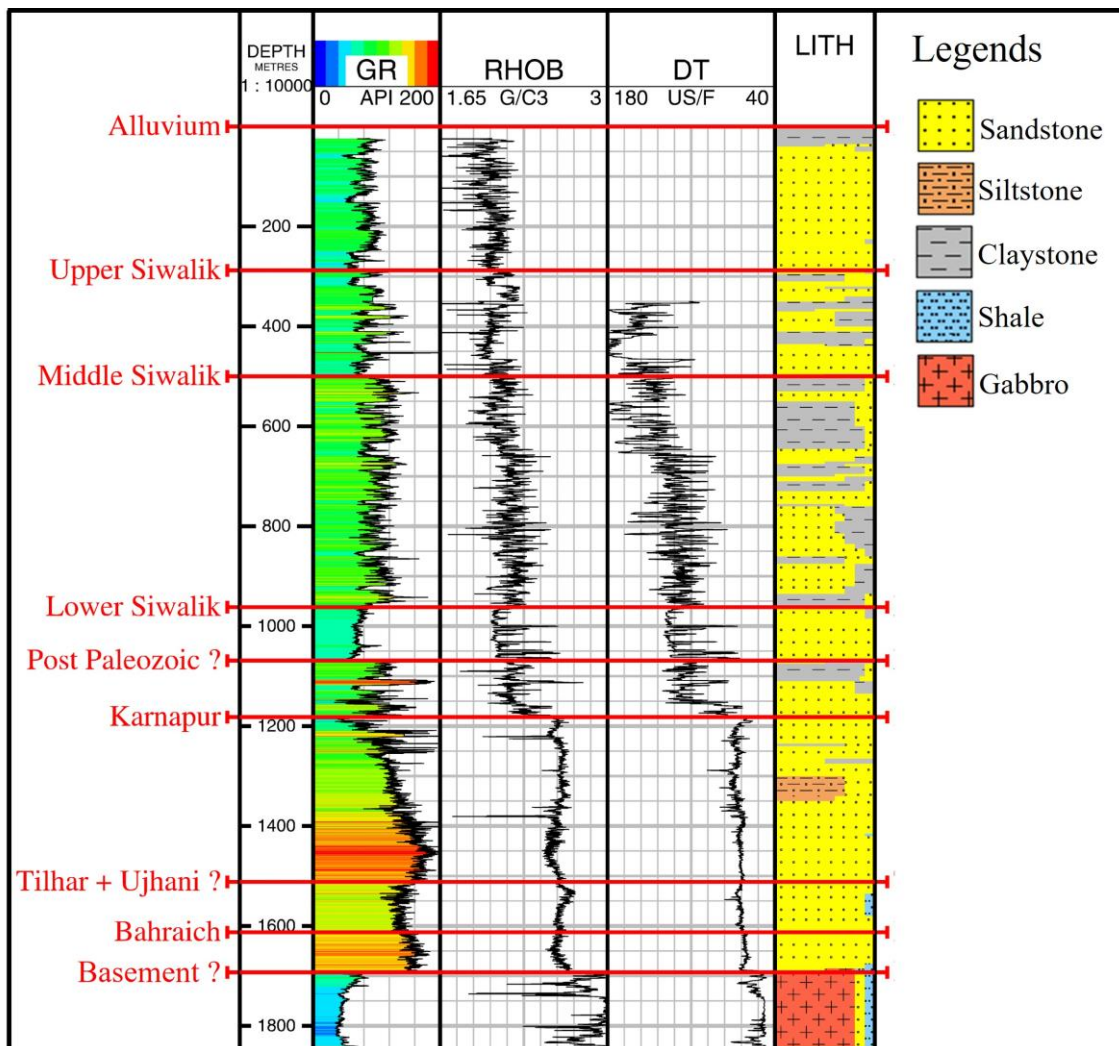


Figure 8.3: Interpreted electrologs of well Indara-1 showing various formation tops.

Above the Bahraich Formation, the stratigraphic column includes the Ujhani, Tilhar, and Karnapur Formations, collectively ranging from the Neoproterozoic to Lower Palaeozoic. The combined Ujhani–Tilhar interval extends from 1512 to 1612 m and is composed of fine- to coarse-grained non-calcareous sandstones interlayered with thin siltstone and claystone beds. The Karnapur Formation, identified between 1182 and 1512 m, exhibits distinct textural variation: its lower part comprises hard, poorly sorted, non-calcareous sandstone, whereas the upper part transitions into reddish-brown pebble-

bearing sandstone with ferruginous nodules, suggesting episodes of high-energy fluvial deposition.

Table 8.3: Lithostratigraphy of well Indara-1.

Age	Formation	Depth (m)	Thickness (m)	Lithology
Quaternary	Alluvium	0-288	288	Loose sand, sandstone, and claystone.
Tertiary	Upper Siwalik	288-500	212	Light brown, grey, dominantly fine-grained, micaceous, calcareous sandstone.
	Middle Siwalik	500-962	462	Grey, brown, fine to coarse-grained, calcareous sandstone and light brown, soft, sticky, sandy, calcareous claystone. Traces of coal/ peat are also present.
	Lower Siwalik	962-1182	220	Light brown, dominantly fine-grained, calcareous sandstone and ochre yellow, dirty white, sandy, calcareous claystone.
Regional Unconformity (RU)				
Neoproterozoic-Lower Palaeozoic	Karnapur	1182-1512	330	Reddish-brown coloured hard and compact pebbly sandstone with some iron concretions, iron-rich hard claystone, oolitic sandstone. Reddish brown, brown, fine to coarse-grained, non-calcareous sandstone.
	Tihar + Ujhani?	1512-1612	100	Fine to coarse-grained, non-calcareous sandstone with minor claystone and siltstone.
Mesoproterozoic	Bahraich	1612-1693	81	Grey, brown, fine to coarse-grained, non-calcareous sandstone with minor shale.
Pre-Cambrian	Basement (?)	1693-1955+	262+	Basic igneous rock (Gabbro).

The overlying Tertiary succession is subdivided into the Lower, Middle, and Upper Siwalik units. The Lower Siwalik (962–1182 m) consists of calcareous claystone, sandstone, and siltstone. The Middle Siwalik (500–962 m) is characterised by interbedded calcareous sandstone, clay, claystone, and siltstone. The Upper Siwalik

(288–500 m) contains alternating sand/sandstone and clay/claystone units, indicating rapid sedimentation under variable energy conditions. The Siwalik sequence is capped by Quaternary alluvium, composed of unconsolidated sand and clay representing recent fluvial deposition across the Ganga Plains.

8.9.2 2D Seismic Sequence Stratigraphic Analysis

The acquisition of new regional-scale two-dimensional (2D) seismic reflection data under the National Seismic Programme (NSP) has significantly advanced our understanding of the deep subsurface framework of the Ganga Basin. These data illuminate the basin's complex geological evolution, particularly within the pre-Tertiary sequences that remain largely concealed beneath thick Cenozoic cover. Sequence stratigraphic analysis is employed in this study as an interpretive tool to reconstruct the depositional history, understand variations in sedimentary facies, and identify chronostratigraphically significant surfaces. By emphasising the vertical and lateral stacking of seismic facies, sequence stratigraphy provides a robust framework to delineate depositional systems, recognise sea-level fluctuations, and infer basin subsidence patterns over geological time.

