

**PETROGRAPHIC STUDIES AND PETROGENESIS OF
ULTRAMAFIC ROCKS IN AND AROUND KWATHA,
TENGNOPAL DISTRICT, MANIPUR**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY**

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RESOURCES MANAGEMENT**

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**PETROGRAPHIC STUDIES AND PETROGENESIS OF ULTRAMAFIC
ROCKS IN AND AROUND KWATHA, TENGNOUNPAL DISTRICT,
MANIPUR**

BY

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Submitted

**In partial fulfillment of the requirement of the Degree of Doctor of Philosophy
in Geology of Mizoram University, Aizawl**

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CERTIFICATE

This is to certify that the Thesis entitled **“Petrographic Studies and Petrogenesis of Ultramafic Rocks in And Around Kwatha, Tegnoupal District, Manipur”** submitted by Mr. **G. Lamzaman** for the degree of Doctor of Philosophy (Ph.D.) **Department of Geology, at Mizoram University** embodies the record of original investigation carried out by him under my guidance and supervision. He has been duly registered and the Thesis presented is worthy of being considered for the award of the Ph.D. degree. This Thesis or any part thereof has not been submitted for any degree of any other University.

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DECLARATION
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OCTOBER, 2025

I **G. LAMZAMUAN**, hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to do the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/Institute.

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CHAPTER- 1

INTRODUCTION

1.1 Introduction of the Research Works

Ultramafic rocks within ophiolite complexes provide essential insights into Earth's upper mantle composition, tectonic processes, and the evolution of the oceanic lithosphere. It is predominantly composed of olivine and pyroxene minerals with less than 45% silica content, these rocks form the basal units of ophiolite sequences and preserve valuable information about mantle dynamics, metamorphic events, and tectonic evolution. These rocks are formed in igneous and meta-igneous environments and are primarily found in ophiolite complexes, fragments of oceanic crust tectonically emplaced onto continental masses. Their study, especially in diverse tectonic settings, is vital for understanding mantle geodynamics and crust-mantle interactions. For example, the ultramafic rocks in the study area are linked to the spreading regimes of ocean floors, formed by the diapirism of upper mantle materials. Their emplacement in the Indo-Myanmar Ranges provides a unique setting for studying tectonic reversal and subduction processes, particularly the subduction of the Indian plate beneath the Myanmar micro-plate.

This present study aims to provide detailed field observations, petrographic analysis, and geochemical characteristics of these ultramafic rocks, which are critical for understanding the interaction between mantle processes and crustal evolution. Petrographic analysis reveals the mineralogical assemblages, textural relationships, and metamorphic histories, offering evidence of the pressure-temperature conditions during their formation and subsequent modifications. Key minerals such as olivine, orthopyroxene, and clinopyroxene, along with their alteration products like serpentine, talc, and amphiboles, provide insights into both primary mantle processes and secondary alterations. The geochemical analysis complements petrographic observations by providing quantitative data on major, trace, and rare earth elements. It helps to determine the degree of partial melting, identification of mantle source characteristics, assess metasomatic alterations, and understand the tectonic setting of

formation and emplacement. Modern scientific advances in analytical tools and techniques, including XRD, XRF, and IC-PMS, have improved the precision of geochemical data, allowing for better constraints on petrogenetic processes and mantle evolution models.

The novelty of this study lies in its investigation of the mineral assemblages, tectonic settings, and petrogenesis features unique to the study area. The peridotitic rocks here were formed and emplaced in specific tectonic contexts. It offers new insight into the region's tectonic evolution, especially into the complex subduction. By integrating petrographic and geochemical data, this research will address fundamental questions regarding the preservation of primary mantle signatures versus secondary modifications, fluid-rock interactions, and the connection between textural development and chemical alterations. Additionally, the study contributes to our understanding of mantle melting, differentiation processes, and the effects of metamorphism and metasomatism on primary signatures, shedding light on the broader implications for global tectonics and crustal evolution. Through this approach, this research aims to advance our knowledge of mantle processes and the wider dynamics of Earth's development, focusing on the intricate relationships between mineralogy, texture, and geochemistry in ultramafic rocks and their role in mantle dynamics.

1.2 General Introduction of Ophiolite

Ophiolites are ultramafic and mafic rock formations representing remnants of oceanic crust and upper mantle, typically found in orogenic belts and closely associated with subduction zones (Dewey and Bird, 1971; Coleman, 1977; Nicolas, 1989; Dilek and Furnes, 2009). The term "ophiolite" derives from Greek "ophios" (snake) and "lithos" (rock), inspired by serpentine-like textures in serpentinites (Juteau, 2003). Initially introduced by Brongniart (1813) for serpentinites in *mélanges*, the concept evolved through Steinmann's "trinity" concept of spatially associated peridotite, gabbro, and diabase-spilite with deep-sea sedimentary rocks in Mediterranean mountain ranges.

The structural composition follows a distinct three-section pattern (Fig.1.1): the lowermost mantle section (harzburgite, lherzolite, dunite with metamorphic fabric and partial serpentinization), the transition zone (cumulate rocks including peridotite, pyroxenites, dunites with chromite pods), and the uppermost crustal section (deep-sea pelagic sediments, volcanic complexes, mafic sheeted dikes, gabbro, and plagiogranite). The Manipur ophiolite complex displays similar lithological architecture, with well-exposed ultramafic sequences dominated by harzburgite and dunite in the mantle section, gabbroic cumulates in the transition zone, and basaltic pillow lavas with associated sedimentary sequences in the crustal section, representing a typical Tethyan ophiolite suite preserved along the eastern margin of the Indian plate.

Modern understanding recognizes ophiolites as typically consisting of tholeiitic pillow basalts, gabbros, sheeted dikes, and associated depleted ultramafic rocks, though not all components may be present (Dilek and Furnes, 2011; Kusky et al., 2013). The classification system by Dilek and Furnes (2011) identifies five distinct tectonic settings, emphasizing mid-ocean ridge and supra-subduction zone (SSZ) types. Ophiolites exhibit global distribution spanning Archean to Cenozoic ages, with significant exposures in India's northern region bordering Tibet and the Indo-Myanmar Range (IMR).

These formations provide crucial insights into mid-ocean ridge and subduction zone processes, mantle dynamics, magma chamber processes, and continental growth mechanisms in accretionary and collisional mountain belts (Dilek and Flower, 2003).

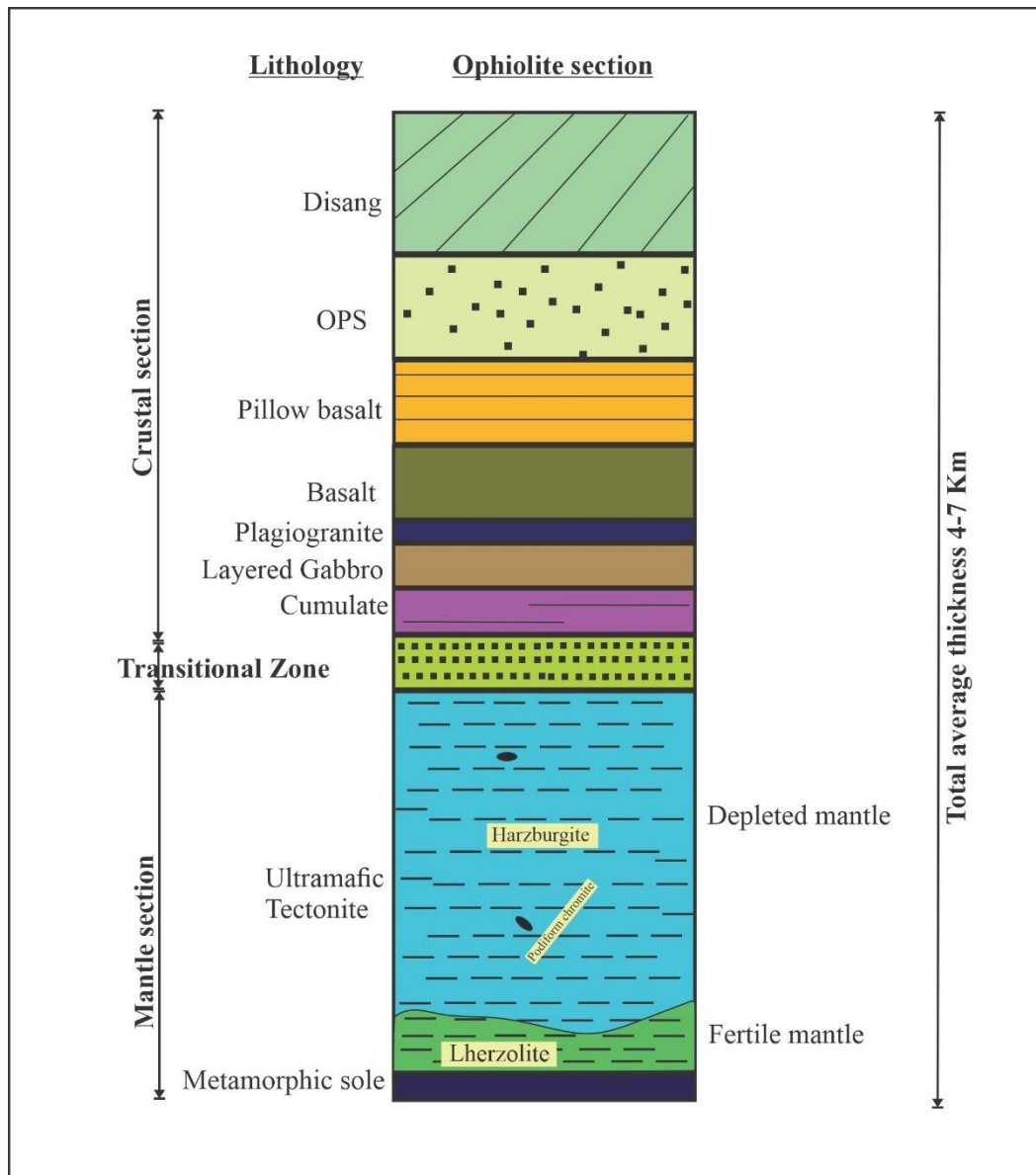


Fig 1.1: Simplified lithological architecture of a typical ophiolite sequence (Modified after Ehlers & Blatt, 1982; Brown & Mussett, 1993), comparable to the Manipur Ophiolite Complex where mantle peridotites are well exposed.

1.2.1 Tethyan ophiolites and their distribution around the India Plate:

The Tethyan ophiolites surrounding the Indian Plate represent remnants of the Tethys Sea's upper mantle and oceanic crust, thrust onto continental margins during the collision of the Indian Plate with the Asian block (north), Myanmar block (east), and

Helmand-Kabul blocks (west) during Mesozoic and early Tertiary periods (Gansser, 1974; Mitchell, 1993; Tapponnier et al., 1981).

These ophiolites are exposed along the western, northern, and eastern margins of the Indian Plate, representing oceanic lithosphere obducted onto the Indian Plate's margin or accreted within the Indus-Yarlung-Tsangpo Suture Zone (ITSZ) during Neo-Tethys closure in Late Cretaceous and Paleocene-Eocene (Thakur, 1981). Geochemical studies suggest origins in fore-arc, arc, and back-arc settings (Khuman and Soibam, 2010; Soibam et al., 2015). The Tethyan ophiolites are divided into three segments: western, northern, and eastern sequences (Fig.1.2).

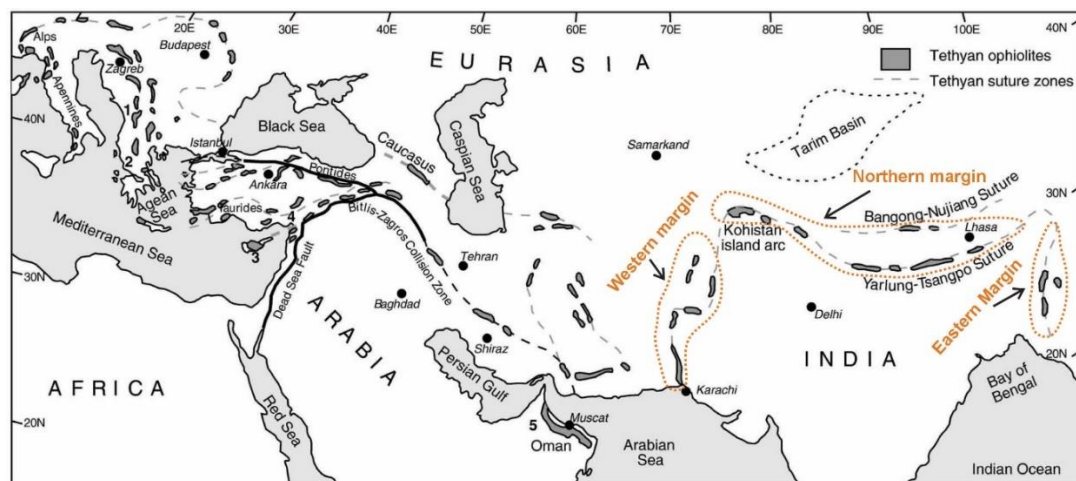


Fig 1.2: Geological map illustrating the key Tethyan ophiolites and suture zones within the Alpine-Himalayan Belt (modified after Dilek & Furnes, 2009).

a) The Western Margin of the Tethyan:

The western belt comprises Bela, Muslim Bagh, Zhob, and Waziristan-Khost ophiolites in Pakistan and Afghanistan (Alleman 1979; Gnos et al. 1997). The Bela Ophiolite, Pakistan's largest, encompasses serpentinitized mantle harzburgite, layered peridotite-gabbro, sheeted dikes, and extrusive rocks. The Waziristan ophiolite (Paleocene-Early Eocene, ~500 km²) consists of dismembered thrust slices over Jurassic-Cretaceous sediments, including ultramafic formations, sheeted dykes, gabbros, and pillow lavas.

b) The northern margin of Tethyan ophiolite:

Ophiolites occur primarily along the Indus-Yarlung-Tsangpo Suture Zone, extending from Central Myanmar Basin to Baluchistan (Valdiya, 1988). Western portions feature klippe-type ophiolites (Kiogar, Yungbwa, Zhongba), while eastern parts comprise Zedang, Jinlu, and Luobusa massifs. Notable complexes include Dargai, Jijal, Sapat (western Nanga Parbat syntaxis) and Dras, Spontang, Nidar-Karzog (eastern syntaxis), dating to Jurassic-Early Cretaceous periods from mid-oceanic ridges and supra-subduction zones (Aitchison et al., 2003).

c) Eastern margin Tethyan Ophiolite

The eastern margin encompasses ophiolite belts along the eastern Himalayan syntaxis, including Tuting metavolcanics connected with Jiaresa-Pangxin and Yigongbai sheets, and the Tidding formation in northeastern Arunachal Pradesh. The Indo-Myanmar Range comprises Paleogene flyschoid sediments with Triassic-Cretaceous rocks, featuring the Naga Hills Ophiolite belt (~200 km) and Andaman-Nicobar Ophiolite belt as disconnected bodies (Acharyya et al., 1991).

1.2.2 Manipur Ophiolite Complex

The Manipur Ophiolite Complex (MOC) is located within the Naga-Manipur ophiolitic belt in the eastern part of the Indo-Myanmar Ranges. This belt is a remnant of Tethyan ophiolites that have been preserved along the eastern edge of the NNE–SSW-oriented Indo-Myanmar Orogenic Belt (IMOB). The MOC formed due to the collision between the Indian plate and the Myanmar plate, marking the eastern suture of the Indian plate (Vidyadharan et al., 1989). Spanning approximately 200 km in length and 2 to 20 km in width, the MOC extends from the Ukhrul district in the north to beyond Haolenphai of Tengnoupal District in the south (Fig.1.3). The complex consists of a chaotic sequence of oceanic lithosphere fragments, including ultramafic peridotite, mafic dykes and sills, pillow lavas, and Oceanic Pelagic sediments such as chert and limestone.

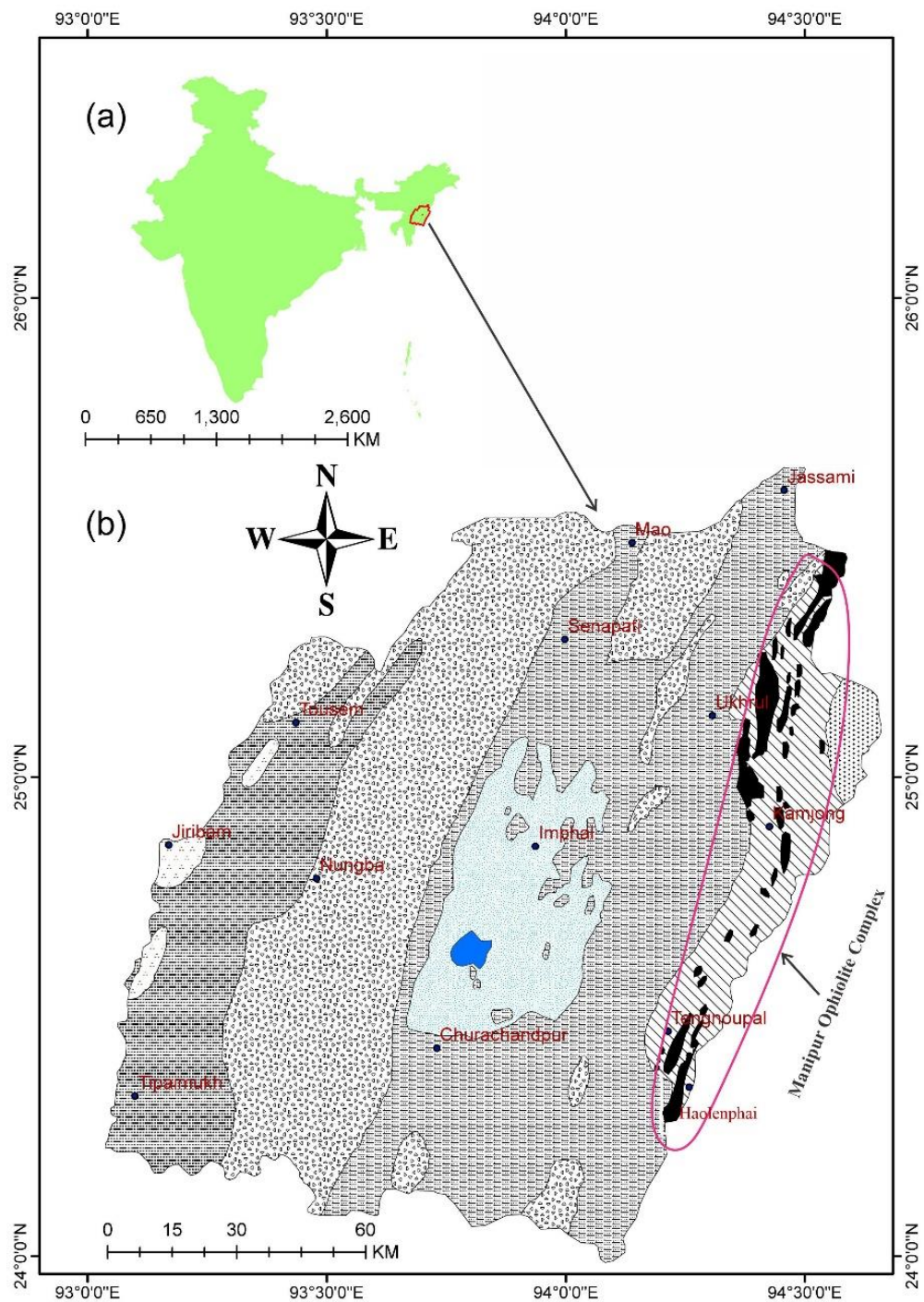


Fig 1.3: Generalized Geological map of Manipur showing the Manipur Ophiolite Complex (MOC) (Modified after Singh,2013).

The mantle tectonites rocks are predominantly harzburgite and lherzolite, containing sporadic chromite. These are sandwiched between pelagic shales, which are dominant and occasionally mixed with flysch-like sediments. The ophiolite belt is bordered by exotic rocks such as diabasic dykes, pillow lavas, conglomerates, and sandstones. These tectonic blocks collectively form the Ophiolite Mélange Zone. The ultramafic rocks primarily consist of serpentinites derived from olivine, with other minerals like bastites, pyroxenes, and spinels. The associated mafic dykes and sills are fine to medium-grained, with phenocrysts of olivine, pyroxenes, and plagioclase, and are typically altered to spilites due to greenschist facies metamorphism. The pillow lavas exhibit variolitic textures and have also been metamorphosed into spilites.

1.3 General Account of Manipur

Nestled in northeastern India, Manipur is a state that captivates with its picturesque landscapes, cultural diversity, and unique geographical location. Often referred to as the "Jewel of India's Northeast," Manipur is a place where tradition and modernity blend seamlessly, offering a unique experience to all who venture here. The State is bordered by Nagaland to the north, Mizoram to the south, Assam to the west, and Myanmar to the east. It covers an area of 22,327 square kilometers and extends approximately between 23°50'N to 25°41'N latitudes and 93°02'E to 94°47' E longitudes (Singh, 2014). The state is divided into 16 districts: Imphal West, Imphal East, Thoubal, Bishnupur, Kakching, Ukhrul, Senapati, Tamenglong, Churachandpur, Chandel, Noney, Pherzawl, Kangpokpi, Tengnoupal, Kamjong and Jiribam. These districts encompass a wide range of communities, cultures, and landscapes, contributing to Manipur's diverse identity. The state's diverse topography includes hills, valleys, and a variety of flora and fauna. The Loktak Lake, located in Manipur, is the largest freshwater lake in northeastern India and is known for its floating phumdis (masses of vegetation).

Geographically, Manipur can be categorized into two main regions: Hills and Mountains and Valleys. The central part of the state, mostly comprised of plains, is encircled by mountain ranges. The average elevation of the hills is approximately 1,300 meters (4,265 feet) above sea level, while the valleys are around 790 meters

(2,592 feet) high. These hills are an integral part of the larger Indo Burma Ranges, bordered by the Naga-Patkai Ranges to the north, and the Mizoram and Chin Hills to the south and southwest.

The Manipur Hills comprise parallel mountain ranges that run in a north-south direction, stretching from the Naga Hills in the adjacent Mizo region to the southern Chin Hills. In the eastern section of Manipur, these ranges attain an average elevation of approximately 1,500 meters, which escalates further to over 1,800 meters in the northeastern portions. Towards the western side of the state, these hills rise dramatically to altitudes exceeding 2,500 meters. Some of the important peaks are Tenipu (2994 meters), Siroy (at 2,835 meters) Khayangbung (at 2,833 meters), Leikot (2,832 meters), Tampaba (2,564 meters), Koubru (2,652 meters), Kachaobung (2,498 meters), alongside Kangchup, Laimatol, Kounuching, and several others (Singh,2014). The primary river systems that traverse the state include the Barak, Manipur, and Chindwin rivers.

1.3.1 Climate

Manipur's climate patterns are influenced by its varied topography, which encompasses valleys, hills, and plateaus. The valleys typically experience milder conditions compared to the hill regions. It features a subtropical climate with distinct seasons.

Winter (December to February): The winter season in Manipur is generally cool and dry. Temperatures can plummet to around 0°C (32°F) in the elevated areas and hill regions, while the valleys and plains experience milder temperatures. Frost is common in the colder zones, and snowfall can be observed in the highest peaks.

Pre-Monsoon (March to May): This season marks the transition from winter to summer. The weather becomes warmer during this phase. March and April are usually pleasant, characterized by comfortable temperatures. However, by May, temperatures start to rise, and the region may witness some hot days, particularly in the valleys.

Monsoon (June to September): Manipur experiences heavy rainfall during the monsoon season. The state receives a substantial portion of its annual precipitation during this period. The southwest monsoon winds carry moisture from the Bay of Bengal, resulting in frequent and occasionally intense rainfall. The hills and valleys become covered in lush greenery. Landslides and flooding can pose challenges in certain areas due to the heavy rains.

Post-Monsoon (October to November): After the monsoon season subsides, the post-monsoon months gradually decrease rainfall. The weather becomes cooler and more pleasant. This period is often considered one of the best times to visit Manipur due to the agreeable weather and the rejuvenated landscape.

1.3.2 Geomorphology:

Manipur is characterized by a predominantly hilly terrain, forming part of the Indo-Myanmar Ranges (IMR), with the Naga-Patkai and Chin-Arakan-Yoma hill ranges bordering its northern and southern sides. The central Imphal Valley, a tectonic depression amidst the hills, is a notable feature. The state's topography can be divided into four distinct units:

- a) *Manipur Western Hills:* Higher hill ranges composed of Barail and Surma sediments, with peaks like Mt. Iso and Koubru-Laimaton-Thangjing Range. They run N-S to NNE-SSW with erosional valleys.
- b) *Manipur Eastern Hills:* Comprising Disang sediments and ophiolitic rocks, with the prominent NNE-SSW running range including Siroy peak. Streams show varied orientations reflecting structural complexity.
- c) *Manipur Central Valley:* A roughly oval-shaped valley surrounded by hills, with an average elevation of 790m. Composed of recent alluviums in the center and foothills, dominated by pebbly alluvial deposits.
- d) *Manipur Western Plains:* Low-lying plains on the western foothills, mainly composed of alluviums with elevations averaging around 100m.

The drainage of Manipur is influenced by the Indo-Myanmar Ranges, with rivers belonging to two major systems:

- a) *Barak Drainage System*: Drains the western side of the state, with rivers following NNE-SSW orientation, showing structural control.
- b) *Chindwin River System*: Includes the Imphal River Sub-System and Yu-Khampat River Sub-System. The former is the main drainage of Manipur central part, while the latter originates from Manipur's eastern hills.

The unique drainage patterns suggest a complex structural and tectonic history. Additionally, Manipur has two more sub-systems belonging to the Chindwin System on its northeastern part: Lanye-Chammu and Sana sub-systems.

1.3.3 Flora and Fauna

Manipur's flora consists of a wide array of plant species, including both endemic and exotic varieties. The state's forests are characterized by a mix of tropical and subtropical vegetation. Common plant species include Shirui lily, orchids, bamboos, pine and conifers, and Medicinal plants.

Manipur's fauna is equally diverse, with a range of mammals, birds, reptiles, and more. The state's forests and wetlands provide habitats for various species like the Brown-antlered Deer (Sangai), which is famous for the Sangai, an endangered subspecies of deer found only in the state. It inhibits the floating biomass (phumdis) of Loktak Lake,

Conservation efforts are crucial to protect Manipur's unique flora and fauna, especially given the challenges posed by habitat loss, poaching, and climate change. The state's biodiversity is not only ecologically significant but also culturally important to the local communities.

1.4 Scope of the work

This study focuses on the ultramafic rocks within the ophiolite complex, aiming to understand their formation, composition, and tectonic significance. The scope includes:

Petrographic Analysis: Examining the mineral composition and textures of ultramafic rocks to identify their formation processes.

Geochemical Analysis: Analyzing the elemental composition of the rocks to determine geochemical signatures and understand their tectonic context.

Tectonic Implications: Integrating petrographic and geochemical data to develop insights into the origin and tectonic evolution of the peridotite rocks within the ophiolite complex.

The study will focus on the ultramafic component of the ophiolite, contributing to the understanding of oceanic lithosphere processes and tectonic interactions.

1.5 Problem of the study area

The study area is part of an ophiolite complex, with a specific focus on ultramafic rocks. These rocks are crucial for understanding processes at mid-ocean ridges and plate tectonics. The formation, alteration, and tectonic significance of ultramafic rocks within this ophiolite complex, however, remain poorly understood.

While previous studies in the Manipur Ophiolite Belt have addressed regional tectonics and stratigraphy, the detailed petrographic and geochemical characteristics of ultramafic peridotites in Manipur are still poorly constrained. Key uncertainties include:

- The degree of partial melting and mantle source characteristics.
- The extent of alteration and metasomatism.
- The tectonic setting of formation and emplacement.

The present study aims to address these knowledge gaps by providing a detailed analysis of the peridotitic rocks, thereby contributing to a clearer understanding of ophiolite formation and associated tectonic processes.

1.6 Aims and objectives of the study

The primary aim of this thesis is to provide a comprehensive geological understanding of the study area by combining geological mapping, petrographic analysis, and geochemical techniques to investigate the petrogenesis of ultramafic rocks. While previous studies in the region, particularly in the Kwatha area of MOC, have focused

on various aspects of regional geology. However, ultramafic rocks critical for understanding regional tectonics and petrogenesis, received limited attention and are greatly neglected. This study aims to address this gap by conducting an in-depth study of these rocks using field observation, petrographic, and geochemical methods. Monodominant ultramafic rocks of the ophiolite suite characterize the ophiolitic complex of the study area. The ultramafic rocks occur as klippe in between sedimentary Disang Formation and Oceanic Pelagic Sediments. The main aims of the present study are to contribute new knowledge to the literature and enhance our understanding of the role of ultramafic rocks in regional tectonic evolution.

The following objectives have been adopted to achieve the above aims:

- i) To undertake detailed Geological mapping of the study area.
- ii) To undertake detailed Petrographic studies of the different rock type of ophiolites.
- iii) Studies of Bulk rock Geochemistry of major oxides, trace, and REE.
- iv) To understand the genesis and tectonic setting of the area based on chemical composition.

1.7 Study area and accessibility

The study area is situated within the Tengenoupal district in the southeastern part of Manipur, India. It extends from Kwatha to Haolenphai and is encompassed by the survey of India topographic sheets numbered 83 L/2, 83 L/3, 83 L/7, and 83 L/8. The area's geographical coordinates range from 94°14' E to 94°18' E longitudes and 24°18' N to 24°15' N latitudes. Due to its proximity to the India-Myanmar border and various challenges like difficult accessibility, elevated terrain, climatic risks, as well as restrictions on photography and the use of topographical maps in the field, the fieldwork primarily consisted of geological mapping and selective sampling along permissible routes, trails, and road sections. National Highway NH-102 connects the area to the rest of the region, and other metalled and unmetalled roads connect the several towns and villages. Imphal International Airport is the nearest airport, while Dimapur is the closest train station.

1.8 Methodology:

The objectives will be achieved through systematic field and laboratory studies, as outlined below:

1.8.1 Literature Survey: A comprehensive review of relevant literature will be conducted using books, published journal articles, and other scholarly sources to gather information on the geology and rock characteristics of the study area.

1.8.2 Field Work:

- Geological mapping at a scale of 1:50,000 will be carried out to identify major lithologic units and collect structural data across the ophiolite mélange zone.
- Various rock samples will be collected for mineralogical, textural, and geochemical analysis.

1.8.3 Laboratory Studies:

- Thin sections of collected rock samples will be prepared for petrographic and mineralogical analysis.
- Powdered samples will be prepared for geochemical analysis using techniques like XRD, XRF, and ICP-MS.

1.9 Literature Review:

1.9.1 Previous studies on Manipur Ophiolite Complex

The Naga-Manipur Ophiolitic Belt (NMOB) in Northeast India has been extensively studied by various researchers, including Theobald (1873), Mallet (1876), Oldham (1883), Pascoe (1912), Evans (1932), Chibber (1934), and Clegg (1938), who conducted field investigations. Oldham (1883) made the pioneering report on the occurrence of cretaceous flysch, comprising limestone and serpentine near Ukhrul in the northeastern part of Manipur. He correlated the limestone-bearing bed around Ukhrul with the Arai formation of Arakan Yoma, considered the tectonic equivalent of the Manipur ranges situated south of the Indo-Myanmar Range (IMR).

Pascoe (1912) documented rocks in the eastern and western parts of the Imphal Valley, grouping sedimentary formations, including shales, sandstones, and occasionally serpentinite enclaves, in the eastern part of Manipur into Disang.

Evans (1932) delineated the geological succession from Upper Assam to the Naga Hills, establishing correlations between the stratigraphic sequences of Manipur and those of Upper Assam, Nagaland, and Arunachal Pradesh.

Mathur and Evans (1964) provided a geological overview of the tectonics in northeastern India, outlining the presence of a 'Belt of Schuppen' characterized by more than eight overthrusts spanning the entire northeastern border of Nagaland, adjacent to the Assam plains.

Brunschweiler (1966, 1974) conducted an extensive mapping of the Indo-Myanmar Range (IMR), detailing its composition of flysch sediments, including exotic facies. He also observed that the highest peaks in the Naga Hills consist of Klippen formed by metamorphic rocks overlying the flysch.

Roy (1980) characterized the ophiolite as rootless, offering evidence that the oceanic crust was formed mainly by a rapid spreading process, with occasional volcanic centers positioned off the ridge after the Indian plate was subducted beneath the Myanmar plate. He also noted that this ophiolite consists of fragmented mafic and ultramafic rocks that are closely linked to oceanic crust.

Chattapadhyay et al. (1983) examined the ophiolites in the vicinity of Chingai in Ukhrul district, Manipur, focusing on the structure and stratigraphy. Their findings suggested that the ultramafic allochthonous bodies were introduced into the area during the diminishing phase of the initial deformation event.

Ghose & Agrawal. (1989) The litho-assemblages of the ophiolite exhibit significant tectonization and dismemberment, indicating three distinct deformation phases that

can be broadly associated with both the Himalayan orogeny and the geological history of the Indian Ocean seafloor.

Acharyya et al. (1990) suggested that the root zone of Naga-Andaman ophiolite nappes, representing the suture, is located to the east, as indicated by the geometry and geological setting of the ophiolites.

Sengupta et al. (1990) reported that the ophiolite belt passing through Nagaland, Manipur, western Burma, and Andaman is flanked to the east by a negative gravity anomaly zone, and the ophiolites occur as rootless, sub-horizontal bodies tectonically overlying Eocene-Oligocene flysch sediments.

Bhattacharjee (1991) proposed that the Indo-Burman Orogenic Belt resulted from the collision of the Indian plate with an island arc, followed by its subsequent collision with the Burma plate. He suggested that the mafic and ultramafic rocks in the NMORB, representing the oceanic crust and upper mantle, were thrust onto the continental margin and classified as Alpine-type ophiolites. The presence of eclogite and blueschist within these rocks indicates a collisional setting, linked to the eastward subduction of the Indian plate beneath the Burmese microplate (Ghose and Singh, 1980; Ghose et al., 2010).

Khuman (2009) and Khuman and Soibam (2010) concluded that partial melting (3–20%) at a depth range of 25–40 km resulted in the derivation of residual lherzolitic and harzburgitic ultramafics in Chandel district, Manipur. He also reported that basaltic melts intruded into the residual ultramafic as dykes.

Singh (2009,2013) proposed that the peridotites found in MOC represent the leftover residue following a low-degree partial melting process of spinel peridotite mantle within a mid-oceanic ridge (MOR) tectonic environment.

Singh et al. (2010) found that ultramafic rocks from the MOC are rich in MgO, Ni, Cr, and Co, with abyssal or alpine peridotite affinities, supporting a mantle-derived origin under specific geodynamic conditions.

Devi and Singh (2011) investigated the peridotites from the Manipur Ophiolite Complex (MOC) show high Mg# values (0.92–0.89) and resemble Sulawesi's Alpine-type peridotites. The PGE mineralization, with higher palladium (Pd) than iridium (Ir), is linked to the fractional crystallization of alkali-poor, high-magnesium picritic magma.

Ghose and Fareeduddin (2010b) described the NHO sequence containing peridotites, serpentinites, basalts, and sediments. Petrographic features indicate rapid cooling and partial melting processes typical of MOR environments.

Ningthoujam et al. (2012) concluded that MOC serpentinites originated at a spreading regime due to low-degree partial melting (10–15%) of a less depleted, fertile mantle melt.

Ibotombi et al. (2013) suggested that the mineralogical compositions and primary Cr-spinel chemistry of peridotites are similar to abyssal peridotites that formed in a mid-ocean ridge setting after a low degree of partial melting. They concluded that the mantle peridotites of the Manipur Ophiolitic Complex originally developed in a spreading environment.

Based on the phase geochemistry analysis of chromian spinel within the Indo-Myanmar Ophiolite Belt, Maibam et al. (2015) deduced that the origin of the podiform chromitite linked with the mantle sequence of the ophiolite can be attributed to boninitic magma. Additionally, they found that the chromite associated with volcanic rocks bears similarities to Mid-Ocean Ridge Basalt (MORB).

Pal et al. (2014) identified chromitite types in the Manipur Ophiolite Belt, suggesting a supra-subduction zone origin. The geochemical analysis points to 20% partial melting of mantle harzburgite, with mixed boninitic and island arc tholeiitic magmas.

Dilek and Furnes (2014) classified the Nagaland-Manipur Hill ophiolite, as an accretionary-type ophiolite, that does not represent an intact sequence like Penrose-type ophiolites.

Fareeduddin and Dilek (2015) described ophiolitic subunits in the Indo-Myanmar Ranges as blocks or thrust sheets within a *mélange* of serpentinite or greywacke matrix. This *mélange* lies between the older Nimi Flysch and younger Disang Flysch accretionary complexes.

Singh et al. (2017) observed that the tectonite peridotites and cumulate pyroxenites lack plagioclase and contain spinel, indicating their formation beyond the plagioclase stability limit in a mid-oceanic ridge setting. They suggest that the ultramafic sequence in the Nagaland and Manipur Ophiolites (NMO) initially formed near the eastern edge of the Indian passive margin within a mid-oceanic ridge environment. Subsequently, it was thrust westward over the continental margin of the Indian Plate during collision and subduction processes with or beneath the Myanmar Plate.

Ovung et al. (2017) noted that the mantle peridotites of the MOB show compositional variation linked to different tectonic settings, with high-Al spinel peridotites associated with MOR and high-Cr spinel peridotites linked to supra-subduction zones.

Dey et al. (2018) categorized the geochemical characteristics of ultramafic rocks into two distinct groups: enriched and refractory mantle types. The enriched group likely resulted from partial melting of a fertile mantle, while the refractory mantle type is thought to have originated from the partial melting of a more resistant mantle.

Khogenkumar et al. (2020) concluded that the Nagaland and Manipur Ophiolite Belt (NMOB) formed through both subduction and non-subduction processes. Mafic rocks in the non-subduction group resemble mid-ocean ridge basalt (MORB) and ocean island basalt (OIB), with high ratios of incompatible elements ($\text{Nb/Yb} > 1$) and enriched trace elements. In contrast, rocks in the subduction group show lower ratios of incompatible elements ($\text{Nb/Yb} < 1$) and depleted trace elements, indicative of a forearc-depleted N-MORB origin.

Ao et al. (2019) suggested that the serpentinized peridotites present in the Nagaland and Manipur ophiolites probably formed in a mid-ocean ridge setting. These rocks would have later been altered by fluids or melts originating from subducting tectonic plates.

Verencar et al. (2020) identified two phases of melt generation in the mantle restite and crustal assemblage. First, a tholeiitic melt, typical of depleted Fore Arc Basalts (FAB), was derived from the upwelling asthenospheric mantle during SSZ fore-arc extension, leaving a refractory upper mantle. Later, the crust and mantle were re-fertilized by boninitic melts due to subduction initiation and slab dehydration.

Kingson et al. (2023) concluded that the serpentinized peridotites within the MNOB are remnants of the Neo-Tethyan mantle wedge, experiencing varying degrees of mantle metasomatism and partial melting processes.

Lamzamuan et al. (2024) The origins of the mantle peridotite rocks indicate a transitional stage between abyssal peridotites and those associated with subduction zones, developing from harzburgite-peridotite.

Lamzamuan and SK Devi (2025). The ultramafic rocks are likely derived from tholeiitic magma with komatiitic characteristics.

1.10 Data management and Interpretation

1.10.1 Data management

Petrographic Data: Thin sections will be analyzed using an optical microscope to identify minerals and textures.

XRD Data: X-ray diffraction will identify mineral compositions, analyzed using Xpert High Score software.

Geochemical Data: Elemental compositions were analyzed and plotted using ORIGIN software for geochemical diagrams.

1.10.2 Data Interpretation:

Petrographic Interpretation: The optical microscope analysis helps in identifying mineralogy and textures, helping to interpret the formation and alteration processes of the rocks.

XRD Interpretation: XRD data, processed through Xpert High Score, identified mineral phases, aiding in understanding the ophiolite's geological history.

Geochemical Interpretation: Geochemical data, processed and plotted with ORIGIN software and GCDkit, revealed elemental trends and geochemical signatures, providing insights into the tectonic environment and alteration history.

CHAPTER-2

GEOLOGICAL SETTING

2.1 Introduction

The collision between the Indian and the Eurasian plates is a key factor in a model that explains the origin of the Himalaya-Tibetan Mountain range, encompassing the distinctive attributes of north-eastern India and its vicinity (Dewey et al., 1989; Aitchison & Davis, 2001; Zhu et al., 2005). The eastern part of Manipur is characterized by the Indo-Myanmar Ranges (IMR), a mountainous region formed by the collision of the Indian Plate and the Myanmar micro-plate, resulting in the upliftment of the Himalayan ranges. This IMR mountain belt, encompassing the Naga-Patkai, Manipur, Mizo-Chin, and Arakan-Yoma hill ranges, is believed to be the northward continuation of the Indonesian-Andaman Arc. This extension is presumed to establish a link with the Eastern Himalayas through the Tidding Suture Zone (Bender 1983; Acharyya et al. 1986a; Nandy 2001). The IMR region was the geological boundary between the Indian subcontinent and Southeast Asia. Its formation is attributed to the diagonal subduction of the Indian Plate beneath the Myanmar Plate (Soibam 1998, 2000, 2015). Specifically, the northeastern segment of this orogenic system, which underlies regions like the Naga, Manipur, and Mizo-Chin hills, is of particular significance due to its role in the tectonic processes that shaped the present-day landscape of the region. The IMR represents a curved thrust-fold belt that predominantly extends in a north-south direction and is situated between the Bengal-Assam basin on its western side and the Central Burma Basin on the eastern side. To the north, the Bengal Basin connects with the Tertiary shelf of Assam, while its southern extension forms the Bengal Delta. Adjacent to the Manipur-Chin Hills on the western side are the low hill areas formed by a north-south trending fold belt, characterized by Neogene molasse sediments. The mobile belt of the IMR extends further to the south, transitioning into the Andaman-Nicobar Island arc.

The study area in the Tengnoupal district in Manipur is a part of the Naga-Manipur Ophiolite belts within the IMR. This range extends northwards from the Indonesian island arc, which is linked with the eastern end of the Himalayas. The present study focuses on the northern part of the Indo-Myanmar area, alongside Manipur and Nagaland, which marks the eastern limit of the Naga-Manipur Ophiolite belts. The "Belt of Shuppens" characterized by extensive Tertiary sediments, marks the western boundary. A notable feature within this belt is the emplacement of an ophiolite suite within flysch sediments during the Upper Cretaceous-Eocene period.

2.2 Regional Geological Setup:

In the North East India region and its adjacent areas, various belts and regions have been delineated based on factors such as physiography, geology, and tectonic characteristics. Notable contributions from various previous workers like Evans (1964), Nandy (1981), and Archaryya et al. (1986), have led to the identification of the following distinct physiographic and tectonic units.

- i. Shillong - Mikir Massif
- ii. Eastern Himalayas
- iii. Tsangpo Ophiolite Belt and Trans Himalayan Magnetic Arc
- iv. Mishmi Hills
- v. Assam Shelf
- vi. Outer Molasse Basin (Naga foothills and Surma Valley)
- vii. Indo-Burmese Range
- viii. Central Burma Molasse Basin
- ix. Highland of Eastern Burma

Bhattacharjee (1991) introduced a physiographic division of Northeast India into three main segments:

- i. Craton: consisting of the ancient Precambrian rocks of the Shillong Plateau.
- ii. Young Mountain Belts: This division includes the young mountain ranges extending to the north, east, and Southeast.
- iii. Brahmaputra Valley

Evans (1964) outlined the structural divisions of the North-eastern region as follows:

- i. The Eastern Himalayas, characterized by overthrusting.
- ii. The Naga Hills, including the Patkai-Kohima synclinorium, are marked by overthrusting.
- iii. The foreland spur, located between the Eastern Himalaya and Naga Hills, extends from the Shillong Plateau northeastward into upper Assam.
- i. Bengal and the Surma Valley, where beds dip gently in the west and exhibit north-south folds in the east.
- ii. A strip with southerly dipping beds between the Shillong Plateau and the Surma Valley, linked to the significant Dauki fault.