The Cenozoic Siwalik formations, extensively developed across the Himalayan foreland region, represent syn-orogenic clastic deposits shaped by the ongoing convergence between the Indian and Eurasian plates. These sedimentary packages typically exhibit a homoclinal northeasterly dip, with thickness increasing progressively towards the Main Boundary Thrust (MBT), reflecting their tectonostratigraphic relation to the rising Himalaya. In contrast, the pre-Tertiary stratigraphic succession including Proterozoic and Paleozoic sequences remains poorly exposed at the surface. Understanding the architecture of these deeper deposits is essential not only for reconstructing the basin's

geological evolution but also for assessing the hydrocarbon potential associated with pre-Siwalik stratigraphic intervals.

In this context, the present study focuses on developing a detailed geological model of the basin by identifying key sequence boundaries (SB), mapping major unconformity surfaces, and interpreting paleo-depositional directions using 2D seismic data. Sequence boundaries in the study area represent regionally extensive erosional or non-depositional surfaces that formed due to sea-level changes, variations in sediment influx, or tectonic reorganisation. These boundaries demarcate genetically related depositional sequences and provide temporal constraints on basin development.

The seismic profiles generated under the NSP provide extensive illumination of the Gandak and Madhubani depressions two major depocenters within the basin. The selected seismic sections (Line-P and Line-Q) reveal distinct high-frequency, high-amplitude reflectors corresponding to the lower, middle, and upper Siwalik formations, all of which are observed dipping consistently towards the northeast. A prominent Regional Unconformity (RU) is observed at the base of the lower Siwalik. Hydrocarbon prospects are inferred to be associated with structural or stratigraphic traps along the RU surface, particularly within the Proterozoic intervals represented by the Tilhar, Ujhani, and Bahraich formations. The central Gandak depression, in particular, exhibits tectonic and depositional settings favourable for the accumulation of hydrocarbons within the Neoproterozoic upper Vindhyan-equivalent sequences.

The following sections provide a detailed interpretation of the two seismic profiles, with emphasis on identifying depositional sequences, recognizing unconformity surfaces, and reconstructing paleo-depositional environments.

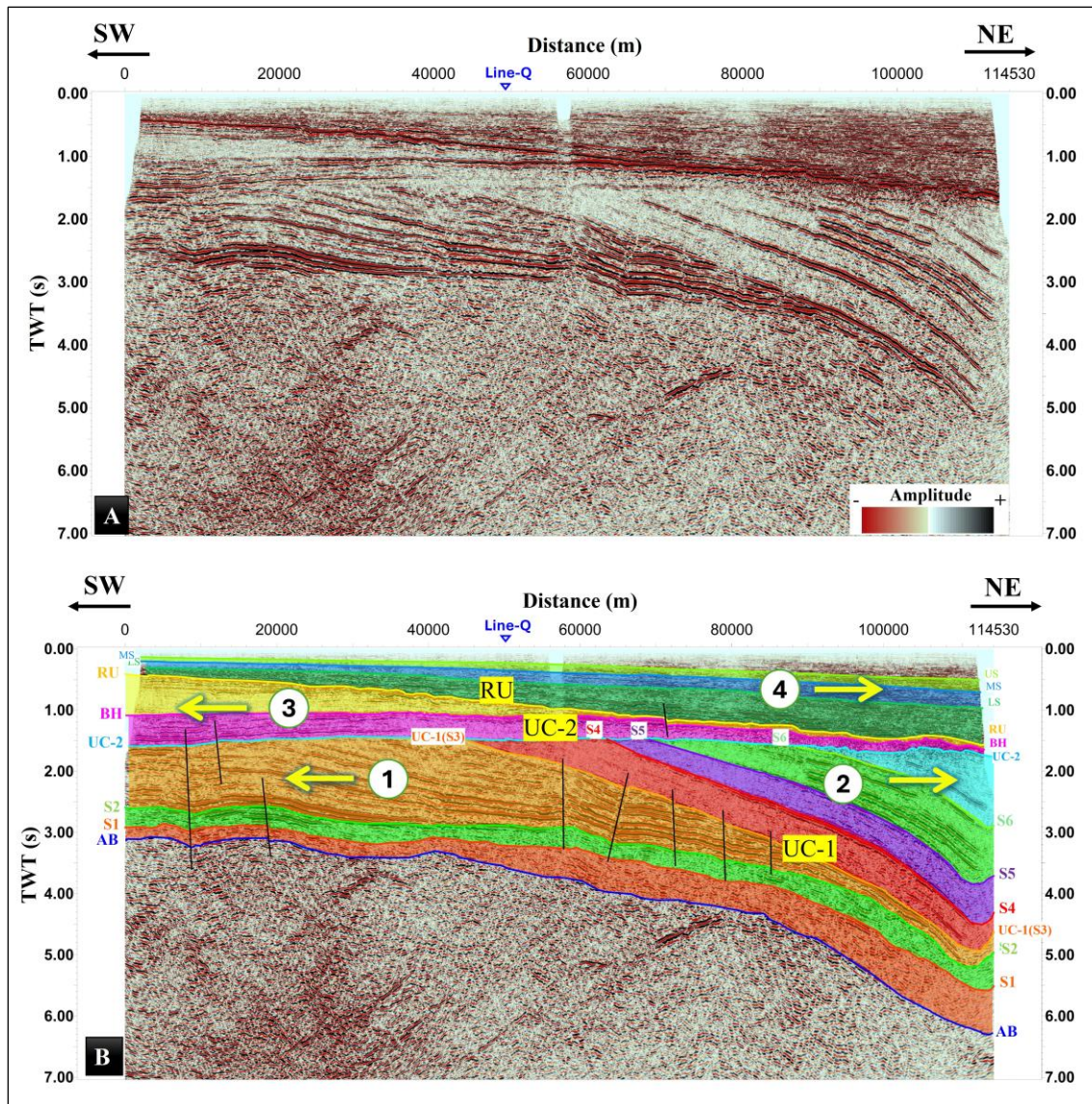


Figure 8.4: Seismic section along Line P. Subfigure A is an uninterpreted section, whereas subfigure B shows interpreted horizons, unconformities and faults with four different stages of deposition pointing (yellow arrows) towards depocenters. Various formations tops and unconformities within the Ganga basin are abbreviated as US (Upper Siwalik), MS (Middle Siwalik), LS (Lower Siwalik), RU (Regional unconformity), BH (Bahraich), UC-1 (Unconformity surface 1), UC-2 (Unconformity surface 2), S1-S6 (Sequence 1-Sequence 6) and AB (Archean Basement). The Line-Q intersects this section at point Q marked on the surface.

Seismic Line-P

Seismic Line-P extends approximately 114 km in a NE–SW direction (Figure 8.4). The seismic section delineates a distinct, high-amplitude reflector beneath the Lower Siwalik, marking the Regional Unconformity. This reflector dips gently north-eastward and is mapped at depths corresponding to 0.5-1.5 s two-way travel time (TWT). The RU surface

is continuous across much of the Ganga Basin, highlighting its significance as a major tectono-stratigraphic boundary. Two additional unconformity surfaces, labelled UC-1 and UC-2 (with UC-1 being the older), have also been mapped. Together, these three surfaces UC-1, UC-2, and RU constitute the primary sequence boundaries in the section. While earlier studies have generally attributed the earliest sedimentation in the basin to Mesoproterozoic rifting associated with the deposition of the Bahraich Group, our analysis identifies six major sedimentary sequences (S1-S6) lying below UC-2. These sequences, therefore, predate the Bahraich Group and may extend back into the Paleoproterozoic.