Meanwhile, Acharyya et al. (1986) identified three sequential sections along the Indo-Burmese Range, from north to south:

- i. *The Naga-Patkai Hills.*
- ii. *The Chin Hills.*
- iii. *The Arakan Yoma.*

These identified units and divisions provide a comprehensive framework for understanding the complex physiography and tectonic settings of North East India and its adjacent regions, as contributed by various workers in the field.

The following are brief explanations of the several belts proposed by Acharyya et al., (1986).

i. Shillong Mikir Massif:

Within the Indian shield, the Shillong Mikir Massif serves as the northeastern continuation of the Precambrian rock formations originating from Peninsular India and extending into the northeastern region of India. To the southeast, and potentially to the northeast as well, this basement high is covered and flanked by Cretaceous-Tertiary shelf sediments. A similar sequence of shelf sediments can be observed along the western periphery of the Bengal Basin in southern India. A thicker

Paleogene sediment column is found towards the north, which unconformably overlays Neogene molasse sediments. These sediment layers are thrust and imbricated along the 'belt of schuppen' bordering the Naga foothills

ii. Eastern Himalayas:

The Eastern Himalayas can be divided into four main sub-divisions:

- a. *Sub Himalayas:* Situated to the north of the Brahmaputra River, this region consists of Neogene and Quaternary molasses sediments. It is separated from the Lesser Himalayas by the Main Boundary Thrust (MBT) in the northern part.
- b. *Lesser Himalayas:* Comprising Pre-Tertiary low-grade metamorphosed rocks, the Lesser Himalayas are underlain by the Main Central Thrust (MCT). Beneath the MCT lies the Central Crystallines, and this tectonic contact is referred to as the Traces-Traces-Axis thrust. The Trans Axis unit in this region is characterized by Phanerozoic fossiliferous sediments of Tethyan origin. In the northern sector of the Lesser Himalayas, one can find basic and acid volcanics known as the Abor volcanic, which represents a composite unit containing products from younger volcanic activity.
- c. *Great or Central Himalayas:* Positioned between the Tethys Himalayas to the north and the Lesser Himalayas to the south, the Central or Great Himalayas are situated in the middle. The Main Central Thrust (MCT) marks its southern boundary. It merges with the Tethys Zone in the eastern part of the Subansiri Valley. This region predominantly comprises high-grade gneisses and schists belonging to the Sela Group.
- d. *Tethyan or Trans-Axis Himalayas:* The Tethyan Himalayas are characterized by marine to paralic sediments with Gondwana facies and floral affinity. They are situated to the north of the Great Himalayas, bordering Tibet in a northeast-to-southwest direction. The Tethyan Himalayas are mainly composed of the Lum La Formation, which dates back to the Mesoproterozoic era. Additionally, a few patches of Neoproterozoic to Cenozoic (Eocene) sediments are also present in the area. These Himalayas are bordered by the vast Tibetan Plateau along the Indus-Tsangpo suture.

- e. *Tsangpo Ophiolite Belt and Trans — Himalayan magnetic arc*: In the northern region of Mount Everest and the southern part of Lhasa, geological investigations have revealed the presence of a tectonic zone that consists of a mixture of rock types and a complete sequence of ophiolites. This discovery was reported by various researchers (Tapponier et al., 1981; Shackleton, 1981; Allegre et al., 1984; Acharyya et al., 1986; Anon, 1986;). Within this belt, four distinct tectonostratigraphic spectrums have been identified:
- f. *Arc Trench Sediments*: These sediments include basal clastics that transition into oceanic pelagic sediments at their base. They contain Radiolarian-rich horizons dating from the Upper Albian to Lower Cenomanian period. Notably, conglomerates within this spectrum consist of pebbles and clasts originating from the ophiolite belt on the southern side. Higher up in these conglomerates, clasts of plutonic and volcanic rocks are found, sourced from the Gangdise magnetic arc on the northern side.
- g. *Melange Zone*: This zone comprises pelagic clays, radiolarian cherts, limestones, and tectonized ophiolite members dating from the Cretaceous to the Jurassic period. Below this zone, there exists a sequence of sedimentary melange and flysch sediments containing exotic blocks of various ages, including Triassic, Jurassic, and Cretaceous flysch sediments. These flyschoid or Mesozoic rocks are exposed as Klipper on the southern side of the Tibetan Himalayas.
- h. *Gangdise Magmatic Arc*: The Gangdise magmatic arc is characterized by large batholiths intruded by marine Mesozoic sediments and calc-alkaline volcanic plutonic rocks. It serves as a physical boundary separating the Benioff zone, which dips northward. The age of the plutonic rocks has been determined to be between 95 and 40 million years ago (Anon, 1980; Allegre et al., 1984). Additionally, Yu (1982) reported earlier phases dating to 250 million years ago and 180 million years ago.
- i. *Epicontinental Palaeozoic Sediments*: South and central Tibet, north of the Tsangpo zone, exposes epicontinental Palaeozoic sediments. These sediments include Palaeozoic diamictites, basic-intermediate volcanic rocks, volcanoclastics, and fauna characteristic of the Tethyan-Peri-Gondwana type, which have also been documented in Lhasa and Tibet.

iii. Mishmi Hill:

The Mishmi Hills are located at the convergence point of the Indo-Burmese Range and the eastern Himalayas. This region is characterized by geological features that include:

- a. The Tidding Suture, which trends in a northwest-southeast direction.
- b. Various rock types, including serpentinite, metavolcanics, metasediments, and the extensive Mishmi diorite-granodiorite batholithic complex.
- c. Running alongside the Dophu Bum area, the Mishmi Hills are geologically separated from the Naga Patkai range's Tertiary turbidity sequences by a thrust fault. This thrust fault is characterized by its rock movement. Known as the Mishmi Thrust, it takes the form of a northwest-oriented strike-slip fault. This fault is bordered by the Indo-Burmese Range, which trends in a north-northeast to south-southwest direction. The Mishmi Thrust Overlays Quaternary sediments found in the foothills of the Mishmi Hills and ultimately truncates the Indo-Burmese fold belt, along with other associated thrust faults.

iv. Assam Shelf:

The Assam shelf region encompasses the Shillong-Mikir massifs, as described by Dasgupta (1979). This area is situated between the Eastern Himalayas to the northwest and the Naga Hills to the southeast. To the northwestern edge of the Shillong massif, one can find Talchir's lower Gondwana sediments and the Barakar formation from the Permian era. Moving south in the Shillong region, there is a presence of basic volcanic flows from the Sylhet Trap, which overlay the basement rocks. These volcanic formations extend up to the Garo Hills and continue into the Mikir Hills to the northeast.

The earliest rock group in the Assam shelf, known as the Jaintia Group, dates back to the Palaeocene-Eocene age. This group comprises basal arkose, limestone, and black shale that originated in littoral to sublittoral environments. During the Palaeocene-Eocene period, Eocene carbonate sediments were deposited in the shelf area.

Subsequently, there was a shift from fluvial deposition to shallower marine and lagoonal environments.

The Oligocene sediments are represented by the Barail Group, which consists of sandstone and argillaceous sediments. These rocks were formed in shallow marine, lagoonal, deltaic, and estuarine environments. Following this deposition, there was an uplift in the region. After this uplift, the Surma Group of sediments was deposited. It's worth noting that the thickness of Surma Group deposits decreases as one moves northward on the Assam Shelf, ultimately merging with the overlying Tipam Group. The Tipam Group of sediments unconformably overlays the Barail Group. The Namsang beds, characterized by coarse-grained sandstone, were deposited after the Tipam Group.

v. Outer Molasse Basin:

The outer Molasse basin in the region is most prominently developed in the Naga foothills, Surma valleys, and Tripura. Among these, the Barails are the oldest rock units exposed within the Molasse basin. These are followed by the younger Surma Group, which has a considerable thickness, exceeding 4000 meters. The Surma Group is primarily composed of deltaic sediments, and its age varies across different regions. It ranges from Lower/Middle Miocene in the Naga Hills, Upper Miocene in Silchar and Cachar Hills, and Lower Pliocene in Tripura.

The Tipam Group, which is also part of this basin, exhibits varying ages ranging from the upper Miocene to the Pliocene in different parts of the region. Mathur and Evans (1964) introduced the concept of a tectonic unit referred to as the "Belt of Schuppen" (BOS). Within the outer Molasse Basin of the Naga Hills, this area displays numerous thrust faults aligned parallel to the NE-SW folding. These thrust faults are bounded by the Naga thrust in the west and the Disang thrust in the east. The Belt of Schuppen (BOS) is characterized by the presence of eight or more overthrusts, one overriding the other, displaying an imbricate pattern.

The composition of the Belt of Schuppen (BOS) primarily includes the Disang Formation, arranged in a homoclinal to open-fold sequence. To the east, it is demarcated by the Disang thrust, representing the outermost limit of the Disang Formation. It is believed that during the Pliocene era, there was significant crustal shortening, estimated at approximately 150-300 kilometres, due to over-thrusting against the Indian shield Evans (1964).

vi. Indo-Myanmar range:

In the current study of the Indo-Myanmar Range, it is evident that there are two distinct sedimentary tectonic zones within this belt. The Central Naga Hills Palaeogene basin is on the western or outer side, characterized by flyschoid sediments. In contrast, towards the eastern or inner side, the presence of ophiolite formations in the Naga and Chin Hills.

a. Naga Flyschoid Sediments:

The Naga Flyschoid sediments occupy the western sedimentary zone of this region. This area is characterized by a folded and thrust formation consisting of a substantial accumulation of uniform flyschoid Disang sediments. These are followed by sandy flyschoid and molassic deposits known as the Barail Formation, where the Disang Thrust contacts the outer Molasse Belt. The Disang Group, with a thickness of about 7300 meters, primarily displays typical turbidity structures, indicating a flysch sequence. Mathur and Evans (1964), along with previous studies by Oldham (1883), Pascoe (1912), and Rao (1983), provide valuable insights into these sediments.

Notably, there is a seamless faunal and floral transition between the Upper Disang and the Barail Group of rocks, with arenaceous beds becoming more predominant in the latter. Faunal and floral similarities suggest a near-shore marine, estuarine, or deltaic depositional environment, possibly related to trench sedimentation. In eastern Manipur, one can find lenses and blocks of Upper Cretaceous limestones from the Eocene age within the shales of the Disang Group. These assemblages include exotic blocks and clasts of Cretaceous and Eocene limestones, parts of the ophiolitic complex, and older gneissic components, among others, embedded in the flysch

(Brunnschweiler, 1966). Moving forward, the Oligocene Barail Group of rocks reveals shallow marine fauna and plant fragments, overlain by the Surma Group.

b. Manipur-Naga-Chin Ophiolite Belt:

Extending approximately 200 kilometers in length and ranging from 2 to 20 kilometers in width from Chokla to Moreh on the Indian side, this region extends into the Chin Hills of Burma. It is characterized by dismembered and tectonized ophiolites located along the Indo-Burma border. These ophiolites are thrust over the lower Disang Formation on the western side, while on the eastern side, they are overthrust by Proterozoic Naga Metamorphics and unconformably underlie the Miocene to Pliocene molasses of the central Burma basin.

The ophiolite assemblages within the Indo-Burma belt are dismembered and date back to the late Cretaceous period. They are unconformably overlain by the Eocene Pokhpur formation. In the Chin Hills of Burma, the ophiolite complex overrides the Disang flysch towards the west and is followed stratigraphically to the east by late Cretaceous to Eocene clastic sediments (Brunnschweiler, 1966). The Upper Albian limestone and Maestrichtian conglomerates are unconformably overlain by ophiolites containing minor clastic material. According to Khim and Wing (1969) and Mitchell (1981), Lower Eocene sediments include various clasts like dacite and tuff.

In the Chin Hills ophiolites, rocks bearing Globotruncana fossils from the Senonian age are associated with sandstone and shale. Similar blocks with limestone deposits are found in the eastern part of Manipur and the Arakan Yoma, Cheduba, and Ramree Islands. Additionally, Upper Cretaceous radiolarian chert, limestone, and other pelagic sediments, closely associated with ophiolite rocks, are unconformably overlain by Eocene sandstone, grits, and shales in the coastal regions of Arakan Yoma and Sandaway Mazin.

c. Central Burma Basin:

The Central Burma Basin is situated between the Indo-Burmese Basin and the Sino-Burmese region, spanning from the Hukawng Valley to the Irrawaddy Delta and the

Gulf of Martaban. In recent decades, significant progress has been made in understanding the geology of this area, through the contributions of various workers (Pascoe, 1912, Chibber, 1934, Barber, 1936, Clegg, 1938 & 1941, Cotter, 1938, Brunnschweiler, 1966 and 1974, Mitchell and Mckerrow, 1975, Curray et al., 1979, and Bender, 1983).

The Tertiary basin of Burma, central to this region, extends approximately 1400 kilometers long and 200 kilometers wide between Gangaw and Mandalay. Notably, the marine Eocene sediments exposed here are about 12,000 meters thick, without Oligocene rocks (Anon, 1978). The Shan fault system defines the basin's eastern margin, which runs parallel to the Shan Tenasserim highlands in a north-south direction. In the central Burma basin, particularly in the southern Chindwin Syncline, sediments in the western belt reach a thickness of 15,000 meters. Available data indicates that in the Prome Syncline, Oligocene-Miocene sediments overlay Cretaceous rocks, as reported by Bender (1983). In the western and eastern sides of the Chindwin Valley, mid to late Cretaceous sediments are situated above the metamorphic basement, according to Clegg (1941) and Brunnschweiler (1966). The basin's inception is marked by the presence of pelagic sediments and abyssal fan deposits (Hamilton, 1988). The area is characterized by three major north-south trending synclines, which are separated by structural highs and various anticlines accompanied by corresponding synclines.

The eastern part of the Central Burma Basin lies between the Shan-Tenasserim highlands and the Magnetic Arc of the Tertiary age. In this region, the Miocene-Pliocene-aged Pegu Formation is most prominently exposed in the Gulf of Martaban. These rock formations are folded within the Pegu synclinorium in the Irrawaddy Delta, Pegu Yoma, and Sittang Valley (Bender, 1983). Linear faulted occurrences of Albian ophiolites are also observed in this area.

d. Magnetic Arc of Burma:

The Magnetic Arc of Burma extends across the central Burma Basin as a broken chain of extrusive and intrusive rocks, ranging from basic to acidic compositions. This geological feature stretches from the Jade Mines in the north to the western

edge of Pegu Yoma in southern Burma. Additionally, the arc includes intra-oceanic islands like Narcodam and Barren Volcanic islands in the Andaman Sea to the south. Within this arc, various rock types are found, including I and S-type granites, tonalites, intrusive basalts, andesites, and quartz diorite. Several researchers have conducted studies in this region, shedding light on its geological history. Chibber's work in 1934 contributed to our understanding of the area. Radiometric dating has revealed the ages of these rocks, with Bender (1983), determining a Cenomanian age (K/Ar age, 93-97 million years ago) for the Wontho area massif. Mitchell (1986) established an Albian age (K/Ar age, 100 ± 5 million years ago) for the lower Chindwin granitoid complex. The formation of Cenozoic subduction-related magnetism in this region began during the Oligocene or late Eocene in certain sectors and continued until the Pleistocene-Recent period. The volcanic arc is characterized by a wide range of rock types, including basic to acidic compositions, late alkaline basalts, andesites, dacites, rhyolites, as well as pyroclastic subaerial flows, stratovolcanoes, and explosive craters.

e. Highland of eastern Burma:

The Eastern Burma Highlands encompasses the East Burmese Highlands, the Shan Plateau, and the region extending into peninsular Burma, Thailand, and Malaysia. Situated between the Central Burma Basin and the Magnetic Arc, the northern portion of the tectonized margin features the Myitkyina and Mandalay Ophiolite Belt, commonly referred to as the MAMO belt.

2.3 Stratigraphic Succession of Manipur

The geological formation of Manipur is primarily characterized by Tertiary and Cretaceous sediments, with few occurrences of igneous and metamorphic rocks. The Tertiary flysch sediments encompass approximately 65% of the state's total land area. These formations are situated within the Manipur Hills, which exhibit a predominant NNE-SSW topographic orientation. These hills are situated between the northward-extending Naga-Patkai Hills and the southward-extending Chin-Mizo Hills, collectively forming an integral part of the broader Indo-Myanmar Hill Ranges.

Within Manipur, various litho-units exhibit significant deformation and are juxtaposed against one another. This results in imbricate thrust systems oriented in an NNE-SSW direction, with younger units found to the west and older ones to the east. Evans, Medlicott (1865), and Mallet (1876) conducted pioneering geological studies in the region. However, the initial comprehensive stratigraphic overview of the Assam province was given by Evans (1932). Subsequently, Mathur and Evans (1964) and Bhandari et al. (1973) contributed to the Tertiary stratigraphy of Assam, incorporating data from oil exploration activities in the area. A generalized stratigraphic sequence for Northeast India, including Assam, was also outlined by an anonymous author (1974).

No standardized stratigraphic succession had been established for Manipur, neither by the Geological Survey of India nor by any other organization until Soibam (1993, 1998). Soibam compiled and established a stratigraphic sequence for Manipur by modifying existing literature and incorporating newly available geological data. The field observations of litho-units generally conform to the sequence outlined in this scheme, although refinements and minor adjustments may be necessary as new insights emerge from studies in petrology, structural geology, and tectonics. The table below provides the stratigraphic succession for the state (Table 2.1). The litho succession of Manipur is categorized into seven groups, which include Alluvium, Tipam, Surma, Barial, Disang, Metamorphic complex, ophiolite complex, and metamorphic complex, ranging in age from Quaternary to Pre-Mesozoic, which are briefly summarised as under.

2.3.1 Metamorphic complex

The metamorphic complex of Manipur is characterized by phyllite schists, quartzite, and marble, among other rock types, exhibiting low to medium-grade metamorphism. Ranging in age from Proterozoic to possibly older, it is observed in the far eastern region of the state. Initially referred to as the Naga Metamorphic Complex by Brunnschweiler (1966), it was later ascribed a Proterozoic age by Acharyya et al. (1986). The complex forms part of the continental crust of the Myanmar plate and is seen as klippen thrusting westward younger lying the younger

Table 2.1: Generalized stratigraphic succession of Manipur (after Soibam, 1998 and Khuman, 2009)

Age	Group	Lithology
Quaternary-Holocene to Pleistocene (?) older	Alluviums	Dark grey to black clay, silt and sandy deposits of fluvio-lacustrine origin of the Imphal Valley. Fluvial alluviums in the Barak valley area of Western plains. Clay, sand, gravel, pebble, and boulder deposits of the foothills and old river terraces.
----- Stratigraphic Break -----		
Miocene	Tipam Group	Molting clay, molting sandy-clay, sandy-shale, clayey shale and sandstone, Greenish to blue, moderate to coarse ferruginous sandstone with sandy shale, clay often brown to orange due to weathering, molasses type of deposits.
 Unconformity 		
Miocene to upper Oligocene	Surma Group	Shale, sandy-shale, siltstone, massive to false bedded ferruginous sandstone. Alternations of sandstone and shale with more horizons in the middle and minor conglomerate. Transitional characters from flysch to molasses sediments.
 Unconformity 		
Oligocene to Upper Eocene	Barail Group	Massive sandstone, alternations of shale and sandstone with bedded structure. Flysch sediment of turbidite character
 Unconformity 		
Eocene to Upper Cretaceous	Disang Group	Arenaceous rocks, dark grey, splintery shale inter-bedded with sandy shale and siltstone in the upper part. Argillaceous grey-shale interbedded with mudstone and minor amount of silt in the lower part.
 Unconformity 		
Lower Eocene to Upper Cretaceous	Ophiolite Complex	Mostly of Ultramafic rocks of harzburgite and lherzolite types with sporadic basic dykes and very thin layer of pillows with associated sediments such as pelagic-chert, shale, limestone etc.
 Unconformity 		
Pre mesozoic or older	Metamorphic Complex	Low to medium-grade metamorphic rocks of various compositions- phyllitic schist, quartzite, micaceous quartzite marble and quartz-chlorite-mica schist.
 (?) Unconformity 		
?	Basement Complex	Unseen. (?) Early Mesozoic/Palaeozoic rocks or Precambrian rocks.

Ophiolite Melange Zone.

2.3.2 Disang Group:

Mallet (1876), originally coined the term "Disang Group" to describe a collection of shale formations with sandstone layers near the Disang Valley in Upper Assam. Similar sedimentary outcrops were later discovered along a wide belt spanning over 60 kilometers within the Assam-Arakan ranges. These rock types are also present in the Manipur-Nagaland Orogenic Belt, which is bordered by Ophiolites in the east, separated by a thrust contact. Their connections with the younger Barail sediments exhibit both gradational and conformable characteristics.

The Disang Group encompasses a range of thicknesses, possibly exceeding 3000 meters, consisting mainly of fine clastic sediments derived from the hinterland. It includes shales, slate, phyllite, greywacke, sub-greywacke, and calcareous shale, with minor occurrences of limestone. This folded and thrust-bounded sequence of predominantly clay-rich rocks is often considered a flysch sequence (Mathur and Evans, 1964). In Manipur, various allochthonous limestone bodies with Maestrichtian fossil assemblages have been discovered. The Disang Group spans from the Upper Cretaceous to the Upper Eocene (Pascoe, 1912). In the Manipur-Nagaland orogenic belt, the argillaceous sequence is divided into two lithologic formations:

i. Lower Disang Formation: The Lower Disang Formation comprises phyllite, slate, and dark grey shale interbedded with mudstone and sandstone, correlating with the Kiphire Formation (Anand, 1991). This formation is well-developed between the Kiphire and Zungki Tizu river sections (Rao, 1983), extending into eastern Manipur. These rocks undergo metamorphism towards the eastern interior, transitioning from shale to slate, phyllites, and schists. They are juxtaposed against the ophiolite belt of Nagaland-Manipur along the easternmost fringe, with a tectonic contact.

ii. *Upper Disang Formation*: The Upper Disang Formation corresponds to the Mao Formation (Anand, 1991), which is equivalent to the Disang Group (Mallet, 1876) from the type area, the Disang River section in Assam. In the eastern Disang thrust, the Lower Disang Formation transitions into a sequence of carbonaceous shales of the Upper Disang (Ranga Rao, 1983). This formation primarily consists of shale with minor sandstone and rare mudstone. The Barail-Upper Disang contact is marked by an increase in sandstone thickness. Mitra et al. (1974) and Krishna Rao and Prasad, (1982) divided it into three units along the Kohima-Dimapur Road: the lower unit comprises dark grey splintery shale, while the upper unit consists of concretionary shale, sandy slates, and sandstones with disseminated carbonaceous matter throughout the entire formation. Several researchers have suggested dating the fauna and flora from the Upper Disang Formation, ranging from the Palaeocene to the Upper Eocene (Evans, 1958; Nagappa 1959; Sinha et al., 1982; Chatterjee, 1992; and Ranga Rao, 1983).

2.3.3 Nagaland-Manipur Ophiolite Belt and melange zone:

The Ophiolite belt is found along the Indo-Myanmar border within the regions of Manipur and Nagaland. These Ophiolites were first reported in the late 1970s. This belt extends in a north-south to north-northeast-southwest direction along the eastern border of the country and is an integral part of the Naga-Arakan Yoma flysch formation, dating from the Upper Cretaceous to Lower Eocene periods. It runs parallel to the eastern ophiolite belt that traverses Central Burma, Sumatra, and Java, characterized by steeply dipping mafic rocks with high gravity properties (Sengupta et al., 1990). This Ophiolite belt stretches approximately 200 kilometers from Chokla (26°06' N and 95°07' E) in the Tuensang district of Nagaland in the north to Moreh (24°23' N and 94°28' E) in the Tengnoupal district of Manipur in the south, with a width ranging from 2 to 20 kilometers. Furthermore, this belt continues southward through the Chin Hills, Arakan Yoma, and extends to the Andaman Nicobar Islands, forming a 1200-kilometer-long narrow belt with a concave arch toward Burma (Myanmar). The formation of this belt occurred during the Cenozoic era due to the

subduction of the Indian lithospheric plate beneath the Burmese plate (Dasgupta and Nandy, 1995), representing the eastern extension of the Major Alpine Tethyan domain.

The complete ophiolite sequence in this region includes various rock types ranging from ultramafic to mafic, such as dunite, harzburgite, lherzolite, wehrlite, clinopyroxenite, websterite, hornblendite, gabbro, dolerite, gabbro-norite, olivine, gabbro, plagiogranite, troctolite, and pillow basalts of the mafic volcanic suite. Additionally, Alpine-type podiform chromite, magnetite, and sulfide ore deposits, as well as associated sediments like chert, greywacke, limestone, and shale, occur as discontinuous bodies within this belt. These ophiolites are found as fault-contacted slices within the pelagic shale-sandstone association. Metamorphic rocks like quartzites, phyllite, and marble overlay the ophiolites in parts of Nagaland and possibly in eastern Manipur. The contact between the ophiolite and sedimentary Disang formations is characterized by fracturing, brecciation, mylonitisation, and silicification. In some places, chlorite, tremolite, quartz, and calcite veins have been injected. There are also reports of contact metamorphic effects in some sedimentary rocks due to the intrusion of ultramafic rocks.

The ultramafic and mafic rocks, along with pelagic limestone and radiolarian cherts, contain chromite and magnetite bodies. Some of these deposits are stratiform, while others are of the alpine type. The ultramafic include harzburgite, dunite, lherzolite, wehrlite, pyroxenite, and hornblende peridotite, with harzburgite being the most common, followed by dunite, and so forth, showing varying degrees of serpentinization.

The Naga metamorphites, consisting of quartzite, serpentinite, phyllite, marble, mica schist, and gneiss, constitute the oldest rocks in the Manipur-Nagaland Ophiolite Belt (Brunnschweiler, 1966). Geological evidence suggests that the ophiolites of the Indo-Burma Orogen are rootless, sub-horizontal, sheet-like, and thrust-bound slices (Sengupta et al., 1990). The asymmetrical folds and the

presence of melange at the base of the ophiolite nappe, as well as younger flysch sediments belonging to the Disang formation beneath the ophiolites, indicate thrusting activity. The age of the ophiolites ranges from the Cretaceous to the Middle Eocene (Venkataramana, 1985) and from the Jurassic to the Early Cretaceous (Bhattacharjee, 1991), as determined by radiolarian fossils and planktonic foraminifera.

The ongoing subduction process during the Eocene-Oligocene period brought the Indian and Eurasian blocks closer together and led to the deposition of interrupted flysch sediments along the western margin of the Indian continental block. The collision between the Indian and Eurasian continental blocks occurred during the late Oligocene, resulting in a gentle dip of these blocks together with the olistostromal trench sediments being thrust westward from the suture. This geological process gave rise to the Manipur-Nagaland Ophiolite Belt in the Indo-Burma orogen. Lastly, it's worth noting that the ophiolites and the surrounding sedimentary rocks have been thrust over by the Naga Metamorphites in Nagaland and the northeastern part of Manipur.

2.3.3.1 Ophiolite melange zone:

The term "Ophiolite Melange" was introduced to the field of geology by Gansser (1964). He defined melange as a geological unit comprising fragmented components of ophiolites. In many parts of the Naga Hills, there is a presence of ophiolite-derived clastic that is intricately associated with the ophiolitic rocks. These clastics are referred to as the Phokhpur Formation (Acharyya, 1986), which consists of olistostromal argillites and rhythmites. The sedimentary deposits associated with these formations reveal diverse deposition environments, and their chronological relationships appear disrupted due to extensive tectonic activity. These sediments are tectonically intermingled, forming a melange, either underlying the primary ophiolite complex or occurring independently in certain areas.

The ophiolite melange zone which has been observed in the field has been divided into the following units:

- The Ophiolite suite: Similar to a typical ophiolite suite, the Manipur ophiolite suite consists of various rock types where the section of the main ophiolite bodies is primarily composed of ultramafic rocks with intermittent dibasic dykes cutting through them. The ultramafics are found wedged between two layers of pelagic shale.
- *The Pelagic Sediments:* These sediments are predominantly shale, chert, and limestone (with occasional dibasic dykes or sills in shale and chert), and they are generally mixed with the Disang and Barail sediments. They are found exposed on the western and eastern borders of the main ophiolitic mass.
- *The Exotic Rocks:* are several exotic bodies or blocks of various sizes made of various rock types that float over or mix with the host pelagic shale in regions close to the eastern and western margins of the main Ophiolitic Suite, where the exposed different rock types are tectonically juxtaposed.

2.3.4 Barail Group:

The term "Barail Group" was introduced by Evans (1932) to describe a sequence of alternating sandstone and shale, often in varying proportions, found in the regions of Assam, Nagaland, and Manipur. The name "Barail" was derived from the Barail Range, situated on the southeastern margin of the Shillong Plateau. Within this group, there are three main formations: Laisong, Jenam, and Ranji. The Barail Group is characterized by predominantly arenaceous (sandy) sediments and slowly transitions from the underlying Disang Group. This transition results in the formation of a substantial thickness of mostly molassic sediments, exceeding 6000 meters in some areas. Consequently, several roughly northeast-to-southwest trending geological belts are present in the northeastern states of India (Sarmah, 1989).

The Barail Group consists of a variety of sediment types, including sandstone, shale, carbonaceous shale, siltstone, clay, and coal. Spheroidal weathering is a common feature within the Barail Group and is well-exposed in the western part of Manipur. These formations can also be found as outliers in the core of synclines.

The contact between the Barail Group and the underlying Disang Group is characterized by angular discordance, as reported by Anon (1984). In a specific section along the Palel-Tamu Road, a thick argillaceous sequence composed of siltstone and shale with minor sandstone, correlating with the Jenam Formation, has been identified by Basu and Ranga Raju (1964). The age of the Barail Group is estimated to be Upper Eocene to Oligocene, based on the analysis of faunal and floral assemblages. This dating has been supported by various researchers, including Evans (1932), Dasgupta (1977), Sinha et al. (1982), and Ranga Rao (1983).

2.3.5 Surma Group:

Mallet (1934), introduced the term "Surma Group" to describe a sequence of rock formations found in the Surma Valley. These formations display alternating bands of bluish-grey sandstone, ranging from medium to coarse-grained, as well as fine-grained sandstone with bluish-grey clay or shale layers. These layers often exhibit varying rates of weathering, as observed by Saxena and Yadekr (1984).

The Surma Group rocks are prominently exposed in a geological feature known as a "Schuppen belt." The contact point between the Surma Group and adjacent formations is characterized by bands of conglomerate. Notable exposures of this contact can be observed in several locations, such as the Hovishe-Phekekrima road, Merapani-Wokha road, and at Lotsu in Nagaland. In Manipur, the Surma Group comes into contact with the Renji Formation near Nungba in the western region. These formations are dated to the Oligocene-Miocene period.

2.3.6 Tipam Group:

Mallet (1876) introduced the term "Tipam" to describe the rock formations that are visible in the Tipam River section of Upper Assam. These formations also extend widely into the Mikir Hills and the Schuppen Belt. The Tipam Group primarily consists of arenaceous rocks, known as the Tipam Formation, which overlay mottled claystone and are accompanied by minor sandstone layers forming the Girujan Formation.

Within the Schuppen Belt, the Tipam rock formations are prominently exposed in proximity to the Naga thrust fault. The sandstones within these formations are typically massive and contain layers of intra-formational conglomerates. In the western part of the region, these exposures are particularly notable. Based on the stratigraphic arrangement and the fossil record found within these formations, they are estimated to range in age from the Miocene to the Pliocene period, as reported by Ranga Rao (1983).

2.3.7 Quarternary Group or Alluvium Deposits

Alluvium deposits overlie the Tipam Group due to the region's uplift after the deposition of Tipam. Major alluvial deposits are found in the Imphal valley, which likely formed during the Pleistocene. These deposits are classified into old and new alluvium. The old alluvium is primarily found in the Barak valley of Jiribam district, while the new alluvium is in the Imphal valley. The upper Imphal valley contains cobbles, boulders, clay, silt, and sand, while the lower part likely has older alluvium. The Imphal valley features fluvial-lacustrine alluvial deposits that are dark grey to black, and rich in carbonaceous matter, indicating swampy conditions. New alluvium in the valley consists of recent river and stream deposits.

2.4 Geology of the study area:

Geologically, Tengnoupal and its surrounding areas display a rich diversity of rocks, encompassing igneous, meta-igneous, and sedimentary rocks, as shown in the geological map of the study area (Fig.2.1 b). These rocks can be broadly categorized into the Metamorphic suite, the Melange Zone within the Ophiolitic Complex, Oceanic Pelagic Sediments (OPS), and the Disang Group. These groups of rock are often overlain unconformably by recent alluvial sediments. The geological successions of the study area are described as follows.

2.4.1 Metamorphic suite: The Metamorphic suite or Naga Metamorphic Group of the Lower to Upper Cretaceous period is the oldest geological formation in the region (Brunnschweiler, 1966). The suite is observed on the eastern and north-eastern edges of the complex (Fig. 2.1 a). It comprises a variety of rocks, including

quartzite, crystalline limestone-marble, phyllite, mica schist, gneiss, sheared granite, and minor serpentinite (Brunnschweiler, 1966; Roy and Kacker, 1980; Chattopadhyay et al., 1983). These rocks are found as klippen, thrust westward over the younger ophiolite belt.

2.4.2 Ophiolite Complexes: The Ophiolite complex is predominantly composed of ultramafic rocks. This complex is observed in thrust contact with the oceanic pelagic sediments (OPS) from the Middle to Lower Eocene. The ultramafic rocks are often found interlayered with pelagic shale. Sporadic outcrops of mafic rocks, including extrusive pillow lavas and dyke rocks, are also observed within the complex.

2.4.3 Oceanic Pelagic Sediments (OPS):

The OPS primarily consists of a thick sequence of shale, with interlayers of chert, variegated clay, and limestone. These sediments are often associated with the Disang and Barail formations. The OPS serves as a characteristic cover over the volcanic ophiolite suite. The limestone bands are fine-grained and occasionally cherty, occurring in shades of grey, white, and pink, composed of micritic and sparitic calcites. The cherts are typically grey or green and contain abundant radiolarian structures, which are rounded to elliptical in shape.

2.4.4 Disang Group: The Disang Group is prominently exposed in the study area and is closely associated with the *mélange* group within the Ophiolitic Complexes. This group primarily consists of various shades of shale along with flaggy sandstone. It is further divided into the Upper Disang Formation and the Lower Disang Formation. The Upper Disang shale appears grey and contains gastropod fossils dating back to the Eocene age. In contrast, the Lower Disang Group comprises dark grey shale, slate, and phyllite interbedded with mudstone and sandstone, with no fossils present. Additionally, minor quantities of gritty sandstone and conglomerate can be observed. These rock groups are overlain unconformably by recent-age soil deposits.

Table 2.2: Geological Succession of the study area (Modified after Ningthoujam et al.,2012)

Age	Geological Group		Lithologic characteristic
Recent	Alluviums		Comprising recent sedimentary soils with peat layers.
 Unconformity 			
Eocene to Lower Eocene	Disang	Upper Disang	Patchy conglomerate with pebble of serpentine, chert, quartz; shale, siltstone, sandstone, rythmite, greywacke, olistostromal limestone, slice of ultramafic rock, pillow basalts, basic dyke, Disang chert and OPS.
		Lower Disang	Dark splintery shale, siltstone, rhymite with greywacke, minor sandstone.
Middle to Lower Eocene	Oceanic Pelagic Sediment (OPS)		Shale, thin sandstone, greywacke, intraformational conglomerate, red and green chert, clastic limestone, basic dykes and volcano sedimentary rocks.
 Tectonic Contact 			
Lower Eocene to Upper Cretaceous	Ophiolite Complex		Serpentinized ultramafic rocks (peridotite), basic dykes, pillow basalt, amygdaloidal volcanics, podiform chromite.
 Unconformity 			
Pre Mesozoic	Metamorphic Complex		Phyllitic schist, quartzite, micaceous quartzite, marble and quartz chlorite mica schist.

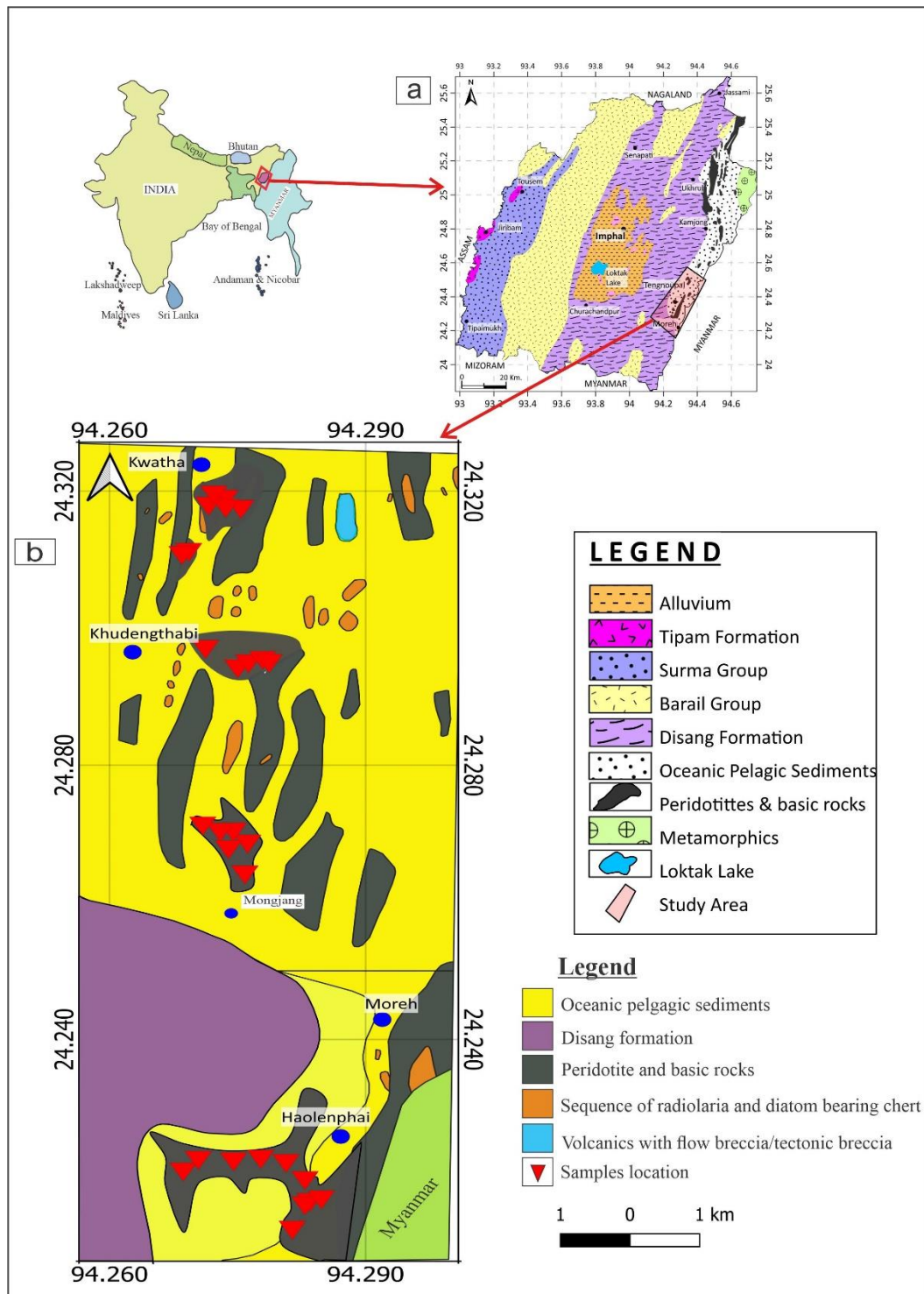


Fig 2.1: a) Generalised Geological map of the Manipur Ophiolite Complex (MOC), Manipur (Modified after Singh,2013). b) Geological map of the study area and location of the sample site.

2.5 Field Observation:

The field observations from the three study sections corroborate and strengthen the interpretation of the regional tectonic framework outlined for the Naga-Manipur Ophiolite Belt. These exposures, spanning approximately 15 km along the Indo-Myanmar border, represent different structural levels and deformation intensities within the broader ophiolite complex, offering insights into the processes of oceanic lithosphere dismemberment and emplacement during the Cretaceous-Eocene collision.

The ultramafic rocks associated with the Manipur Ophiolite Complex in these sections represent portions of the upper mantle from oceanic lithosphere, consistent with the regional interpretation of this belt as the northward continuation of the Indonesian-Andaman Arc system. These ultramafic rocks, primarily composed of olivine and pyroxene, form the bottom-most unit of an ophiolite sequence. They are the most prevalent rock type in the current study area, typically hosted within the Disang Formation. These outcrops are interspersed with oceanic pelagic sediments, consisting of shale, chert, sandstone, and limestone. Shale, the most abundant type of sediment, is commonly found sandwiched between layers of ultramafic rocks or serving as a host for tectonically transported exotic rocks, which are often observed on both sides of the Ophiolite Suite. Harzburgites in the study region cover extensive areas and exhibit various colors, including brown, light green, and light yellow. However, they turn dark with increasing serpentinization. The studied ultramafic rock in the field can appear in two distinct forms: a) as tectonite, and b) as transitional peridotite. The tectonite unit is the most predominant litho-unit in the study area which is characterized by a significant presence of intensely serpentinized harzburgite and lherzolite whereas the transitional peridotite is characterized by a moderate degree of serpentinization and occurs above the tectonite peridotite. The major litho-unit is massive serpentinized. The intensely serpentinized and greatly altered serpentinites typically exhibit olive green colors, while the least altered sections of these outcrops and the least serpentinized are dark green. Melanocratic rocks are characterized by predominantly large, brownish phaneritic crystals with a

shining appearance under sunlight. These lighter crystals are embedded within a darker-colored groundmass which are visible in hand specimens. Neither the rock in the field nor the hand specimen displays any distinct signs of tectonic fabric, such as lineation or foliation.

The field observations conducted in the study area have been categorized into three distinct sections: the Kwatha-Khudengthabi section, Mongjang section, and the Haolenphai section, each of which is described in further detail below to provide a comprehensive understanding of the study area.

2.5.1 Kwatha and Khudengthabi section

This section, located in the central portion of the study area, exemplifies the highly tectonized nature of the ophiolite belt described in the regional framework. The intense serpentinization and presence of rodingite blocks reflect the hydrothermal alteration processes typical of ophiolite emplacement zones, while the association with oceanic pelagic sediments confirms the melange character predicted by the regional tectonic model.