The sequences below UC-2 are characterised by complex deformation patterns, including folding, faulting, and fracturing, suggesting early basin tectonism. These deformed sedimentary packages have the potential to form structural and stratigraphic traps for hydrocarbons (Figure 8.4). The Archean basement complex is encountered between 3 s and 6 s TWT.

To examine sediment provenance and depositional evolution, seismic Line-P was flattened sequentially along the identified unconformity surfaces. Flattening allows reconstruction of paleo-surfaces and provides valuable insights about changes in sediment supply, shoreline migration, and basin physiography.

Stage 1: Deposition Prior to UC-1

Flattening on UC-1 (Figure 8.5C) reveals that sedimentary units belonging to sequences S1-S3 progressively thicken towards the southwest. This geometry implies that sediment was sourced from the northeast and transported towards a southwestward-located depocenter. The stacking pattern suggests rapid transgression, consistent with a rising sea level that inundated the shelf and platform regions. Retrogradational sequences

dominate, indicating shoreline retreat and landward migration of marine facies during the Paleoproterozoic.

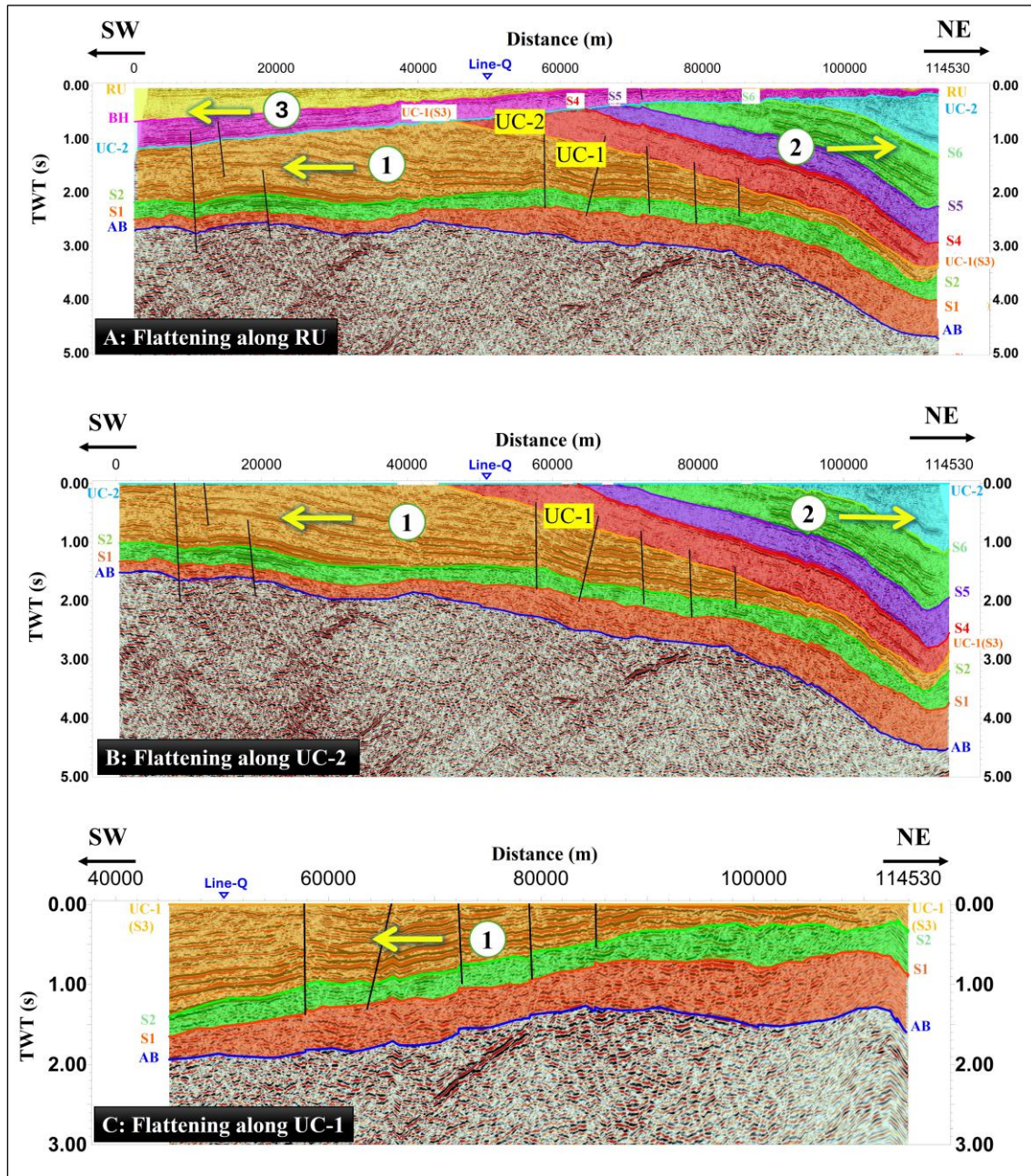


Figure 8.5: Seismic Line-P has been flattened over various unconformity surfaces to enhance stratigraphic and structural features. Subfigure A shows the seismic section flattened along the Regional Unconformity (RU), whereas subfigures B and C show the section flattened along UC-2 and UC-1, respectively.

Stage 2: Deposition Between UC-1 and UC-2

Using UC-2 as the flattening horizon (Figure 8.5B), Stage 2 captures the deposition of sequences S4-S6. The seismic character across UC-2 indicates an erosional transgressive surface. Notably, strong seismic reflectors show a distinct change in dip direction, signifying withdrawal of the shoreline and forced regression. The depocenter during this stage migrated towards the northeast. High sedimentation rates relative to available accommodation space produced progradational parasequences, truncated by the sequence boundary UC-2. The lower boundary of this forced regression corresponds to UC-1.

Stage 3: Deposition Between UC-2 and RU

Flattening along the Regional Unconformity (Figure 8.5A) represents the deposition of the Vindhyan-equivalent formations Bahraich, Ujhani, and Tilhar during the Neoproterozoic to Paleozoic. This unconformity surface is marked by the top of the Karnapur formation having a strong reflector. Sediment thickness again increases towards the southwest, similar to Stage 1. This suggests a re-establishment of southwestward-directed sedimentation, likely reflecting broader changes in basin geometry or tectonic subsidence patterns.

Stage 4: Tertiary Sedimentation Above RU

Overlying these older sequences, the Tertiary Siwalik formations were deposited above the RU surface (Figure 8.5B). These fluvial successions include the lower, middle, and upper Siwalik, all showing pronounced thickening towards the Himalayan foothills. This pattern reflects active Himalayan uplift and southward propagation of sediment-laden river systems depositing in the foreland basin. The basin also received sediments from Vindhyan/Satpura range in the South.

Seismic Line-Q

Seismic Line-Q, 123.44 km long, trends NW–SE and intersects Line-P near its midpoint (Figure 8.6). This seismic section also displays a strong reflector corresponding to the RU, dipping northwestward and mapped at 0.66-1.11 s TWT.