The ultramafic exposures around the Kwatha area are highly serpentinized and altered (Fig.2.2 a). However, in some locations, relatively fresh and least serpentinized blocks are found embedded within the highly serpentinized matrix, often protruding above the extensively altered ultramafic surface (Fig.2.2 b). Rodingite is also found in the area as small blocks ranging from a few centimeters to several meters within the serpentinized ultramafic rocks (Fig.2.2 c). Additionally,

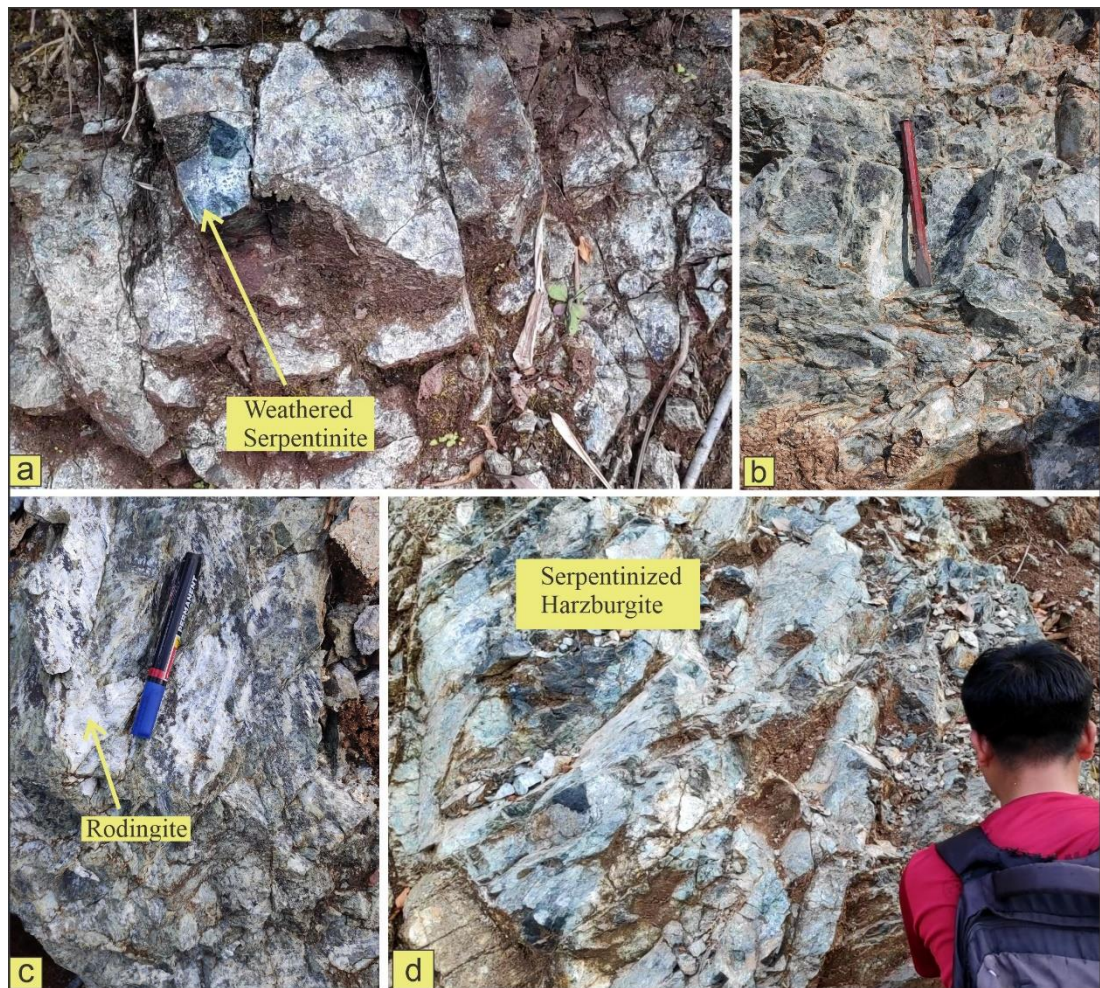


Fig.2.2. Field photograph showing: a) Highly serpentinized ultramafic rocks, near Kwatha village, b) Least serpentinized ultramafic rocks, near Khudengthabi Village, c) Rodingite (whitish) within serpentinized ultramafic rocks, and d) Exposure of serpentinized harzburgite, near Kwatha village.

rodingite is found associated with oceanic pelagic sediments. Serpentinized harzburgite is more common than lherzolite in this region. These rocks are dark green and have large grains, with altered pyroxenes embedded within serpentine, likely derived from olivine (Fig.2.2 d). The weathered surfaces of these boulders exhibit a distinctive hob-nail texture (Fig.2.3 a). There is a noticeable correlation between the deformation and the presence of magnesite veins that are linked with serpentine. Fractures and cracks in the ultramafic peridotites are commonly filled

with secondary magnesite and serpentine minerals. The transformations in the serpentine have a significant influence on the formation of these magnesite veins (Fig. 2.3 b & 2.4 a). Lherzolite is characterized by its greenish-black to dark green color, medium grain size, conchoidal fracture, and shows a moderate level of serpentinization (Fig.2.4 b). Additionally, there is an exposure of pillow lavas nearby which are sub-rounded to rounded in shape, typically appearing as exotic bodies or blocks that float over and intermingle with the host ultramafics and pelagic shales (2.4 c and 2.4 d).

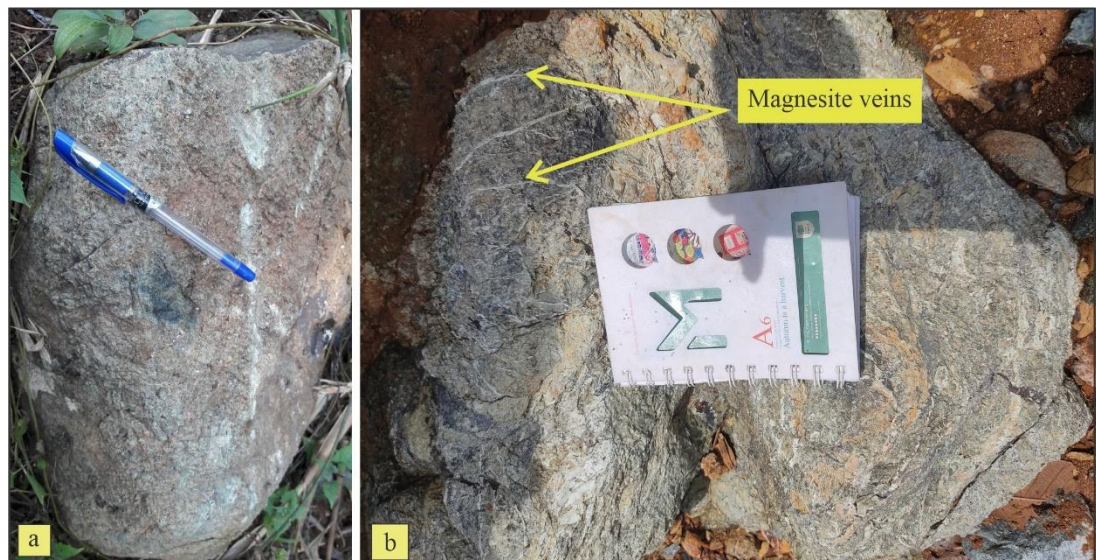


Fig.2.3. Field photograph showing: a) Hob-nail pattern in serpentinized ultramafic rocks and b) Asbestos (chrysotile) veins associated with serpentine showing a close relation to deformation in the serpentine sole.

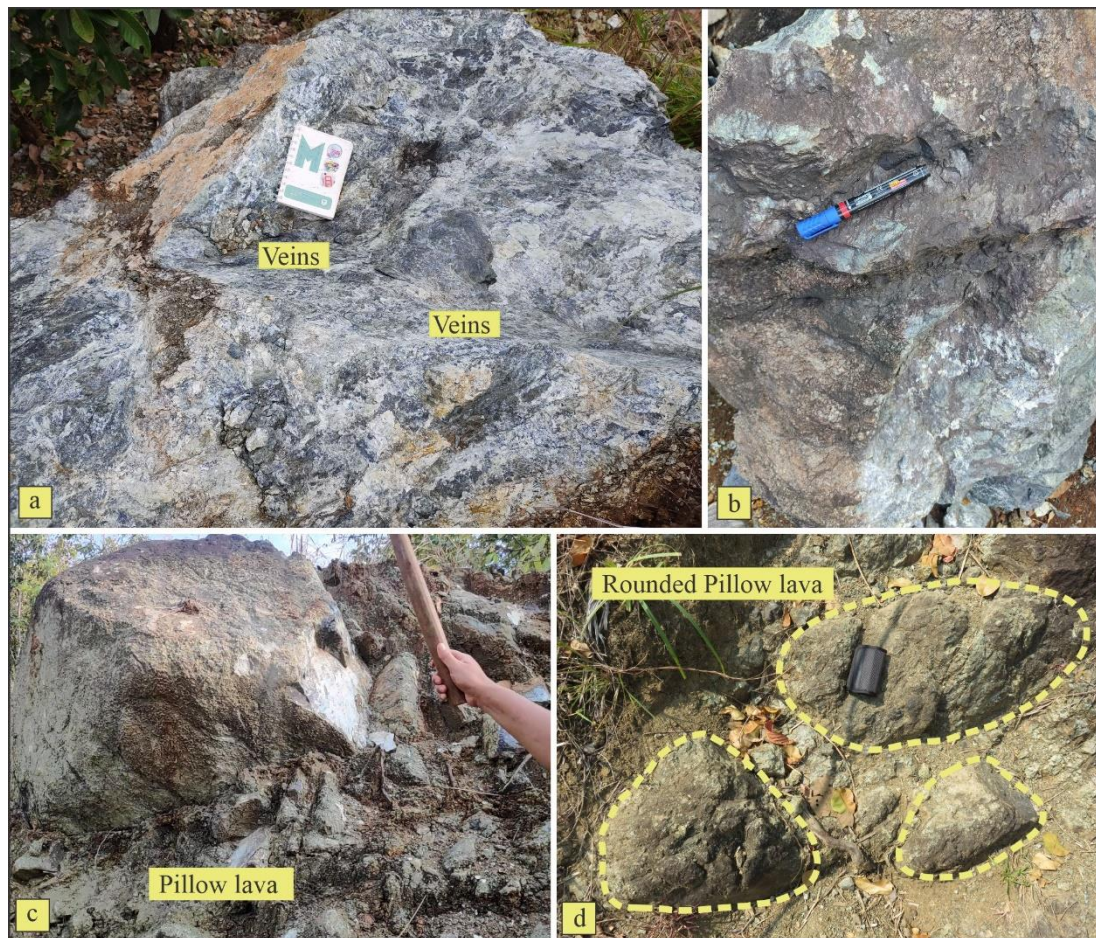


Fig.2.4. Field photograph showing: a) Fibrous veins of serpentine in ultramafic peridotite rocks, b) Exposure serpentinized lherzolite c) Boulder pillow lava observed between Khudengthabi to Moreh road section d) Rounded pillow lava (yellow dotted line represents pillow lava), Near Khudengthabi Village.

2.5.2 Mongjang Section

The Mongjang section, representing the northern extent of the study area, provides evidence for the transitional nature of the ophiolite complex from tectonite to less deformed peridotite. This structural variation aligns with the regional understanding of the belt as comprising thrust-bound slices with varying degrees of preservation, reflecting different positions within the original oceanic lithosphere column.

The ultramafic peridotite exposures are predominantly less serpentinized in the area between New Monjang and S. Moljol. The most common peridotite here is

harzburgite, which ranges from brown to light green (Fig.2.5 a). In some areas, patches of serpentinized harzburgite are exposed, covered by soil at the foot of the hill (Fig.2.5 b). Large Blocks of transitional peridotite are interspersed within an extensively serpentinized and sheared ultramafic formation. The ultramafic peridotite displays jointed planes in certain areas (Fig.2.5.c).

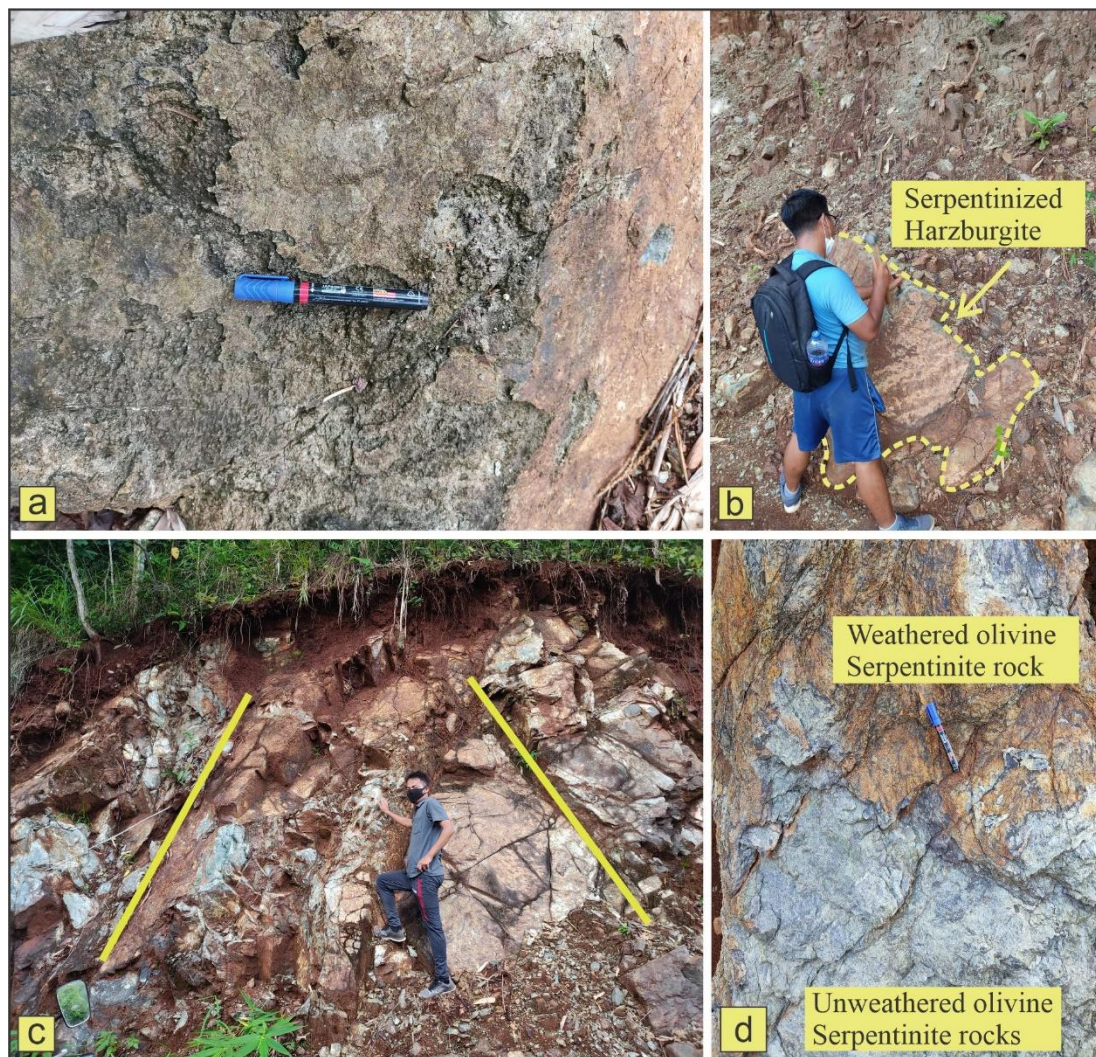


Fig.2.5. Field photographs showing: a) Harzburgite in ultramafic rocks, b) Patches of serpentinized harzburgite exposed along the foothill, c) Blocks of transitional peridotite are interspersed within an extensively serpentinized and sheared ultramafic formation. The peridotite displays 3 sets of jointed planes in certain areas. (Monjang

to S.Moljol road section), and d) Ultramafic rocks show a brown weathering rind, the dark green part shows fresh serpentized peridotites.

Fresh green ultramafic peridotite is usually preserved 3-4 cm beneath the weathered surface which contains partially serpentized olivine (Fig.2.5 d). Notably, there are occasional altered grains of orthopyroxene, which are euhedral and become prominently visible in the weathered brown portion of the rock. The weathering surface are likely driven by the interaction of surface water (rain) and atmospheric gases with olivine, which is not stable under surface conditions (Bucher and Grapes, 2011).

2.5.3 Haolenphai section

The Haolenphai section, positioned at the southern margin of the study area near the Indo-Myanmar border, demonstrates the tectonic contact relationships that characterize the regional ophiolite belt. The observed thrust contact between serpentized ultramafics and sedimentary sequences provides direct evidence for the westward thrusting of the ophiolite nappe over younger Disang flysch sediments, as predicted by the regional tectonic framework.

The primary lithotype in and around Haolenphai Village is a large exposure of serpentized harzburgite, with red limonitic soil forming at the top of this unit (Fig.2.6 a). In the southern region of Moreh, extending towards Haolenphai, a transitional peridotite unit is exposed along a road section, accompanied by a sequence of sandstone and shale. A clear thrust contact is observed between these two units (Fig.2.6 b).

Among the ultramafic, harzburgite is the most common rock variety and typically exhibits serpentization and varying degrees of weathering (Fig.2.6 c and 2.6 d). It is characterized as hard and compact, with a slight bronzy lustre. The weathered surface of pyroxene minerals in serpentine rocks, which are resistant, displays a brown to grey color and an elephant skin-like texture (Fig.2.7 a). The ultramafic peridotite has undergone intense fracturing, with larger cracks marked by green

serpentine and exhibiting striations reminiscent of slickensides, indicating extensional shearing during the process of exhumation (Fig.2.7 b). Chromitites are associated with ultramafic peridotites in the field, with massive podiform chromite observed within serpentized peridotite near Haolenphai (Fig. 2.7 c). Several chert blocks are found floating above the ultramafic rocks within the Menal riverbed, close to the bridge near the Indo-Myanmar border (Fig.2.7 d).

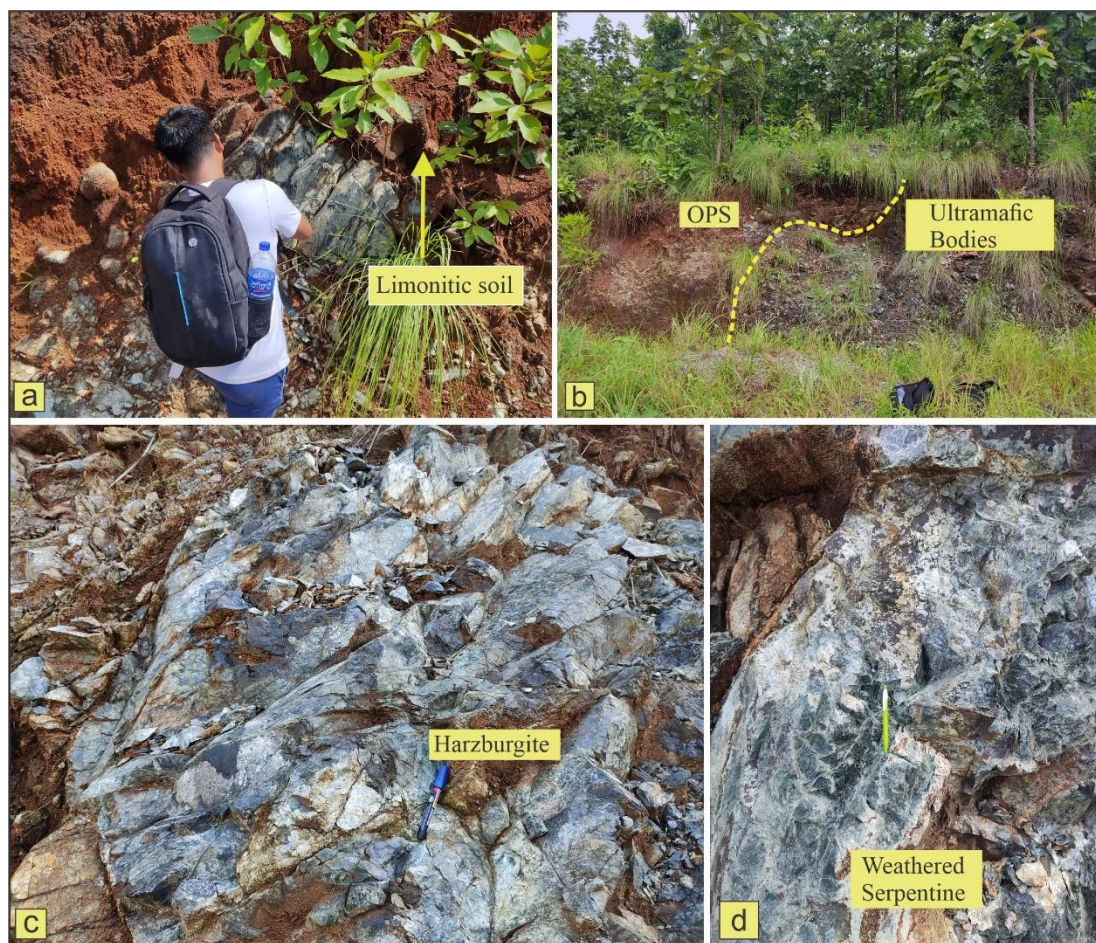


Fig. 2.6. Field photographs showing: a) Serpentinized harzburgite combined with limonitic soil, a form of transitional peridotite. (Near Haolenphai Village). b) Tectonic thrust contact between Oceanic pelagic sediments and Serpentinised Ultramafic rock was observed between Moreh and Haolenphai road sections. c) Exposure of Serpentinized harzburgite in and around Haolenphai Village d) Highly weathered Serpentinized ultramafic rocks Near Haolenphai Village.

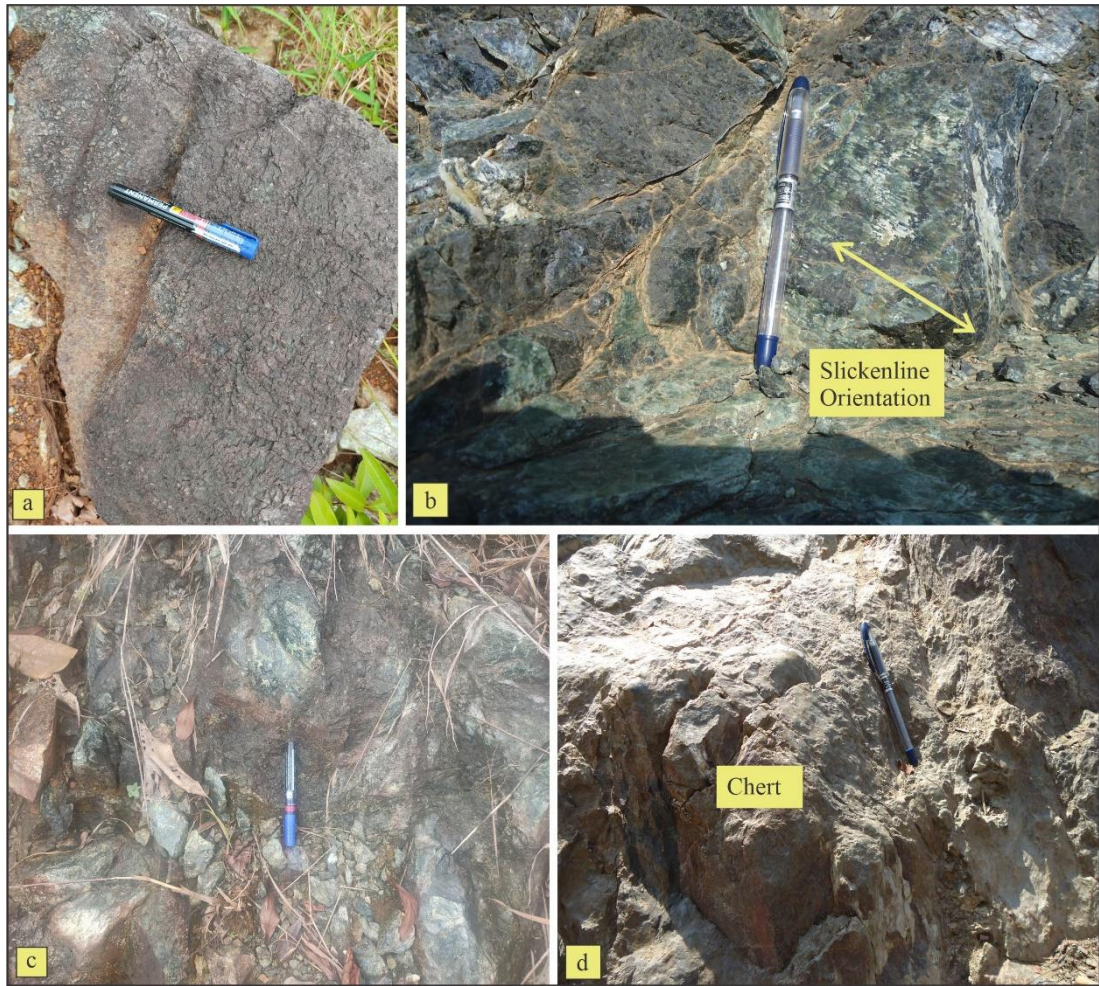


Fig. 2.7. Field photograph showing: a) Brown to grey Pyroxene-serpentine rocks displaying elephant skin weathering surfaces, b) Intensely fractured ultramafic peridotite near Moreh, Cracks are filled with serpentine and display striation similar to slickenside, c) Exposure of massive Chromite in Ultramafic rock near Haolenphai Village, and d) Exposure of chert boulder near the river Menal bank in Moreh.

2.5.4 Regional Significance of Field Observations

The field observations from the three study sections collectively validate and refine the regional tectonic model for the Naga-Manipur Ophiolite Belt. The spatial distribution of rock types and structural features across the Kwatha-Khudengthabi, Mongjang, and Haolenphai sections reveals:

Structural Continuity: The north-south alignment of ophiolite exposures confirms the regional NNE-SSW structural trend identified for the broader Indo-Myanmar Range system.

Tectonic Processes: The varying degrees of serpentinization and deformation across the sections reflect the complex emplacement history of oceanic lithosphere onto the Indian continental margin during the Cretaceous-Eocene collision.

Melange Characteristics: The intimate association of ultramafic rocks with pelagic sediments and exotic blocks supports the regional interpretation of this belt as an accretionary complex formed during subduction processes.

Border Location Significance: The proximity to the Indo-Myanmar border places these exposures at the critical juncture where the Indian Plate collision effects transition into the Myanmar micro-plate domain, making them key to understanding regional tectonic processes.

These local observations thus provide essential field-based evidence data for understanding how the broader Indo-Myanmar Range system developed and its role in the larger context of Himalayan-Tibetan orogenesis.

CHAPTER-3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter describes the research method used to analyze the geological characteristics and processes of the studied area. A combination of field-based observations and laboratory analyses, including petrographic studies and geochemical analysis, was used to gather comprehensive data essential for understanding the geology, mineral composition, and geochemical characteristics of the region. The methodology is divided into several key components, including geological mapping, fieldwork, petrographic analysis, and geochemical analysis, all of which lead to a better knowledge of the geological processes being studied.

3.2 Field studies

The detailed study and collection of rock samples for this research were carried out across various locations in the Tengenoupal district during the autumn of 2020 and 2022. Autumn was chosen as the prime season for fieldwork due to the dense vegetation that covers most of the study area; during this time, visibility improved significantly, making it easier to observe outcrops. Geological mapping at a scale of 1:50,000 was conducted to delineate the major lithologic units and establish their relationships, with sample locations recorded and plotted on the base map. The initial fieldwork took place from Kwatha village to Khudenthabi, where the exposure of ultramafic rocks was predominantly weathered. Despite the challenging terrain, a variety of fresh samples were collected. The subsequent fieldwork covered the south-eastern region, including Mongjang near Moreh, and extended towards Haolenphai Village, where ultramafic exposures were notably better. Samples were obtained from road cuttings, footpaths, and river courses. The primary focus of the study was the thorough examination of outcrops and the collection of hand specimens from various litho-units for subsequent laboratory analysis.

3.3 Sample preparation and instrumentation

The collected rock samples were prepared for petrographic and geochemical analysis to study the mineralogical characteristics, textural, and compositional in details. The detailed thin section preparation for petrographic analysis and geochemical analysis, including XRF and ICP-MS, is given below:

3.3.1 Thin section Preparation for petrographic studies

A representative number of thin sections of the ultramafic rock samples from the study area were prepared at the Department of Geological Sciences, Gauhati University and thoroughly examined under the polarising microscope (Leica DM2700P) at the Department of Geology, Mizoram University. Through detailed petrographic analyses, the mineralogical and textural variations of all rock assemblages in the study area were inherently disclosed, facilitating the distinction between different rock types and deformational events within this ophiolite complex.

3.3.2 X-Ray Diffraction Analysis

X-ray diffraction analysis was performed on eleven representative ultramafic samples at the Sophisticated Analytical Instrument Facility (SAIF), Gauhati University, Guwahati. The analysis was conducted using an Empyrean PANalytical diffractometer with CuK α radiation and Ni filter. The samples were scanned between 0° and 90° (2 θ values) with a rotation rate of 1 minute. Sample indexing was performed using PANalytical Data Collector and High Score Plus software, and the results were compared with the ICDD PDF2 database.

Empyrean Powder X-ray Diffractometer:

The Empyrean, installed in 2020, is a state-of-the-art, fully automated, computerized powder X-ray diffractometer that represents the pinnacle of X-ray diffraction technology. Manufactured by PANalytical, this instrument supports a wide range of X-ray diffraction, scattering, and imaging applications, making it an essential tool for scientists and XRD experts across diverse research fields. Its versatility accommodates both teaching purposes, with large doors for multiple-user access, and high-demand Research & development environments across various industries. The system features a powerful 4 kW X-ray generator, the Empyrean offers an extensive operational range

of $-111^{\circ} < 2\theta < 168^{\circ}$, with a minimal addressable increment of 0.0001° and an angular reproducibility of $< 0.0002^{\circ}$, ensuring accurate and reliable results. The system's XRD services include a wide range of analyses, such as X-ray diffractograms, peak positions, d-values, and relative intensity data. Notable applications of the Empyrean include phase identification, mineral quantitative analysis, grazing incidence XRD for thin films, unit cell parameter determination, and particle size analysis.

Key Specifications:

- Model: Empyrean
- Manufacturer: PANalytical
- Detector: PIXcel3D
- X-ray generator: 4 kW (max 60 kV, max 100 mA)
- Usable Range (with accessories): $-111 < 2\theta < 168^{\circ}$
- Smallest Addressable increment: 0.0001°
- Angular Reproducibility: $< 0.0002^{\circ}$
- 2θ linearity (entire range): $\pm 0.01^{\circ}$ or better
- Maximum Angular Speed: 15 deg/s
- Angular Resolution: 0.026° FWHM on LaB_6

Sample Requirements for XRD:

Solid samples should be prepared as dry powder of 300 mesh size. Approximately 3g of sample should be spread uniformly on a glass slide measuring 2cm x 3.5cm with a thickness of 0.2cm. The sample layer should cover an area of 2cm x 1.5cm on one side of the slide. In special cases, XRD analysis can be performed on smaller sample quantities or user-specific samples.

3.3.4 Sample preparation for Geochemical analysis:

Geochemical analyses require different preparation methods. The first step is often homogenization of the rock sample. This involves crushing and grinding the rock into a fine, uniform powder, ensuring that the analyzed portion accurately represents the whole sample. Press-pellet preparation is common for major element analysis using X-ray fluorescence (XRF). The homogenized rock powder is mixed with a binding

agent and pressed into a solid disc. This method provides a flat, uniform surface for X-ray analysis, improving the accuracy of elemental quantification. Rare Earth Element (REE) analysis using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) requires open-system acid digestion. In this process, the rock powder is dissolved in strong acids under controlled conditions, converting the solid sample into a solution suitable for introduction into the ICP-MS instrument.

XRF and ICP-MS:

A precisely measured 100 mg of finely ground whole rock sample (-200 mesh size) was formed into a pressed powder pellet (PPP) under approximately 200 MPa of pressure for 2 minutes, with the addition of five drops of saturated aqueous polyvinyl alcohol solution. This compressed sample pellet was utilized for major oxide analysis using X-ray fluorescence (XRF) at the Central Laboratory of the Wadia Institute of Himalayan Geology (WIHG) in Dehradun. USGS reference materials, including BCR, BCR-II, and BVRO, were employed to calibrate and validate the major oxides. The precision and accuracy for all major oxides were determined to be less than 5%. Loss on ignition (LOI) values were obtained by heating 5 grams of powdered sample in a silica crucible at 900°C for two hours. The detailed analytical procedures followed were similar to those outlined by Saini et al. (2000).

Whole rock rare earth elements (REEs) were analyzed using an Agilent 8900 ICP-MS/MS (Agilent Technologies, Santa Clara, USA) in no gas mode at the Central Laboratories of WIHG, Dehradun. The sample introduction setup included an SPS-4 auto-sampler, a micro mist nebulizer, a 12-roller peristaltic pump, and a Peltier-cooled double-pass Scott-type quartz spray chamber. Nickel cones were used for the sampler and skimmer, ensuring efficient ion transfer. High purity argon ($\geq 99.999\%$) was employed as the plasma Gas. External calibration was performed using basalt (JB-1a) and peridotite standards. A rhodium (Rh) internal blank standard of 3 ng/mL ppb was employed to monitor matrix effects and signal drift during ICP MS counting. The optimizing parameters for the ICP MS/MS are provided below the table.

Parameter	Setting	Unit
RF Power	1550	W
RF Matching	1.80	V
Sampling Depth	8.0	mm
Plasma Gas Flow Rate	15.0	L /min
Carrier Gas Flow Rate	1.06	L /min
Nebulizer Gas Flow Rate	0.99	L /min
Makeup Gas Flow Rate	0.48	L /min
Extraction Lens 1	-12.0	V
Extraction Lens 2	-250	V
Omega Bias lens	-140	V
Omega Lens	-9,6	V
Scan Mode	No gas mode	
Integration Time	1	V
Replicates	3	times
Sweep	10	times

Sample preparation

A precise amount of 100 milligrams of standard samples was placed in a 7 ml Savilex® vial for decomposition. An acid mixture consisting of HCl, HNO₃, and HF in a 1:3:6 ratio was introduced to the sample and maintained on a custom-made hot plate at 130C for 48 h. Once the solutions became clear, they were exposed for evaporation. Fluoride precipitation was observed in all samples, and fluoride residues were eliminated by adding and evaporating conc. HNO₃ twice. A transparent, clear solution was achieved by adding 3% HNO₃, free of fluoride and bulk sample residues. In some sample solutions where fluoride crystals appeared, two drops of conc. HCl was added, and the mixture was kept on the hot plate for 12 hours to remove them.

Loss on Ignition (LOI):

Loss on ignition (LOI) is a technique utilized in geochemistry to quantify the volatile substances within a sample, typically soil, sediment, or rock. To conduct this method,

one gram of finely powdered rock sample is weighed using an electronic balance under room temperature conditions. The sample is then carefully transferred into a clean and suitable crucible. Subsequently, the weighed samples are subjected to ignition within a furnace, where they are placed in an agate crucible. This process involves heating the sample to temperatures typically ranging from 550 to 900°C and maintaining it in a controlled environment for 24 hours. During this heating phase, volatile components such as water, carbon dioxide, organic matter, and sulfates are volatilized or decomposed, leaving behind the non-volatile components, such as minerals. Following the heating process, the loss in weight of the sample is measured and expressed as a percentage of the initial weight. This percentage signifies the proportion of volatile substances present in the sample before heating, thereby termed as "Loss on Ignition." The formula for calculating Loss on Ignition (LOI) as a percentage is:

$$\text{LOI (\%)} = \frac{(W_i - W_f)}{W_i} \times 100 \%$$

Where LOI (%) is the loss of ignition expressed as a percentage.

W_i refers to the initial weight of the sample prior to heating.

W_f refers to the final weight of the sample after heating.

This formula calculates the percentage of weight lost during the ignition process, representing the volatile components that were driven off or decomposed during heating.

CHAPTER-4

PETROGRAPHY

4.1 Introduction

The petrographic analysis involves a comprehensive examination and categorization of rock types using various methods, including field observations, megascopic hand-specimen analysis, microscopic thin section study, and mineral composition, texture, and structure. Ultramafic rocks in the MOC are particularly interesting to geologists and earth scientists due to their high magnesium and iron content, providing valuable insights into the Earth's mantle composition and dynamics. These rocks, formed during the planet's differentiation process, are typically found in the mantle. Some may be brought near the surface through diapiric upwelling associated with lithospheric spreading, while others may result from basaltic magma crystallization caused by partial melting of upper mantle materials during diapirism. Consequently, studying ultramafic rocks enhances our understanding of fractionation processes, origins, and tectonic settings.

4.2 Megascopic studies:

The ultramafic rocks studied in the MOC can be categorized into tectonite, cumulate, and serpentinite types (Fig.4.1), with their classification based on mineral content and degree of alteration presented in Table 4.1. Tectonite ultramafics dominate the study area, with limited cumulate samples occurring as blocks within the tectonite, often protruding from exposed ultramafic serpentinite surfaces. Tectonite ultramafic units exhibit moderate to high serpentinization with tectonic fabric. The three study locations (Kwatha, Haolenphai, and Mongjang) primarily consist of serpentinite harzburgite over lherzolite serpentinite, appearing as grayish to greenish-black units well-exposed along the Kwatha-Khudengthabi road section. Ultramafic cumulate outcrops in the area show less serpentinization and a granular texture, with an olive green to dark green color and medium to coarse grain size, which is larger compared to the tectonite ultramafic.

In hand specimens, the rocks display a greenish-black color on their altered outer surface, while the inner appearance varies based on mineral assemblages and serpentinization degree. Most primary mineral phases have been altered, leaving behind relict grains of olivine, orthopyroxene, and clinopyroxene. Tectonite ultramafic varieties generally exhibit an olive-green color, while less serpentinized ultramafic cumulates are deep green to black, medium to coarse-grained, with a conchoidal fracture, and some exhibit hob-nail texture. Brownish phenocrysts are predominantly present in hand specimens of this melanocratic rock type. These large crystals are shiny in reflected light and identified as serpentinized pyroxene grains (bastites) under microscopic examination.

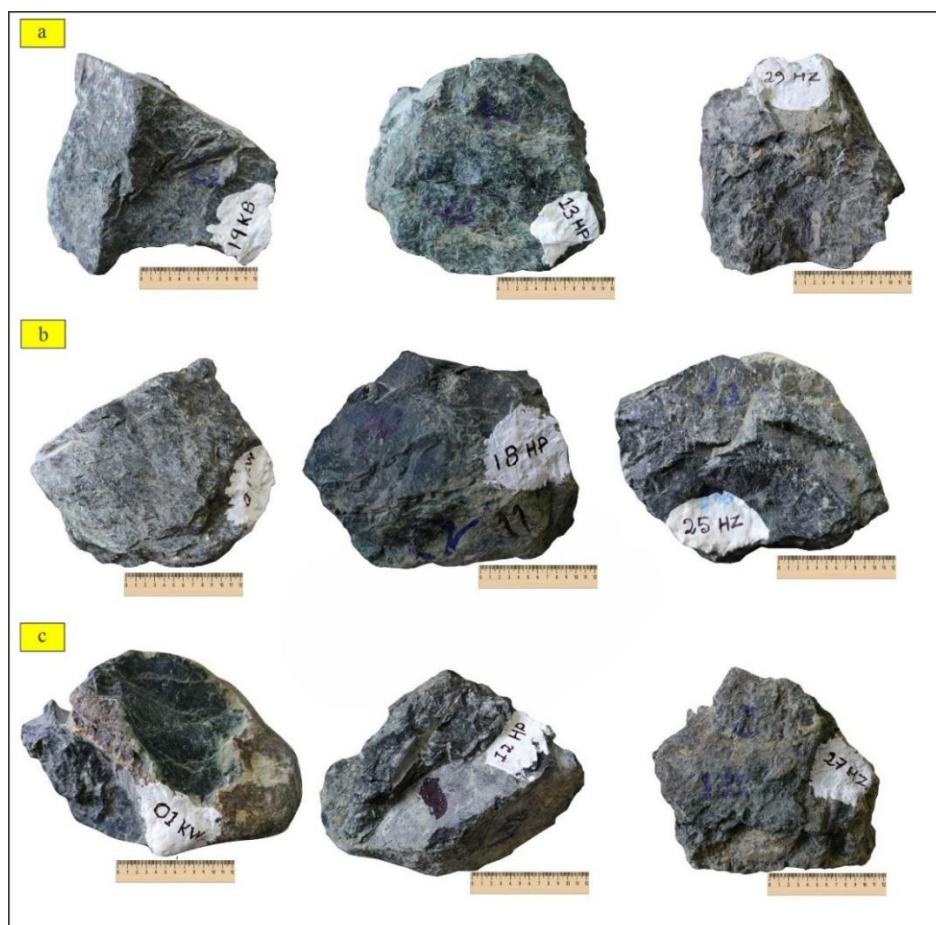


Fig 4.1. Photograph of a representative hand specimen of the studied ultramafic rocks a) Tectonite, b) cumulate, and c) serpentinite from Kwatha, Haolenphai, and Mongjang.

4.3 Microscopic studies:

The ultramafic rock samples collected from the study area have undergone various degrees of serpentinization alteration. Petrographic analysis was conducted on carefully chosen samples that exhibited relatively unaltered characteristics. The dominant rock type is harzburgite, composed of olivine and orthopyroxene with lesser lherzolite characterized by a significant proportion of olivine and clinopyroxene (Fig.4.2 a). The predominant texture observed in most samples is medium to coarse-grained porphyroclasts. These porphyroclasts serve as remnants of the initial mineral composition of orthopyroxene and clinopyroxene; less frequently, olivine is enveloped by finer grains mostly altered in nature (Fig.4.2 b).

Olivine:

Olivine, a dominant mineral component of ultramafic rock, is prominent in all the samples examined. It is the first to crystallize and is typically anhedral to slightly elongated subhedral in shape. The majority of olivine grains are medium-sized and exhibit significant fracturing. In some samples, these grains have been reduced to smaller sizes due to deformation. It's common to find smaller subhedral olivine crystals enclosed within larger pyroxene crystals (Fig.4.2 a, 4.2 b & 4.2 c). More often than not, olivine is observed to transform into serpentine. Even in some of the higher-grade serpentinite samples, remnants of olivine phenocrysts can be found within a fibrous serpentine matrix. The alteration or serpentinization process appears to have initiated from fractures and /or grain boundaries, gradually extending into the grain's interior. Characteristic olivine fractures are visible in low to medium-grade serpentine, and mesh textures are preserved in higher grades, indicating the transformation from olivine.

Orthopyroxene:

Orthopyroxene, primarily of enstatite composition, is the second most abundant mineral after olivine. It is typically found as coarse grains that are anhedral to subhedral in shape. Orthopyroxene crystals frequently contain inclusions of olivine and other opaque minerals, including spinel and magnetite (Fig.4.3 a and Fig.4.3 c). They often display fine exsolution lamellae of clinopyroxene along their cleavage

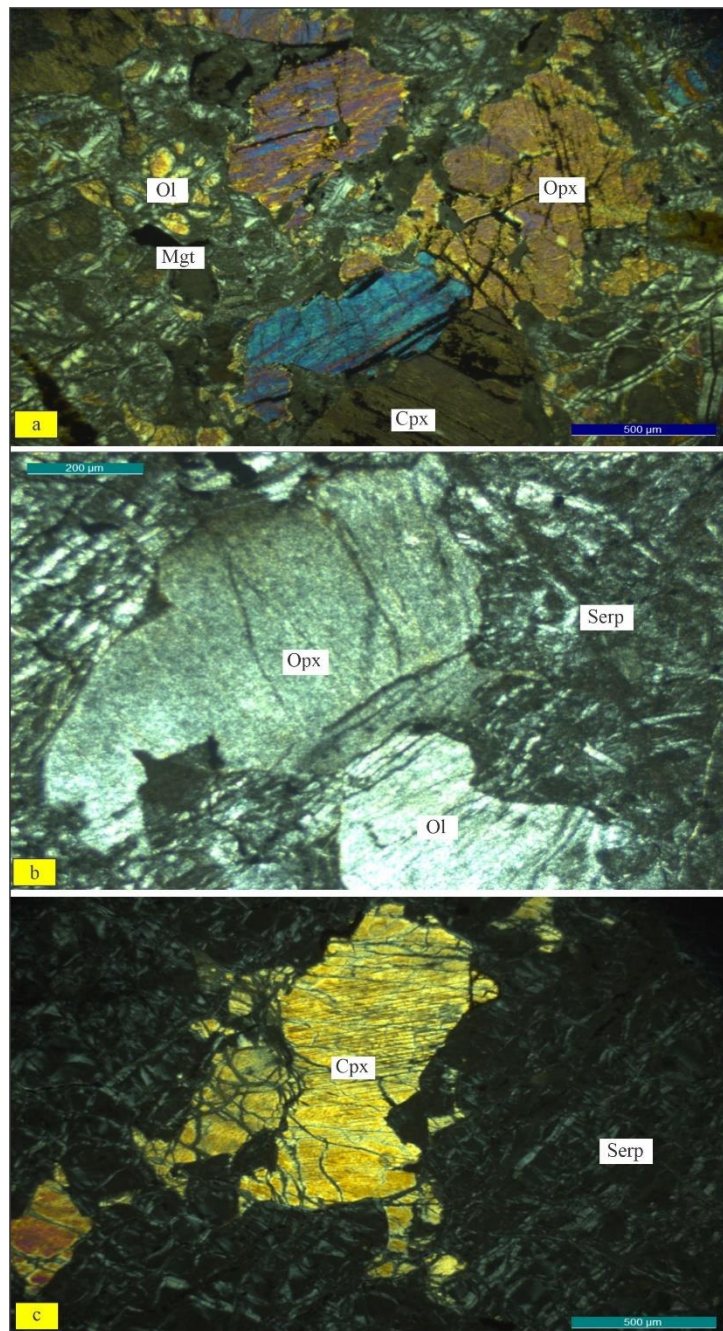


Fig 4.2. Photomicrograph showing: a) Harzburgite with the significant mineral's olivine and orthopyroxene with accessory opaque minerals in ultramafic rock under cross-polarized light, b) Porphyroblast of orthopyroxene and olivine surrounded by serpentine under cross-polarized light. and, c) Clinopyroxene crystals surrounded by serpentine grains under cross-polarized light. (Abbreviation: Ol-olivine; Opx-orthopyroxene; Cpx- clinopyroxene; Serp- serpentinite; Mgt- magnetite).

planes. Compared to olivine and clinopyroxene, orthopyroxene appears to be less susceptible to grain-size reduction and is often observed as very coarse anhedral porphyroclasts (Fig.4.3 c). The petrographic study of relatively fresh samples indicated orthopyroxene interlocks grain boundaries with olivine. It's common to observe the transformation of orthopyroxene to bastite, a pseudomorph of serpentine.