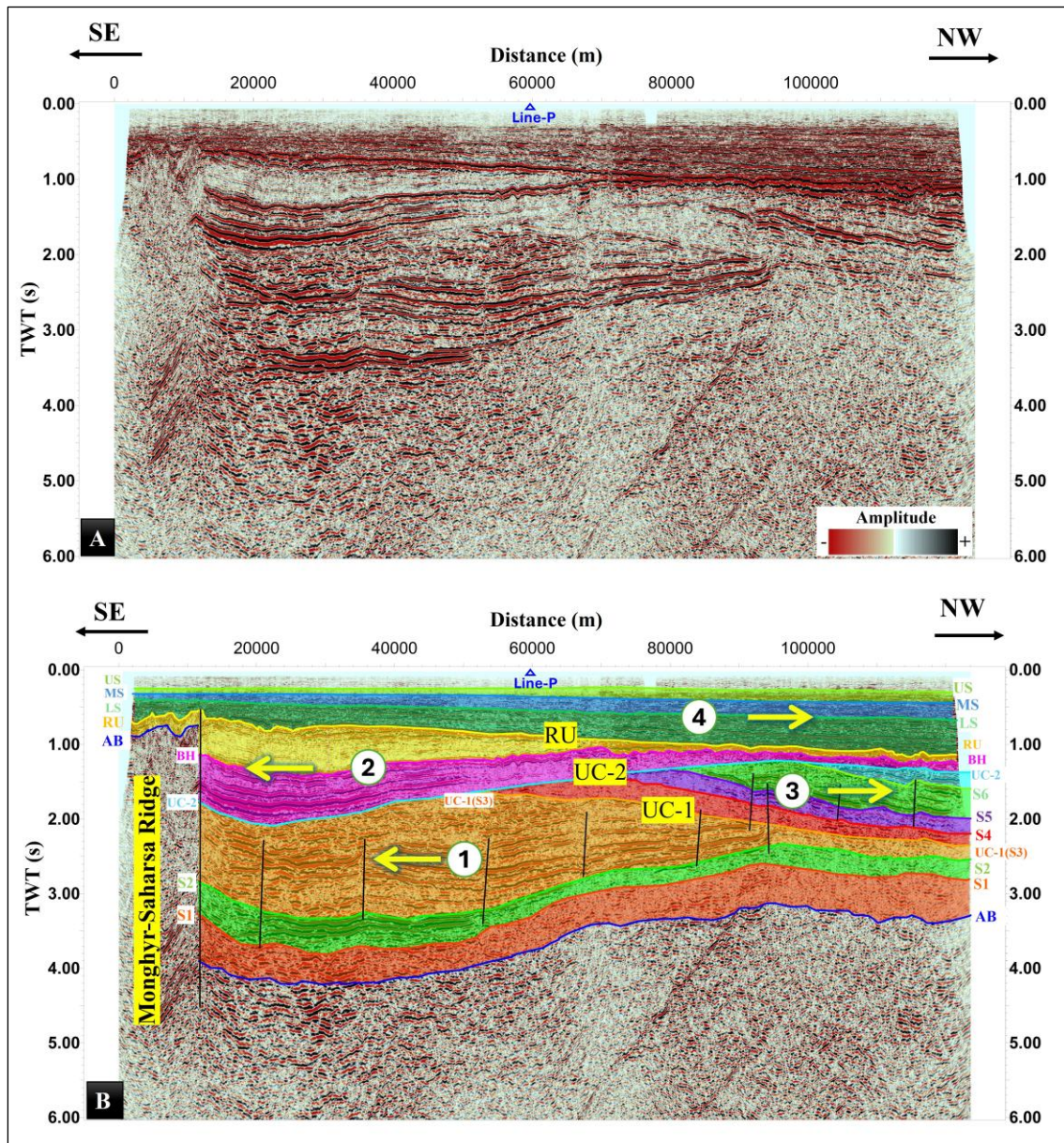


Figure 8.6: Seismic section along Line-Q. Subfigure A is an uninterpreted section, whereas subfigure B shows interpreted horizons, unconformities, faults and ridge along with four different stages of deposition pointing towards depocenters. The Line-P intersects this section at point P marked on the surface.

The unconformity surfaces UC-1 and UC-2 identified in Line-P are also observed here, demonstrating the regional continuity of these sequence boundaries. The six pre-UC-2 sedimentary sequences (S1-S6) are likewise present.

The seismic character of Line-Q reveals a compressional structural style dominated by high-angle reverse faults, which suggests a phase of tectonic shortening predating Tertiary deformation. Additionally, the Monghyr–Saharsa Ridge is imaged as a basement intrusion in the southeastern part of the section. The Archean basement top is mapped between 3.2 s and 3.9 s TWT.

As with Line-P, paleo-flattening was used to reconstruct depositional stages.

Stage 1: Deposition Prior to UC-1

Flattening along UC-1 (Figure 8.7C) indicates deposition of sequences S1–S3 in a paleodepocenter located to the southeast. These sequences, inferred to be Paleoproterozoic, reflect early basin development under relatively stable tectonic conditions.

Stage 2: Deposition Between UC-1 and UC-2

Flattening on UC-2 (Figure 8.7B) shows that sequences S4–S6 accumulated in a depocenter that had migrated northwestward. This phase represents progressive basin deepening and culminates in the development of UC-1 as a basal sequence boundary. A marked shift in sediment dip direction reinforces the interpretation of a shoreline regression or tectonic tilting.

Stage 3: Deposition Between UC-2 and RU

Flattening on the RU surface (Figure 8.7A) reveals deposition of the Bahraich, Ujhani, and Tilhar formations collectively equivalent to the Vindhyan system. These sequences thicken southeastward, indicating a return to depositional conditions similar to Stage 1.