Clinopyroxene:

Clinopyroxene, primarily composed of diopside, typically appears as medium-grained anhedral to subhedral crystals. Coarse-grained clinopyroxene with a subhedral structure can occasionally be found, though it is not commonly encountered. Most inclusions within clinopyroxene are predominantly spinels and some are also in olivine (Fig.4.3 b and Fig.4.3 d). It's common to find coarse-grained pyroxene crystals intersected by veins that have undergone serpentinization.

Opaque minerals:

Opaque minerals can be observed in euhedral, subhedral, and anhedral forms. Euhedral opaque minerals typically appear as elongated crystals and exhibit a reddish-brown color when viewed under cross-polarized light. Within the fracture network of olivine grains, predominant opaque minerals include chrome-spinel and magnetite. A significant number of chrome-spinel grains show signs of alteration along fractures. This alteration of mafic minerals leads to the formation of secondary magnetites along grain boundaries and within fractures (Fig. 4.3 a, 4.3 b, & 4.3 c).

4.3.1 Ultramafic tectonite

In the area under study, it has been observed that mantle peridotites undergo significant deformation and experience varying degrees of serpentinization, ranging from partial to complete. Transitional peridotite is characterized by partially serpentinized harzburgite, which includes serpentinized olivine, chloritized orthopyroxene, and unaltered chromite (Fig. 4.2 a). The primary grains of olivine are largely serpentinized, and the coarse grains of orthopyroxene are chloritized (Fig. 4.4a). Compared to tectonites, transitional peridotites are less altered and retain remnants of orthopyroxene and a small amount of olivine. The residual orthopyroxene grains

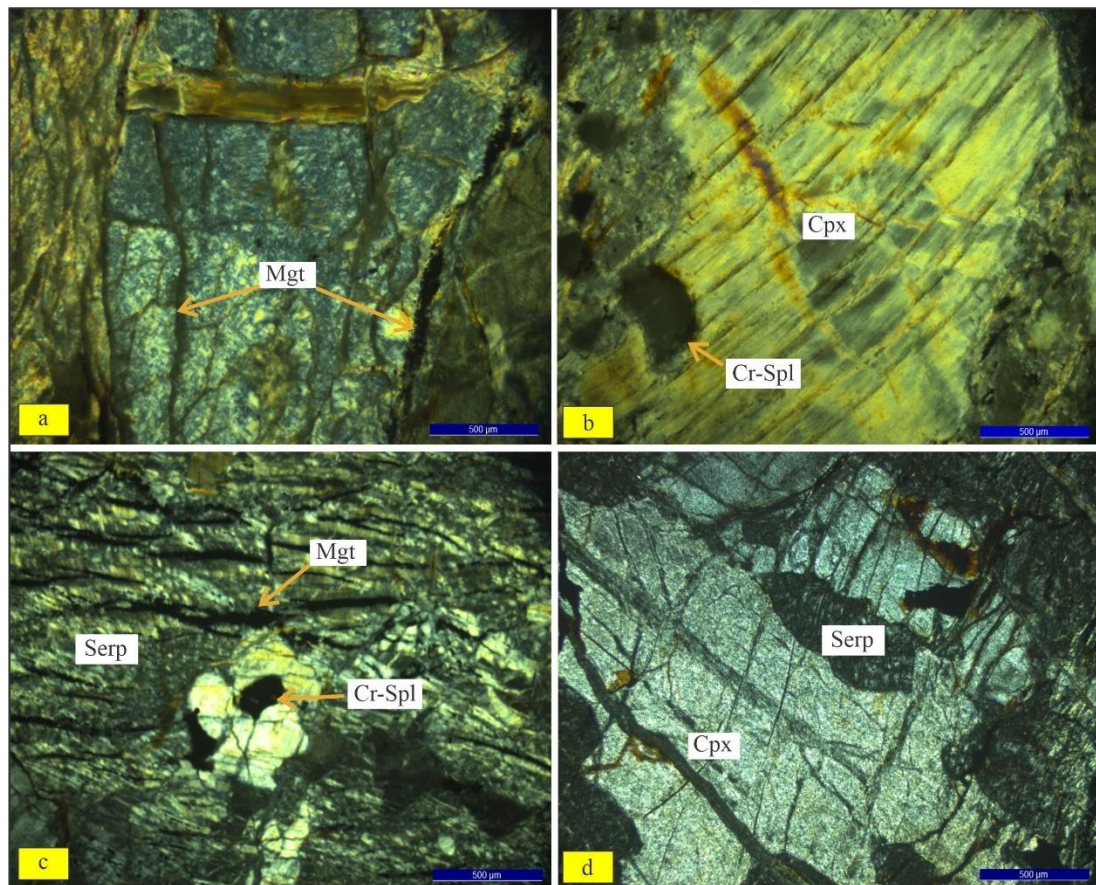


Fig.4.3. Photomicrograph showing: a) Orthopyroxene with fractures filled with magnetite under cross-polarized light, b) Clinopyroxene porphyroblast is present alongside bastite, with spinel neoblasts visible as inclusions within the clinopyroxene, c) Chrome-spinel relics are inclusions in orthopyroxene, with fractures filled by magnetite minerals in serpentinite ultramafic rock, d) Olivine serpentine enclosed within clinopyroxene in ultramafic rocks under cross-polarized light. (Abbreviation: Ol-olivine; Opx-orthopyroxene; Cpx-clinopyroxene; Serp-serpentinite; Cr-Spl. - Chrome Spinel; Mgt- Magnetite).

exhibit embayment and are partially replaced by relatively fresh and smaller grains of olivine. In contrast, the harzburgitic tectonite in the studied area, characterized by a greenish-yellow color, has undergone extensive serpentinization. This process results in a complex, interlocking serpentine texture, giving the rock a greenish, greyish, and oily appearance. This texture includes occasional remnants of pseudomorphic olivine

and large grains of orthopyroxene that have been chloritized. The abundance of olivine and orthopyroxene minerals in the rock varies according to the degree of serpentinization and the development of porphyroclastic and granoblastic textures in the peridotites. The transformation of olivine minerals into serpentine occurs due to water infiltration. Orthopyroxene porphyroclasts are found within a matrix of olivine remnants and serpentine minerals (Fig. 4.4 b). The porphyroclastic texture and deformation features, including undulatory extinction, strain lamellae, and kink structure, indicate that the rocks are tectonites. Additionally, both clinopyroxene and orthopyroxene porphyroclasts exhibit kink bands and undulatory extinction (Fig.4.4 a & Fig.4.5 a). Grains or clusters of Cr-spinel have an irregular, amoeboid, or vermiform shape, characterized by blocky segments with protruding arms. Cr-spinel commonly occurs in association with enstatite and typically displays a translucent, brownish-yellow color (Fig.4.6 c). Moreover, tectonites contain a higher abundance of spinels compared to peridotites that form in stratified sequences. The distinguishing features of these tectonites include the presence of spinel and the lack of plagioclase, suggesting their origin from mantle sources deeper than the stability limit of plagioclase. While spinels typically exhibit an octahedral shape, they can also appear in lensoid or equidimensional forms (Fig. 4.5 d).

In some areas, orthopyroxene grains encircled by olivine and clinopyroxene grains have been altered to greenish chlorite in serpentinized harzburgite (Fig.4.5 c). Enstatite can be found both as isolated grains and in clusters, with their shapes varying from equant and rectangular to highly elongated and irregular. The largest grains measure 2-3 mm in width and the largest grains measure 2-3 mm in width and contain narrow lamellae of exsolved diopside (Fig 4.6 a). In addition to the exsolution

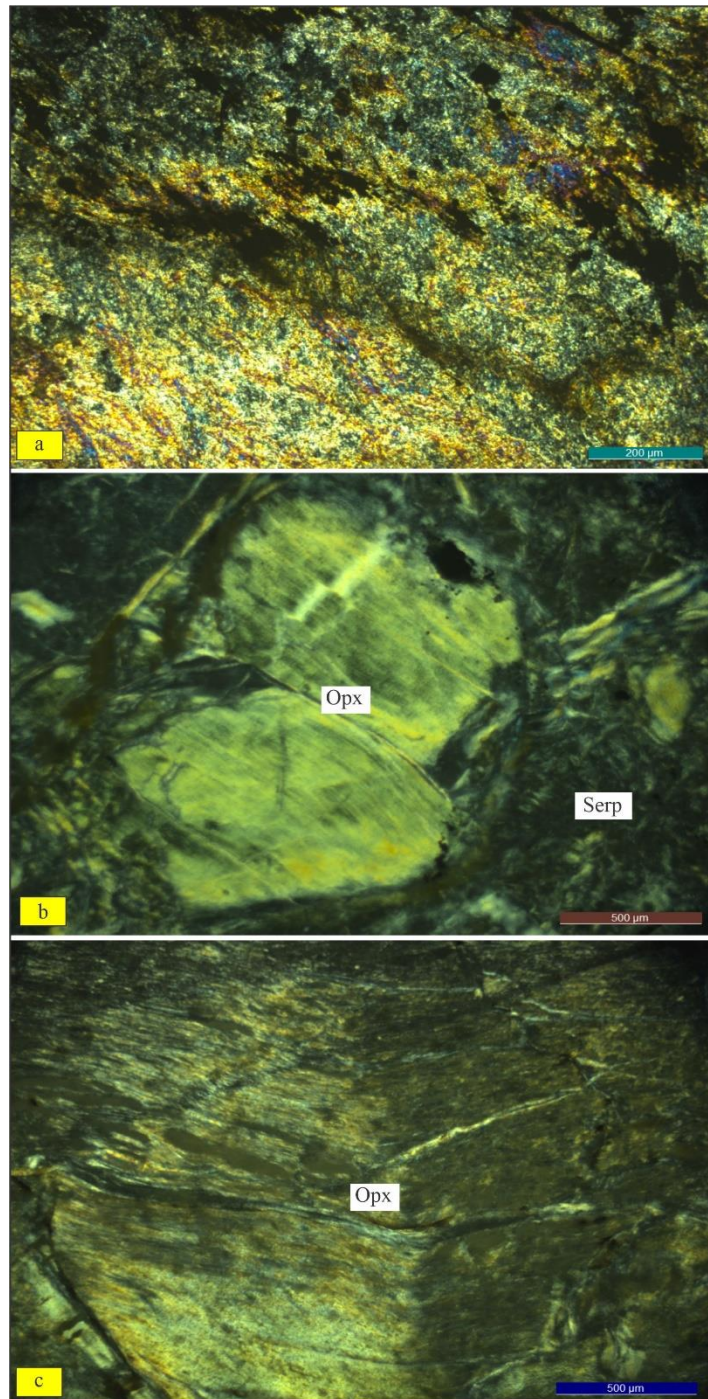


Fig.4.4. Photomicrograph showing: a) Serpentine mineral with alteration of Olivine and pyroxene under cross-polarized light, b) orthopyroxene porphyroclasts in ultramafic peridotites under cross-polarized light, and c) Kink banding in Orthopyroxene under cross-polarized light. (Abbreviation: Ol-olivine; Opx-orthopyroxene; Cpx-clinopyroxene; Mgt-magnetite).

lamellae within enstatite, diopside also appears as separate grains in most samples. These grains are angular, crystalline, completely unaltered, and exhibit diallage parting, likely indicating they are fragments of larger pre-existing grains (Fig.4.5 b). In lherzolitic peridotite, clusters of diopside grains can occasionally be found alongside enstatite grains. Diopside shows fewer deformation effects compared to olivine and enstatite, with kinking being rare. However, bent diopside grains are relatively common in these peridotites.

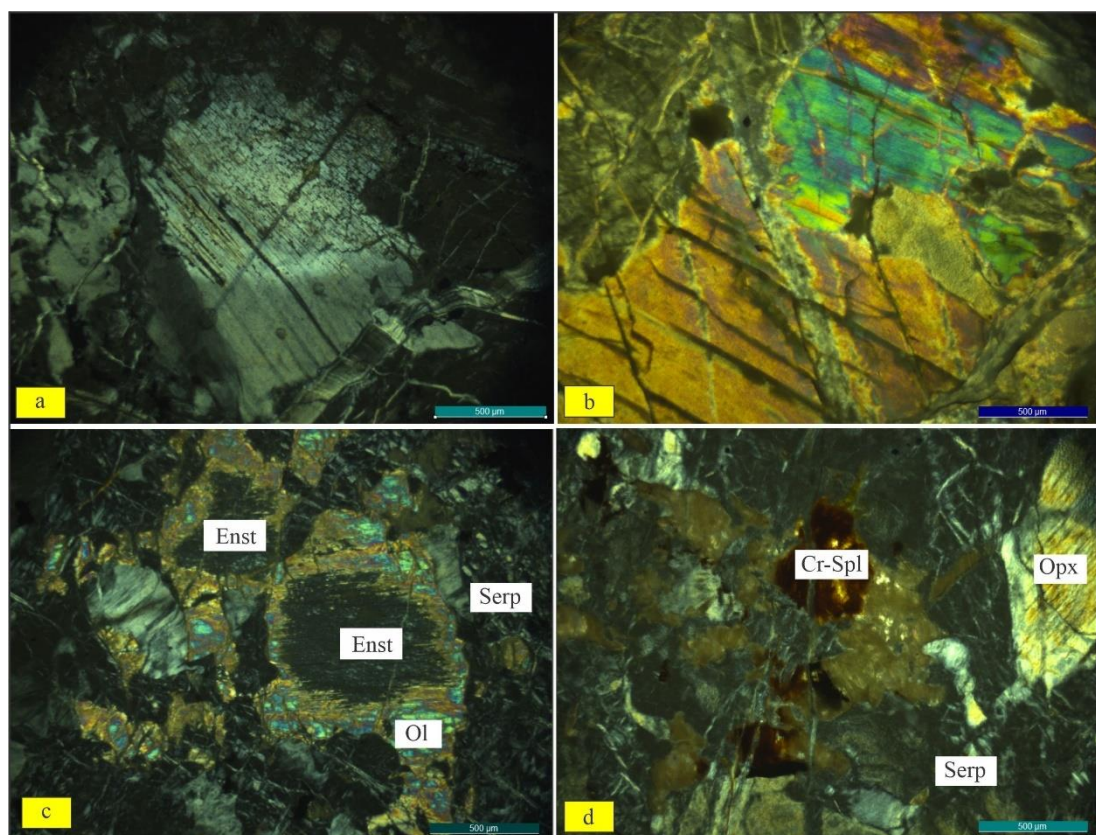


Fig.4.5. Photomicrograph showing: a) Kink banding in olivine crystals and showing undulatory extinction in Ultramafic rocks b) Ubiquitous exsolution lamellae in pyroxene relics, c) An enstatite porphyroblast surrounded by shells of olivine and serpentine minerals in a highly serpentinized harzburgite, d) Spinel harzburgite consisting of opx, cpx, and serpentinized olivine. (Abbreviation: Ol-olivine; Opx-orthopyroxene; Cpx- clinopyroxene; Enst-Enstatite; Serp-serpentinite; Cr-Spl-Chrome spinel).

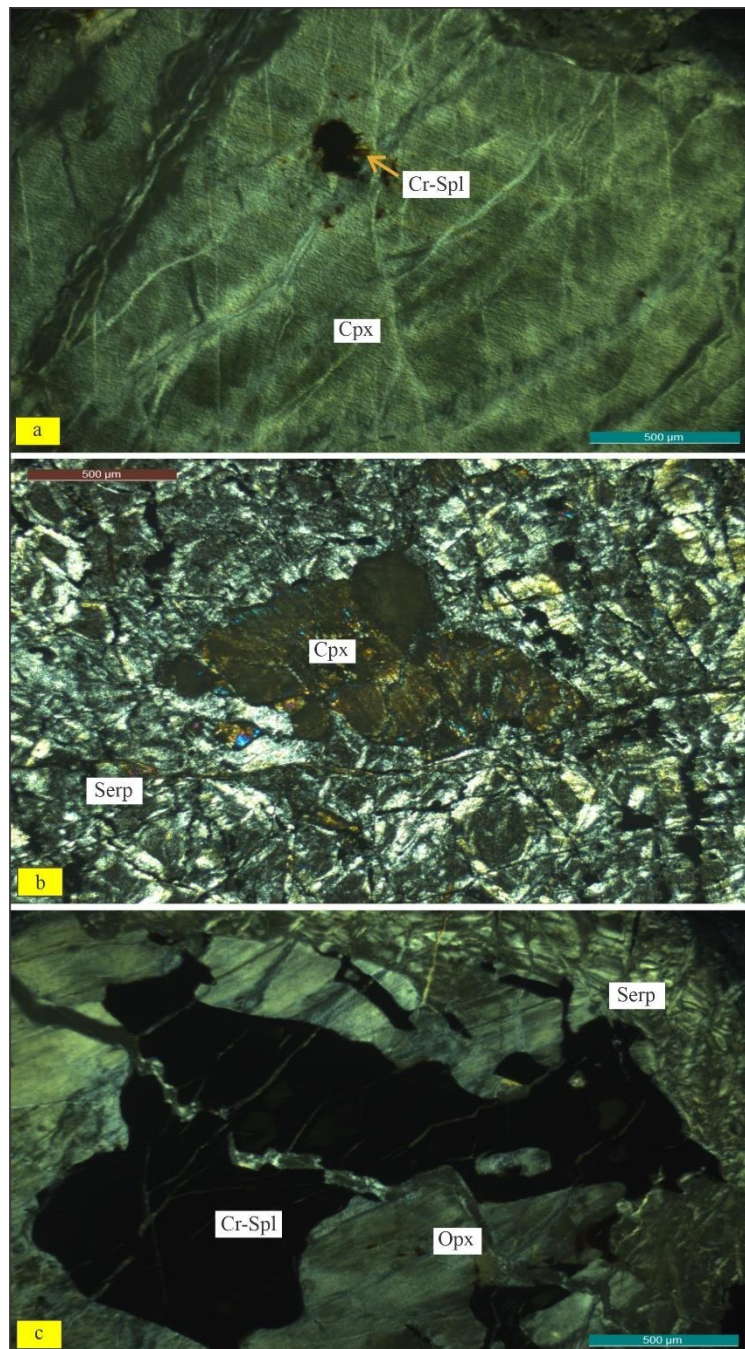


Fig.4.6. Photomicrograph showing: a) Clinopyroxene occurs as large anhedra crystals with smaller exsolutions of Cr-spinel b) Relict clinopyroxene surrounded by serpentine c) Partially eroded orthopyroxene minerals are found alongside spinel and orthopyroxene that are intergrown within serpentinized peridotite. (Abbreviations: Cr-spl-chrome spinel, Cpx- clinopyroxene, Opx- orthopyroxene, serp- serpentinite)

4.3.2 Ultramafic cumulate:

The ultramafic cumulate exhibits a protogranular texture, characterized by a medium to coarse grain size (Fig.4.7 a). The crystals display tabular and smoothly curved forms, with grain sizes ranging from coarse to fine. Notably, there are no observable signs of foliation, lineation, or strain effects within these ultramafic peridotites. The majority of the chrome spinels are subhedral to anhedral, with some exhibiting skeletal and occasionally octahedral shapes. Spinel commonly fills irregularly dispersed cracks found within olivine and along the edges of grains. These structural changes facilitate the formation of serpentine, which often occupies the spaces between the olivine, larger pyroxene, and spinel grains.

While orthopyroxene can contain inclusions of spinel and olivine, poikilitic clinopyroxene is observed to enclose both orthopyroxene and olivine within harzburgite (Fig. 4.7 b). Despite these complex mineral interactions, there are no signs of strain shadows or kink banding in the olivine or pyroxene phases within the cumulate peridotite. From a petrographic perspective, the mineral phases present in the ultramafic cumulate include serpentine, olivine, orthopyroxene, clinopyroxene, and spinel. The boundaries between the olivine, pyroxene, and spinel grains are commonly filled with serpentine as a result of alteration processes, though these minerals retain an interlocking texture.

In some areas, magnetite veins are found filling the conchoidal fractures within the olivine, further highlighting the alteration history of the sample. Another notable feature in the peridotite is the presence of orthopyroxene lamellae, which have been partially dissolved into clinopyroxene, contributing to the overall complexity of the texture (Fig.4.7 c). This dissolution process, along with the serpentine alteration and vein formations, reflects the dynamic and evolving nature of the ultramafic cumulate during its geological processes.