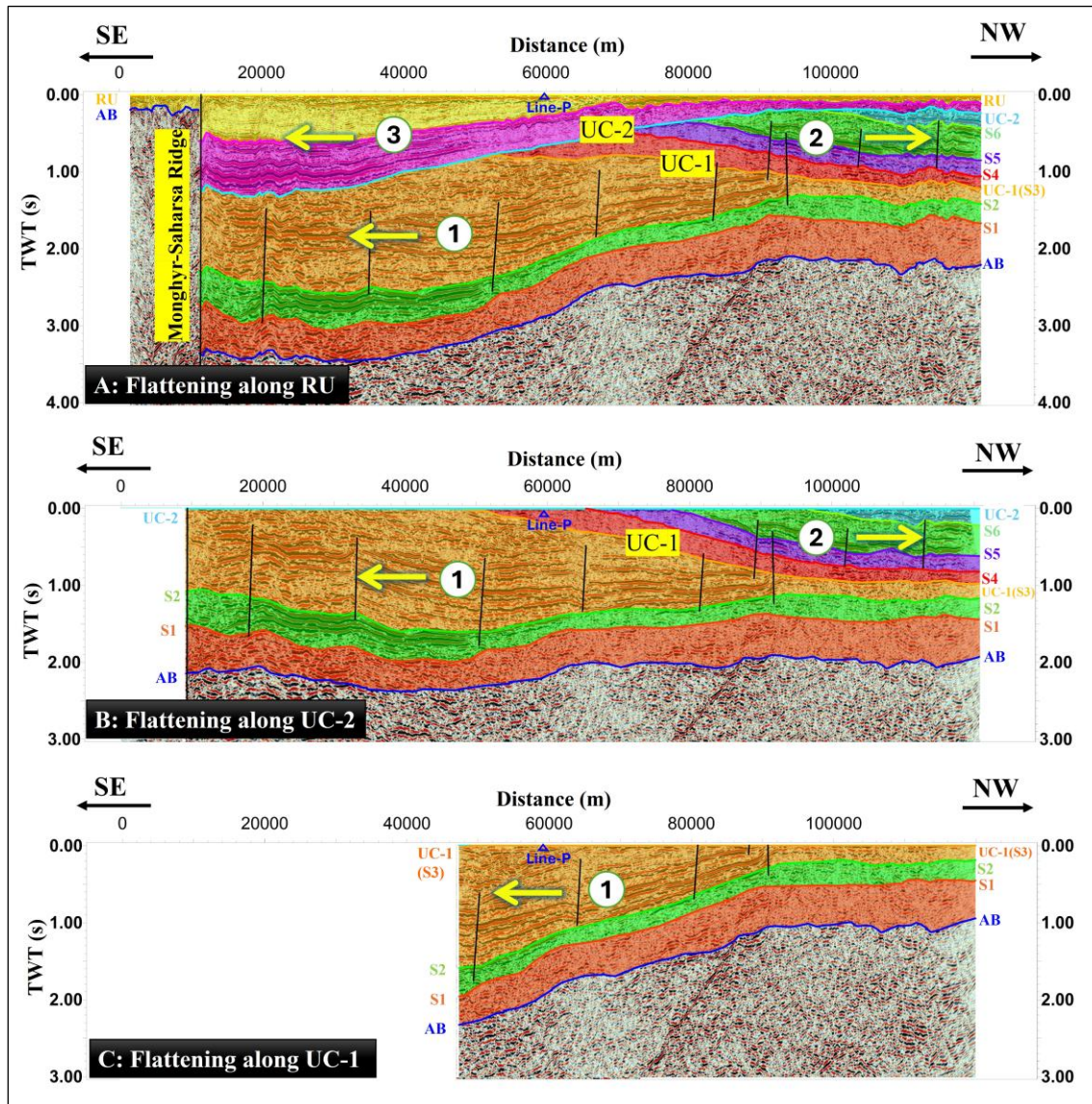


Figure 8.7: Seismic Line-Q has been flattened over various unconformity surfaces to enhance stratigraphic and structural features. Subfigure A shows the seismic section flattened along the Regional Unconformity (RU), whereas subfigures B and C show the section flattened along UC-2 and UC-1, respectively.

Stage 4: Tertiary Sedimentation Above RU

Following a prolonged depositional hiatus represented by the RU, which is the third and widespread unconformity in the Ganga basin, Siwalik sedimentation commenced during

the Tertiary (Figure 8.7B). On Line-Q, the Siwalik facies reflect prograding fluvial systems that deepened towards the northwest, corresponding to sediment influx from the rising Himalaya.

8.9.3 Gravity Data Analysis

A detailed gravity analysis was carried out along seismic Line-P to complement the seismic interpretation and to enhance understanding of density variations within the subsurface stratigraphic units (Figure 8.8). A residual gravity profile was generated from Bouguer gravity anomaly data and compared with a forward-modelled gravity response to identify density contrasts associated with different geological formations and depositional stages of the basin. Residual gravity anomalies were extracted using a high-pass filtering technique applied to satellite-derived gravity data, thereby isolating the contributions from relatively shallow subsurface features. These filtered anomalies were subsequently inverted to estimate the density distribution of major stratigraphic units. For modelling purposes, the gravity sources were classified into four geological categories: Cenozoic deposits, Neoproterozoic–Paleozoic formations, Mesoproterozoic–Paleoproterozoic sequences, and the Archean basement complex.

The residual gravity profile along Line-P displays a consistent increase in anomaly values from southwest to northeast, ranging from approximately -1.8 mGal to 22 mGal. Although this trend superficially corresponds with the northward thickening of Cenozoic Siwalik and alluvial deposits, these lithologies are characterized by relatively low densities and therefore cannot account for the observed positive anomaly. Instead, the rising gravity signature is more plausibly attributed to deeper, denser lithologies situated beneath the Regional Unconformity.

Correlation of the gravity pattern with subsurface stratigraphy suggests that the anomaly increase is associated with the thickening of Mesoproterozoic marine sequences S4, S5, and S6. These sequences are interpreted as equivalents of the Bijawar Formation, which is known to contain dense phosphorite-bearing horizons, thereby explaining the elevated gravity response. Additionally, the older sequences S1, S2, and S3, located below these units, may represent an extension of the Paleoproterozoic Gwalior Group, which hosts high-density lithologies such as Banded Iron Formations (BIF). The modelled depth to the Archean basement along the profile varies significantly, ranging between 6 km and 13 km, reflecting substantial structural relief and the long-term tectonic evolution of the Ganga Basin.

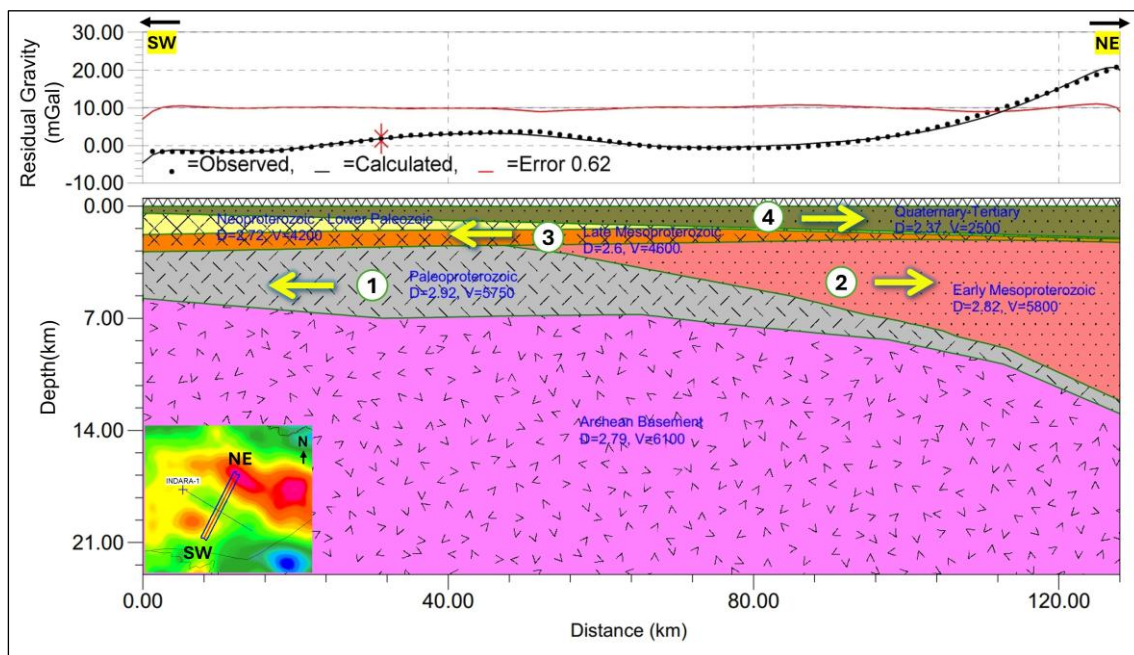


Figure 8.8: Residual gravity profile along the seismic Line-P. Numbers with arrows (yellow) represent depositional sequences identified in four different stages pointing towards depocenters in the Ganga basin. Note that the modelled gravity profile follows nicely along with the observed residual gravity profile. Velocity (in m/s) and density (in gm/cc) values have been given in the figure for each unit.

8.10 Discussion

The present study applies the paleo-flattening technique to reconstruct the geological evolution of the Ganga Basin, delineating four major depositional stages that span from the Paleoproterozoic to the Cenozoic. Each stage reflects distinct sedimentary environments, tectonic regimes, and depositional directions, and is separated by marked erosional hiatuses that represent significant gaps in the geological record. While earlier studies have broadly classified the stratigraphy of the basin up to the Bahraich Formation (Table 8.2), the integration of newly acquired NSP seismic data in the current investigation has facilitated the identification of previously unrecognized subsurface sequences (S1–S6). These sequences, lying beneath the Bahraich Group, are interpreted to belong to Paleoproterozoic to Mesoproterozoic time and represent the earliest sedimentation on the Archean basement (Figure 8.9).

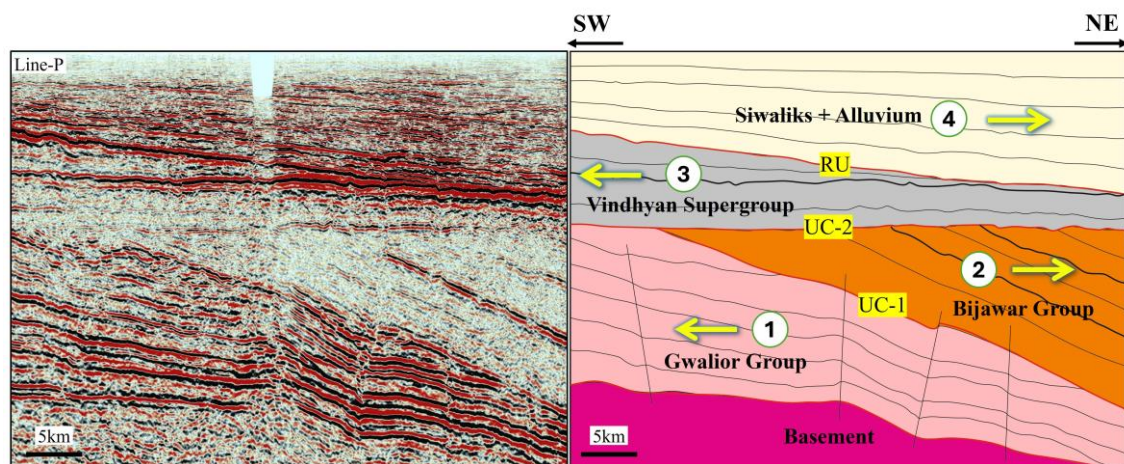


Figure 8.9: Interpretation of Line-P (left section) has been sketched in the right section showing the depositional sequences at four different stages and directions of the depocenters. Stage-1 and stage-2 are correlated with Gwalior Group and Bijawar Group, respectively.

Along the southern margin of the basin, the exposed Gwalior Formation of the northern Indian shield constitutes one of the oldest sedimentary units and provides an analogue for understanding the deep subsurface framework. The formation comprises quartzite, phyllite, shale, volcanoclastic units, and locally developed Banded Iron Formations (BIF),

indicating a combination of sedimentary and volcanic processes during its evolution. Geochronological studies have constrained its deposition between 1914 ± 120 Ma and 1801 ± 21 Ma. Given its regional extent and stratigraphic position, it is plausible that the Gwalior Formation continues beneath the Ganga Basin. In this context, the deeper seismic sequences S1–S3 can be correlated with the Gwalior lithologies. The prominent seismic reflections associated with these units may be attributed to strong acoustic impedance contrasts caused by alternating high-density layers, such as BIF, interbedded with finer clastic sediments.

Following a major depositional break represented by the unconformity surface UC-1, the basin experienced renewed sedimentation during the Mesoproterozoic. Sequences S4, S5, and S6, characterized by northeastward dips, are interpreted as correlatives of the Bijawar Group, which is exposed along the southern and southeastern basin margins adjoining the Bundelkhand massif. The upper Moli Formation of the Bijawar sequence has been dated to approximately 1691 ± 180 Ma. Dominated by limestone, dolomite, shale, chert, phosphorite, and quartzite, the Bijawar succession reflects deposition in shallow to marginal marine environments, with periods of significant chemical sedimentation. In the subsurface of the Ganga Basin, these units represent transitional basement-cover sequences underlying the Vindhyan Supergroup and contribute to the density contrasts observed in gravity modelling.

The subsequent Neoproterozoic stratigraphy represented by the Bahraich, Ujhani, Tilhar, and Karnapur formations marks a renewed phase of sedimentation after another prolonged hiatus (UC-2) and is considered broadly equivalent to the Vindhyan succession. These formations were deposited in a passive margin setting and exhibit considerable lithological diversity. While the Ujhani and Karnapur formations are dominated by clastic sediments, the Tilhar Formation is characterized by carbonate-rich

facies, suggesting the development of a stable carbonate platform. The depositional conditions and reservoir-prone facies within this system indicate potential hydrocarbon prospects within the Neoproterozoic section of the Ganga Basin. Regression following the Karnapur deposition produced a widespread erosional surface, expressed as the Regional Unconformity (RU), which is a key stratigraphic marker across the basin.

The final tectono-sedimentary phase corresponds to the Cenozoic evolution of the basin, shaped by the uplift of the Himalaya and the associated decline in sea level. This stage is demarcated by a well-defined sequence boundary at the RU. The basin subsequently accumulated thick molasse deposits derived predominantly from the rising Himalayan orogen, mixed with sediments sourced from the Vindhyan highlands. The resulting stratigraphy includes the Lower, Middle, and Upper Siwalik formations, deposited in fluvial to deltaic settings during the Tertiary, and capped by extensive Quaternary alluvium.

Collectively, the findings demonstrate that the Ganga Basin preserves a complex and multi-stage geological history, governed by repeated cycles of tectonism, marine transgression–regression, and sediment supply variations. These insights significantly enhance current understanding of basin architecture, stratigraphic evolution, and associated resource potential.

8.11 Conclusions

The present study delineates the long and complex evolutionary history of the Ganga Basin, summarizing four major stages of basin development, each marked by distinct depositional regimes, sedimentary environments, tectonic influences, and fluctuations in sea level. The Proterozoic record, in particular, reflects repeated cycles of marine transgression and regression that governed the deposition of sequences S1 through S6. During the Paleoproterozoic, the earliest sedimentation (S1, S2, and S3) took place

directly above the Archean basement, followed by the accumulation of sequences S4, S5, and S6 in the Mesoproterozoic. These deep-seated stratigraphic units collectively attest to the dynamic nature of the early basin. The seismic and gravity attributes of these sequences suggest strong correlations with the Gwalior and Bijawar formations of the northern Indian shield, as manifested by the pronounced gravity anomalies observed beneath the cover sequences of the Ganga Basin. Their subsurface continuation is particularly evident toward the southwestern basin margin, proximal to the Monghyr–Saharsa Ridge and the Faizabad Ridge. These Paleoproterozoic units, concealed beneath thick Vindhyan and Tertiary successions, represent a structurally significant component of the basin framework and exert considerable influence on its tectonic configuration.

A major shift in basin dynamics occurred during the Neoproterozoic, as rising sea levels facilitated landward transgression and deposition in shallow marine shelf settings. Formations such as Ujhani and Tilhar were deposited during this interval, with the carbonate-rich Tilhar Formation indicating the establishment of a stable platform environment. The presence of limestone and associated facies highlights promising zones that merit further evaluation for hydrocarbon exploration. This phase concluded with a pronounced regression, recorded regionally as the Regional Unconformity (RU), which forms a key stratigraphic boundary across the basin.

The Tertiary evolution of the basin was dominated by the influx of Siwalik sediments, deposited within a high-energy braided fluvial system. This transition corresponds with the uplift of the Himalayan orogen and a concurrent drop in sea level, profoundly altering sediment supply and depositional patterns.

Through the integration of seismic interpretation, gravity data, and well information, this study reconstructs a coherent and refined geological history of the Ganga Basin. The

findings offer valuable insights into its stratigraphic architecture, tectonic evolution, and resource potential, thereby providing a robust foundation for future geological and exploration endeavours.

Chapter 9 : Conclusion and Future Scope

9.1 Major Contributions

This study significantly advances the understanding of the tectono-stratigraphic evolution and hydrocarbon prospectivity of the eastern Ganga Basin through the integrated interpretation of newly acquired National Seismic Programme (NSP) seismic data, gravity modelling, and well-log information. The major original contributions of this research are summarized below:

- Six previously unrecognized Proterozoic stratigraphic sequences (S1-S6) were identified beneath the Regional Unconformity, extending the known stratigraphic framework of the basin.
- Two regionally significant unconformities (UC-1 and UC-2) were mapped and interpreted, providing new insights into the tectonic evolution and depositional history of the basin.
- Integrated seismic and gravity modelling demonstrates that the regional gravity highs are primarily associated with dense Paleoproterozoic sedimentary successions rather than crystalline basement uplifts, thereby revising previous interpretations of the basement configuration.
- Paleo-flattening and sequence stratigraphic restoration enabled reconstruction of the basin evolution from the Paleoproterozoic to the Cenozoic, establishing a tectono-stratigraphic framework linking sedimentation, deformation, and basin development.
- Spectral decomposition using the Time–Frequency Continuous Wavelet Transform (TFCWT) successfully enhanced the imaging of both Tertiary fluvial systems and pre-Tertiary shallow marine depositional environments,

demonstrating its applicability for depositional environment characterization within the Ganga Basin.

9.2 Geological Observations

The integrated interpretation of seismic, gravity, and well-log datasets provides several observations that support these major findings.

- The seismic interpretation identified basement-controlled structural highs, depressions, faults, and regional unconformities that collectively define the structural architecture of the basin. The deepest sediment accumulation occurs within the Gandak Depression, whereas the Faizabad Ridge and Monghyr–Saharsa Ridge act as major structural controls on sediment distribution and basin geometry.
- Correlation of the newly interpreted Proterozoic sequences with the Gwalior and Bijawar successions strengthens regional tectono-stratigraphic relationships across the northern Indian shield. Furthermore, the interpreted structural, stratigraphic, and structural-cum-stratigraphic traps indicate favourable conditions for hydrocarbon accumulation within the pre-Tertiary succession.
- Spectral decomposition further revealed depositional geometries associated with Tertiary palaeochannels and shallow marine depositional systems near the Regional Unconformity (RU), providing additional evidence for changes in depositional environments associated with basin evolution. These two separate depositional environments from pre-Tertiary to Tertiary uncovers the sea level fluctuation from RU to Lower Siwalik, in which riverine sediments thickened towards the north-east from pre-Tertiary to Tertiary period.

9.3 Implications for Hydrocarbon Exploration

The integrated interpretation of seismic reflection data, gravity modelling, well-log analysis, and spectral decomposition significantly improves the understanding of the tectono-stratigraphic framework and petroleum prospectivity of the eastern Ganga Basin. The identification of six previously unrecognized Proterozoic sedimentary sequences (S1-S6) beneath the Regional Unconformity extends the known sedimentary succession of the basin and establishes a new exploration framework for the pre-Tertiary section. These deeper successions represent potential exploration targets that were not recognized in previous geological models.

The revised basement configuration obtained through integrated seismic and gravity interpretation demonstrates that several regional gravity highs are associated with dense Paleoproterozoic sedimentary successions rather than crystalline basement uplifts. This finding has important implications for hydrocarbon exploration because it indicates that thick sedimentary packages may be preserved beneath areas previously interpreted as basement highs. Consequently, these regions may provide favourable conditions for source rock preservation, hydrocarbon generation, and trap development.

The seismic interpretation identified several structural, stratigraphic, and structural-cum-stratigraphic trapping geometries within the pre-Tertiary succession. Basement-controlled structural highs, fault-bounded closures, anticlines, and unconformity-related pinch-out geometries provide multiple potential trapping mechanisms. In particular, the central and southern parts of the Gandak and Madhubani depressions contain thick sedimentary successions and favourable structural configurations, suggesting that these areas are suitable for detailed exploration.

The recognition of the Regional Unconformity (RU), together with the newly identified unconformities UC-1 and UC-2, provides a better understanding of the tectonic evolution

and depositional history of the basin. These unconformities may influence reservoir distribution, hydrocarbon migration pathways, and trap formation by controlling sedimentation patterns, erosion, and structural development. Their regional continuity also provides reliable stratigraphic markers for future seismic interpretation and basin-wide correlation.

The application of spectral decomposition using the Time–Frequency Continuous Wavelet Transform (TFCWT) successfully enhanced the visualization of depositional features within both the Tertiary and pre-Tertiary successions. The delineation of palaeochannels within the Lower Siwalik Formation and shallow marine depositional systems associated with the Karnapur Formation demonstrates the effectiveness of spectral decomposition in identifying subtle depositional geometries that are difficult to recognize using conventional seismic attributes alone. Such information is valuable for predicting reservoir distribution and heterogeneity.

The integrated workflow adopted in this study demonstrates that combining seismic interpretation with gravity modelling, well-log calibration, and spectral decomposition reduces the uncertainties associated with individual datasets and improves confidence in geological interpretations. This multidisciplinary approach provides a more robust framework for evaluating basin architecture, identifying prospective exploration targets, and reducing exploration risk in the underexplored eastern Ganga Basin.

The revised tectono-stratigraphic framework, improved understanding of basement architecture, identification of previously unknown Proterozoic sedimentary successions, and recognition of favourable trapping geometries provide a stronger geological basis for future hydrocarbon exploration. The methodology developed in this study can also be applied to other underexplored Proterozoic sedimentary basins where integrated

geophysical interpretation is required to evaluate deep petroleum systems and exploration potential.

9.4 Future scope recommendations

Geophysical studies

- Acquisition of pre-stack seismic data to perform seismic inversion, Amplitude Versus Offset (AVO) analysis, and rock physics modelling for improved lithology, fluid, and reservoir characterization.
- Acquisition of closely spaced 2D seismic profiles and targeted 3D seismic surveys, particularly across the Gandak and Madhubani depressions, to improve structural imaging and delineation of identified trap geometries.
- The present study uses post-stack seismic data and interval velocities constrained by available well logs. More accurate and laterally varying velocity models would improve depth conversion and reduce uncertainties in the geometry of the deeper Proterozoic sequences and basement.
- Development of density models together with joint gravity - magnetic inversion to better constrain basement architecture and its density variations.

Geological & Geochemical validation

- The currently available exploratory wells in the Ganga Basin provide calibration only for the Tertiary succession and the upper pre-Tertiary formations (Karnapur-Tilhar-Ujhani). Drilling of deep stratigraphic wells targeting the newly identified Proterozoic sequences (S1-S6), together with comprehensive petrographic, petrophysical, geochemical, and biostratigraphic analyses to validate the seismic interpretations.

- Balanced cross-section restoration and basin modelling to quantify deformation history, burial evolution, source rock maturity, hydrocarbon migration, and trap preservation.
- Detailed geochemical investigations, including Total Organic Carbon (TOC), Rock-Eval pyrolysis, vitrinite reflectance, biomarker, and stable isotope analyses of available cores and cuttings, would provide direct information on source rock richness, kerogen type, thermal maturity, hydrocarbon generation potential, and oil-source rock correlation. Integration of these data with the interpreted tectono-stratigraphic framework would improve petroleum system evaluation and reduce uncertainties in hydrocarbon prospectivity.

Regional applications

- Beyond the Ganga Basin, the methodology and workflow adopted here can be extended to conduct comparative studies with other Proterozoic basins in India (e.g., Vindhyan, Chhattisgarh, and Cuddapah basins) and globally. Such comparative basin analysis could contribute to a broader understanding of Proterozoic petroleum systems, depositional patterns, and tectonic controls, thus enhancing exploration strategies in underexplored regions. With advancements in seismic acquisition, processing, and machine learning-based interpretation techniques, future work holds the potential to unlock new hydrocarbon prospects and expand the energy resource base of the Ganga Basin and similar geological settings worldwide.

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List of Publications

Journal Publications

- **Argal, J., & Sinha, S. K.** (2026). Proterozoic depositional sequences in the Ganga Basin, India: the Gwalior, Bijawar and Vindhyan formations. *Marine Geoscience and Energy Resources*, 193, 207831. <https://doi.org/10.1016/j.marger.2026.207831>
- **Argal, J., Sinha, S.K.** (2026). Evaluation of Proterozoic sedimentary sequences observed on the recent seismic data in the Ganga basin using gravity modelling. *Marine Geoscience and Energy Resources*. 185, 207660. <https://doi.org/10.1016/j.marger.2026.207660>
- **Argal, J., & Sinha, S. K.** (2026). Evaluation of Paul Wavelet-based TFCWT in comparison to Ricker and Morlet Wavelets for Seismic Spectral Analysis. *Journal of Earth System Science*, 135(1), 22. <https://doi.org/10.1007/s12040-026-02742-2>
- **Abul Aas, A., Sinha, S. K., Yadav, K. K., & Argal, J.** (2025). Shear wave velocity-based liquefaction geohazard study of alluvial deposit in the south of the foothills of tectonically active Himalayan region. *Journal of Applied Geophysics*, 241, 105818. <https://doi.org/10.1016/j.jappgeo.2025.105818>

Conference Publications

- **Argal, J., & Sinha, S. K.** (2024). Assessment of hydrocarbon prospects in pre-Tertiary sequences within the Ganga Basin, India. 85th EAGE Annual Conference & Exhibition (pp. 1–5). Oslo, Norway. <https://doi.org/10.3997/2214-4609.2024101508>
- **Argal, J., Yadav, K. K., & Sinha, S. K.** (2024). New prospectivity insights of Proterozoic sequences in the Ganga Basin, India. EAGE/AAPG Workshop on New Discoveries in Mature Basins (pp. 1-3). Kuala Lumpur, Malaysia. <https://doi.org/10.3997/2214-4609.202471047>
- **Argal, J., & Sinha, S. K.** (2023). New perspective of stratigraphic sequences in the Gandak Depression, Ganga Valley Basin, India. 14th Biennial International Conference & Exposition (SPG 2023). Lulu Bolgatty International Convention Centre (LBICC), Kochi, Kerala, India. <https://spgindia.org/Kochi2023->

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- Yadav, K. K., Aas A., **Argal, J.**, S.K. Sinha, (2023). Detection of Underground Utilities for Smart City Development Using Non-Destructive Ground Penetrating Radar Technology. Abstract Proceedings of the 2nd EAGE Indian Near Surface Geophysics Conference & Exhibition. <https://doi.org/10.3997/2214-4609.202375030>.

Conference Presentations

- **Argal, J.**, & Sinha, S. K. (2024). Exploration of Subsurface Structures: Gravity and Seismic Data Analysis in the Ganga Basin, India. 15th SPG International Conference & Exposition (Oct 2025)
- **Argal, J.**, & Sinha, S. K. (2024). Decoding regional unconformity in pre-Tertiary to Tertiary sediments in Ganga Basin, India. Oral presentation at the International Conference on Transforming Upstream: Breakthrough Technologies and Sustainability (ICTU 24), RGIPT, Amethi, Uttar Pradesh, India.
- **Argal, J.**, Yadav, K. K., & Sinha, S. K. (2024). New prospectivity insights of Proterozoic sequences in Ganga Basin, India. Poster presented at the EAGE/AAPG Workshop on New Discoveries in Mature Basins, Kuala Lumpur, Malaysia. (30-31 Jan 2024)
- **Argal, J.**, & Sinha, S. K. (2023). New perspective of stratigraphic sequences in Gandak Depression, Ganga Valley Basin, India. Poster presented at the 14th Biennial International Conference & Exposition (SPG 2023), Lulu Bolgatty International Convention Centre (LBICC), Kochi, Kerala, India (3-5 November 2023).
- **Argal, J.**, Yadav, K. K., & Sinha, S. K. (2023). Machine learning approach for attenuating random noise in land seismic data from Ganga Valley Basin, India. Poster presented at the 7th National Geo-Research Scholars Meet on Geosciences: Emerging Methods (NGRSM 2023), Wadia Institute of Himalayan Geology, Dehradun, India.
- **Argal, J.**, & Sinha, S. K. (2022). Prospectivity analysis of Ganga Valley Basin with NSP data. Poster presented at the 5th South Asian Geosciences Conference and Exhibition (Geo India 2022), JECC, Jaipur, Rajasthan, India

Contributed to Industrial Funded Projects at RGIPT

- **Geoscientific Data Analysis of Ganga-Punjab and Vindhyan Basins**

Directorate General of Hydrocarbons (DGH), Government of India (September 2023)

Developed tectono-stratigraphic framework of the Ganga–Punjab and Vindhyan basins through correlation of 26 exploratory wells and interpretation of more than 40 regional 2D seismic lines and 110 km² of 3D seismic data. Integrated seismic, gravity, petrophysical, and inversion datasets for regional hydrocarbon prospectivity assessment.

- **3D Geomechanical Model Development of Balimara Field**

OIL India Limited (June 2023)

Developed three-dimensional geomechanical model by integrating seismic and petrophysical data to estimate pore pressure and in-situ stress over a 30 km² area, supporting reservoir characterization and well planning.

- **India Hydrocarbon Appraisal Programme (I-HAP)**

Ministry of Petroleum & Natural Gas (MoPNG), Government of India (April 2023)

Mapped all 26 Indian sedimentary basins to assess appraised vs. under-explored areas for future geophysical and petrophysical data acquisition. Supported national-scale basin ranking and exploration strategy development.

Competitive Industry Projects and Achievements

- **BP India Student Challenge 2025-26**

Organized by bp and EAGE

Awarded **Second Place** among 59 teams (277 participants) for conducting an integrated reservoir characterization and redevelopment study of a mature UK Continental Shelf (UKCS) turbidite reservoir.

- **Imperial Barrel Award (IBA) 2023 - Penobscot Basin, Nova Scotia**

Organized by the American Association of Petroleum Geologists (AAPG)

Awarded **Third Place (Asia Pacific Region)** for evaluating the hydrocarbon potential of the Penobscot Basin through integrated interpretation of approximately 80 km² of 3D seismic data and well logs, including time-depth conversion, velocity modelling, seismic attribute analysis, sequence stratigraphy, and prospect evaluation.