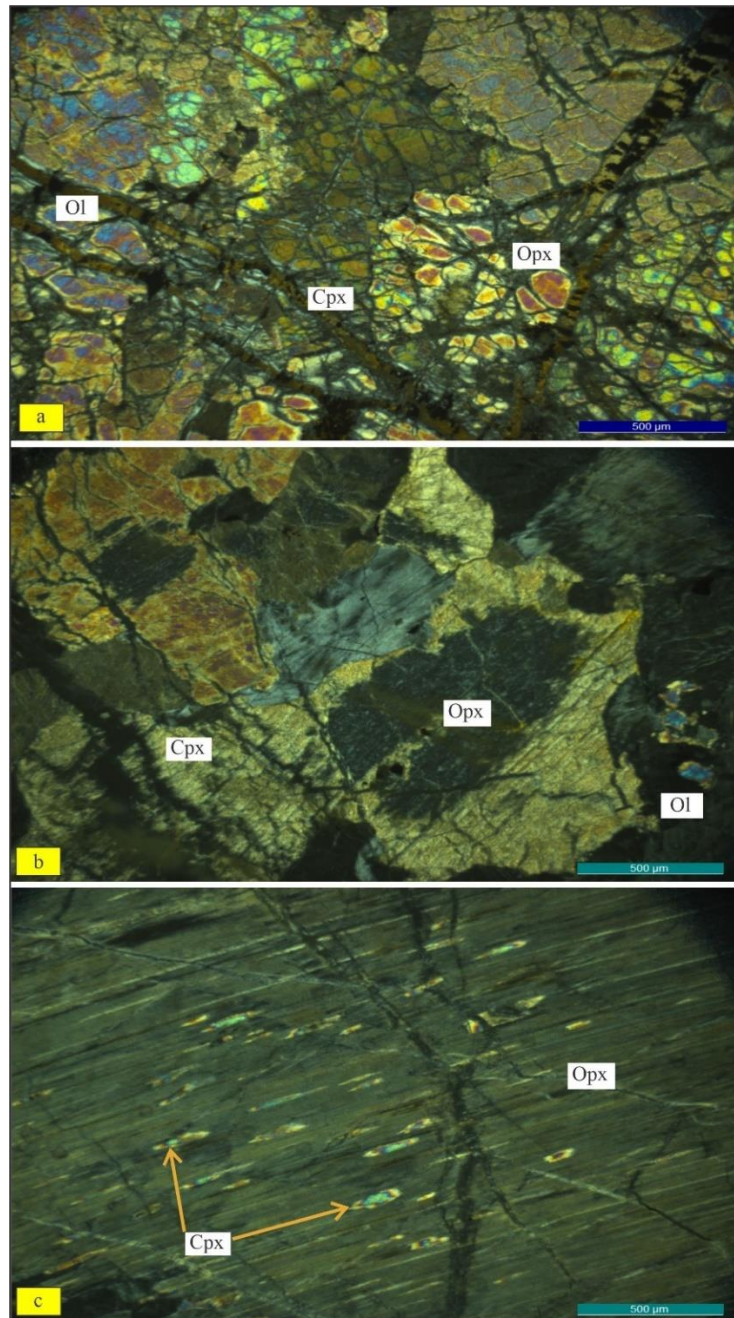


Fig.4.7. Photomicrograph showing: a) cumulative ultramafic rocks from the study area displayed harzburgite with highly fractured olivine and cross-cutting magnetite vein under crossed polarized light, b) Poikilitic clinopyroxene in harzburgite containing inclusions of orthopyroxene and olivine, and c) Orthopyroxene exsolved clinopyroxene lamellae in ultramafic rocks under cross-polarising light. (Abbreviation: Ol-olivine; Opx-orthopyroxene; Cpx- clinopyroxene).

4.3.3 Serpentine

The serpentinite in the studied area exhibits medium- to coarse-grained textures, transitioning from mosaic to porphyroclastic structures. The primary minerals that contribute significantly to serpentine formation through hydration are olivine and pyroxene which occur as relics surrounded by serpentine in ultramafic rocks (Fig.4.8 b). These rocks contain olivine crystals and varying amounts of orthopyroxene and clinopyroxene, accompanied by subordinate chromite and magnetite (Fig. 4.8a). Additionally, secondary minerals such as lizardite, chrysotile, carbonates, talc, chlorite, and magnesite are present. Chromite occurs as dispersed subhedral crystals with cusped boundaries, while lizardite has replaced olivine and orthopyroxene. Chrysotile veins intersect olivine and pyroxene crystals, and altered pyroxene forms bastite minerals within the serpentinitized groundmass.

The serpentinite in the study area can be categorized into two main types: massive serpentinite and sheared serpentinite. The massive serpentinites are fine- to medium-grained granoblastic textures characterized by a distinctive dark-greenish appearance and a soapy texture. It predominantly consists of minerals such as Lizardite, chrysotile, and antigorite, along with lesser amounts of magnetite, chromite, magnesite, talc, tremolite, and chlorite. Lizardite serpentinite forms through retrograde metamorphism, replacing minerals like olivine and orthopyroxene (enstatite). This replacement process leads to the formation of various textures, including mesh and hourglass textures (Fig.4.8 c & Fig.4.8 d). The presence of a mesh texture often indicates that lizardite has replaced other serpentine minerals, resulting in greenish-colored rocks. These lizardite features can be observed in different forms, including flat, tabular crystals found within veins and throughout the matrix.

Some lizardites within the mesh rims exhibit a fibrous structure. In the mesh textures, elongated lizardite crystals with triangular apices are oriented toward the center of the mesh. Notably, lizardite in the central regions of the mesh patterns tends to be finer-grained and less well-crystallized compared to lizardite in the mesh rims. An hourglass texture, eliminating the distinction between the mesh rim and the mesh center. this

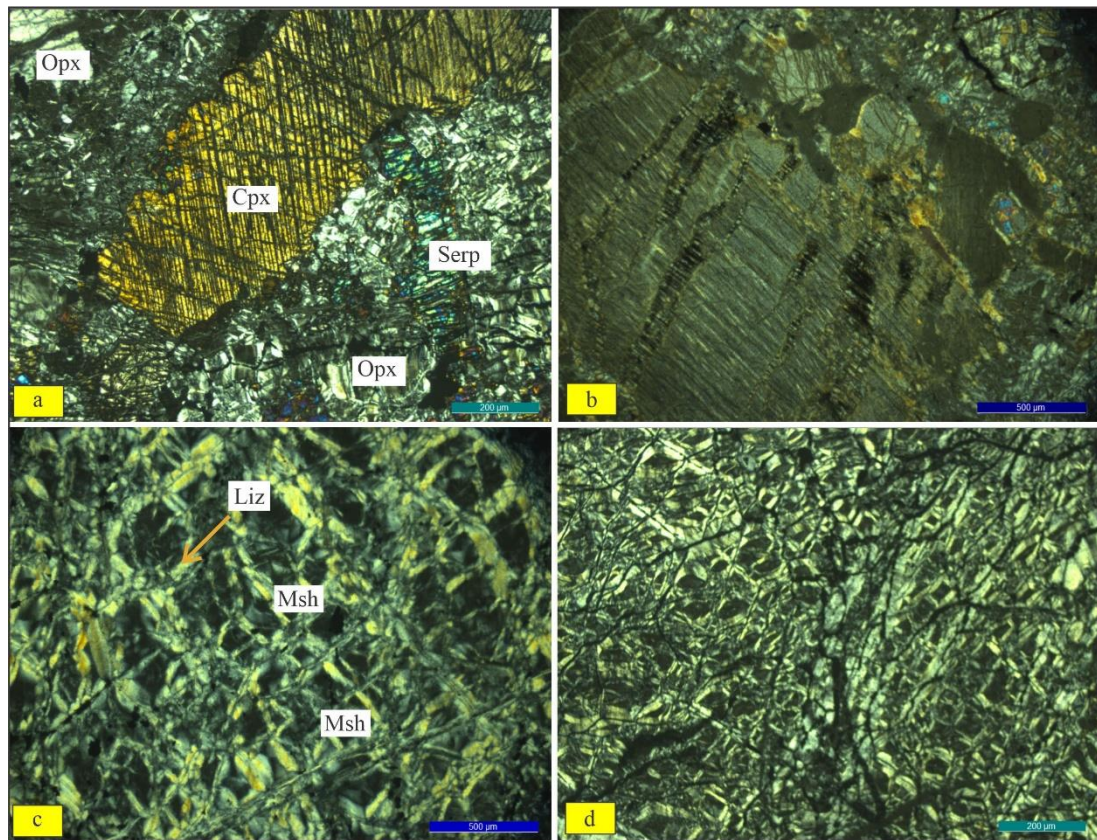


Fig. 4.8. Photomicrograph showing: a) Large porphyroclastic grains of diopside and bastite in a groundmass formed by olivine and serpentine minerals. b) Serpentinite with pyroxene relics. c) Mesh texture, which is developed after olivine, d) Hourglass texture. (Abbreviation: Opx- orthopyroxene; Cpx- clinopyroxene; Serp- serpentine Msh- mesh; Liz- lizardite).

texture exhibits sweeping extinction when the microscope stage is rotated. Chrysotile is primarily composed of chrysotile, with the main accessory minerals being magnetite and chromite. It is present in the form of cross-fibrous veinlets that traverse the initially formed serpentine mesh texture, suggesting that it crystallized at a later stage under stable conditions. Chrysotile veins commonly intersect bastites, and in certain samples, chrysotile entirely replaces the lizardite bastite (Fig.4.9 a and Fig.4.9 b). Antigorite is exceptionally rare within the study area and is observed as interpenetrative plates, veins, or aggregates with a fine-lamellar structure. The sheared serpentinite exhibits a composition characterized by serpentine blades with

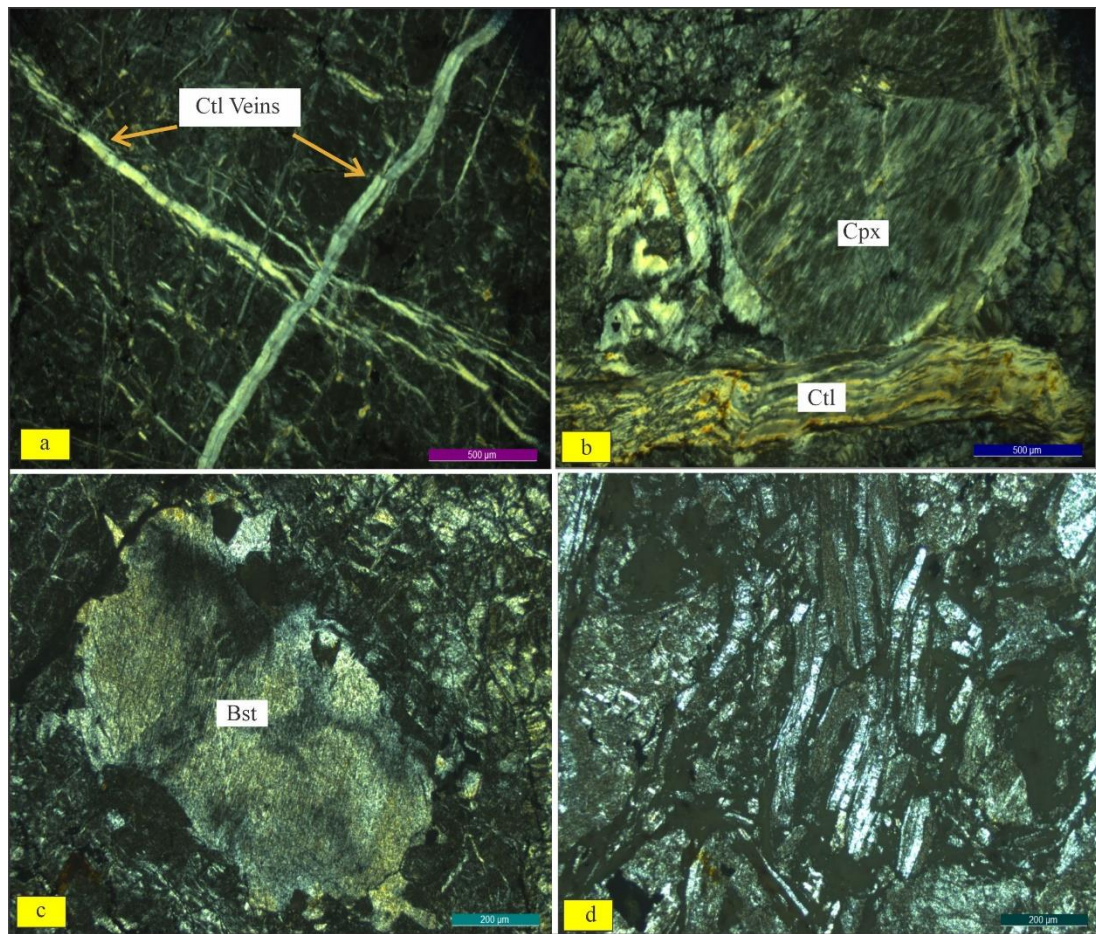


Fig. 4.9. Photomicrograph showing: a) Fibrous chrysotile veins observed in serpentinitized ultramafic rocks under cross-polarising light b) Chrysotile occurring together with clinopyroxene in serpentinitized ultramafic rocks c) Bastite texture-pseudomorphs of serpentine after orthopyroxene d) Fibrous ribbons of serpentine in serpentinite. (Abbreviation: Cpx- clinopyroxene; Ctl-chrysotile; Bst-bastite).

interpenetrating textures. Within the rock, there are indications of preserved orthopyroxene. Additionally, the rock is intersected by veins containing magnetite, which is associated with thinly recrystallized minerals. Abundant bastite is evident, hinting at the possibility that the original rock, or protolith, was either a harzburgite or pyroxenite (Fig. 4.9c). In some bastite sections, rare exsolution lamellae of clinopyroxene (Cpx) are also preserved. The majority of clinopyroxene grains exhibit fractures, suggesting the possibility of significant shearing within the rock.

Orthopyroxenes (opx) are predominantly composed of enstatite and bronzite. The presence of bent lamellae and undulose extinction in these minerals suggests that they have undergone deformation due to strain. Also, a kink band texture is observable in both opx and cpx minerals. It can be observed the transformation of remnants of olivine and orthopyroxene into a greenish color, is characterized by the presence of chlorite and talc. Talc-carbonates are evident as alteration byproducts of serpentine minerals that occur as finely-grained clusters or patches and occasionally appear in micro veinlet-like structures. In retrograde serpentinite, the dominant deformation mechanisms of pressure solution and frictional sliding lead to the development of ribbon texture (Fig.4.9 d). The ribbons consist of the mineral chrysotile and lizardite, which aligns with strong crystallographic and shape-preferred orientations often appearing shiny. Folding in serpentinite is characterized by the accumulation of spinel along the axis of the fold and the presence of crenulation cleavages (Fig.4.10 a & Fig.4.10 b). The serpentinite that has undergone significant shearing and foliation contains talc and tremolite. In extreme cases, this can lead to the development of mylonitic tectonic breccia.

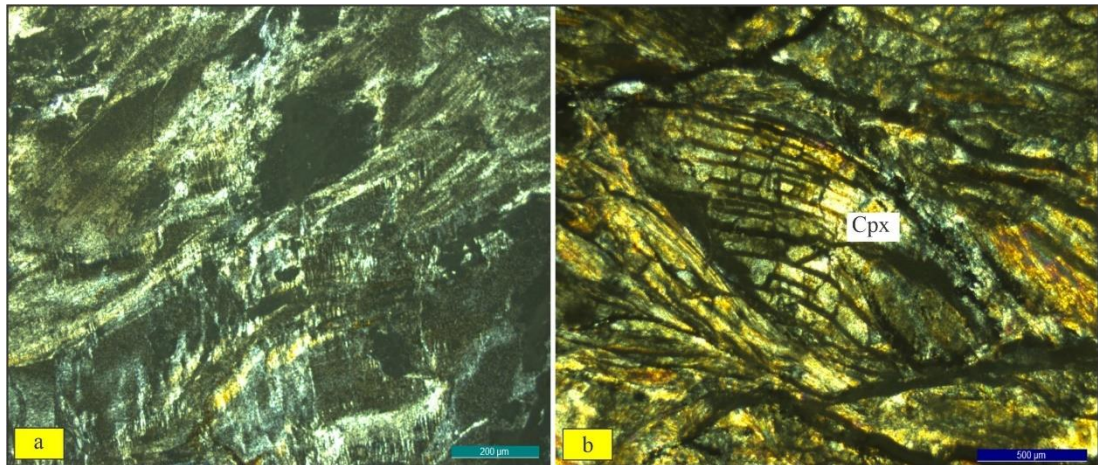


Fig.4.10. Photomicrograph showing: a) Folding in serpentinite is characterized by the alignment of spinel minerals along the fold axes and the presence of crenulation cleavage, and b) Bend and crenulated serpentinite minerals due to thrusting.

Table: 4.1: Petrographic characteristics along with latitude and longitude of each rock of the studied ultramafic rocks.

	Sample	Lat/Long	Rock types	Mineralogy	Degree of alteration	Name of rocks
KWATHA-KHUDENGTHABI	01KW	E94°16' 20" N24°19' 08.3"	Ultramafic cumulate	Cpx, olivine, opx, serpentine, and opaque minerals.	Moderate	Serpentinite lherzolite
	02KW	E94°16' 24.7" N24°19' 04.8'	Ultramafic tectonite	Opx, cpx, olivine, magnetite and serpentine	Moderate	Serpentinite harzburgite
	03 KW	E94°16' 25.0" N24°19' 02.4"	Serpentinite	Relicts of opx, cpx, olivine, chromite, and magnetite	Moderate	Serpentinite harzburgite
	04 KW	E94°16' 17.5" N24°19' 03.1"	Serpentinite	Cpx, opx, olivine, magnetite, serpentine	Moderate	Serpentinite harzburgite
	05 KW	E94°16' 31.2" N24°19' 00"	Ultramafic tectonite	Opx, bastite, and serpentine	Moderate	Serpentinite harzburgite
	06 KW	E94°16' 09.4" N24°18' 37.8"	Serpentinite	Cpx, opx and serpentine	Moderate	Serpentinite harzburgite
	07 KW	E94°16' 07.3" N24°18' 37.2"	Ultramafic tectonite	Relicts of Olivine, pyroxene, serpentine	Moderate	Serpentinite harzburgite
	19KB	E94°16'16.68" N24°17'47.04"	Serpentinite	Relicts of opx, cpx, olivine and opaque minerals	Moderate	Serpentinite harzburgite

	20KB	E94°16'41.44" N24°17'40.42"	Ultramafic tectonite	Relicts of opx, cpx, olivine and magnetite	Moderate	Serpentinite harzburgite
	21KB	E94°16'40.32" N24°17'41.46"	Ultramafic tectonite	Opx, cpx, olivine and serpentine	High	Serpentinite harzburgite
	22KB	E94°16' 35.4" N24°17'39.48"	Serpentinite	Opx, cpx, magnetite and serpentine	High	Serpentinite harzburgite
HAOLENPHAI	23KB	E94°16'30.36" N24°17'36.88"	Serpentinite	Relicts of opx, cpx, olivine, cr-spinel, magnetite and serpentine	Moderate	Serpentinite harzburgite
	08HP	E94°17'4.308" N24°12'57.38"	Ultramafic tectonite	Relicts of opx, cpx, olivine, serpentinite, chrome-spinel	Moderate	Serpentinite harzburgite
	09 HP	E94°16'52.78" N24°12'41.74"	Serpentinite	Relicts of Olivine, magnetite, orthopyroxene, serpentine	Moderate	Serpentinite harzburgite
	10 HP	E94°16'59.7" N24°12'52.96"	Ultramafic tectonite	Opx, olivine, serpentinite, and opaque minerals	Moderate	Serpentinite harzburgite
	11 HP	E94°16'58.38" N24°12'55.62"	Serpentinite	Relicts of opx, magnetite and serpentine	Moderate	Serpentinite harzburgite
	12 HP	E94°17' 0.78" N24°12'55.86"	Ultramafic cumulate	Opx, Cpx, olivine, Magnetite, serpentine and opaque minerals	Moderate	Peridotite

	13 HP	E94°16'58.98" N24°13' 8.04"	Ultramafic tectonite	Relicts of opx, cpx, olivine, serpentine and opaque minerals	Moderate	Serpentinite harzburgite
	14 HP	E94°16'6.996" N24°13'13.18"	Serpentinite	Relicts of opx, olivine, cpx, serpentinite	High	Serpentinite harzburgite
	15 HP	E94°16'13.46" N24°13'19.18"	Serpentinite	Relicts of opx, olivine, cpx and serpentine	Moderate	Serpentinite harzburgite
	16 HP	E94°16'29.12" N24°13'18.16"	Ultramafic tectonite	Opx, olivine, serpentine, and opaque minerals	Moderate	Serpentinite harzburgite
	17 HP	E94°16'40.58" N24°13'19.48"	Serpentinite	Relicts of olivine, opx, cpx, magnetite	Moderate	Serpentinite harzburgite
	18 HP	E94°16'50.48" N24°13'17.42"	Serpentinite	Relicts of olivine and pyroxene, serpentine	Very high	Serpentinite harzburgite
MONGJANG	24HZ	E94°16'19.42" N24°16'11.64"	Ultramafic tectonite	Relicts of Opx, cpx, olivine, serpentinite and opaque minerals	Moderate	Serpentinite harzburgite
	25HZ	E94°16'23.42" N24°16'11.28"	Ultramafic tectonite	Relicts of olivine, opx, cpx, and opaque minerals	High	Serpentinite harzburgite
	26HZ	E94°16'29.24" N24°16'5.772"	Serpentinite	Relict of cpx, opx, olivine, and serpentinite	High	Serpentinite harzburgite
	27HZ	E94°16'28.46"	Ultramafic	Olivine, opx, cpx and opaque minerals	Moderate	Serpentinite harzburgite

		N24°16'11.28"	cumulate			
	28HZ	E94°16'31.296' ' N24°16'6.168"	Ultramafic cumulate	Relicts of olivine, opx, cpx and serpentine	Low	Serpentinite lherzolite
	29HZ	E94°16'33.04" N24°16' 1.02"	Ultramafic cumulate	Olivine, opx, cpx, serpeninite and opaque minerals	Moderate	Serpentinite harzburgite

4.4 XRD Investigation

Eleven (11) representative samples of serpentinized ultramafic rocks were analyzed by Empyrean PANalytical at SAIF, Gauhati University, Guwahati. The indexing of the samples was performed using PANalytical Data Collector and HighScore Plus and compared with the PDF-2 database of ICDD. The characterized d-values (Å) calculated from the diffractograms are presented in the table. X-ray diffraction (XRD) analysis not only confirmed minerals identified through microscopy but also detected new minerals not visible under the microscope. The identified minerals and their corresponding d-values are listed below in Table 3.2.1 and illustrated in Figure 3.2.1.

Serpentine: XRD analysis identifies all three polymorphs of serpentine: lizardite, chrysotile, and antigorite. Lizardite is colorless to pale green, fine-grained, and exhibits parallel extinction. It is confirmed by a d-value of 7.30 Å, 7.26 Å, 7.24 Å, 7.20 Å, and 2.50 Å. Chrysotile is also colorless, fibrous, and has low relief with parallel extinction. It is confirmed by d-values of 4.56 Å. Orthochrysotile and Clinochrysotile are the polymorphs of chrysotile, which were confirmed by the XRD d-value of 7.32 Å, 7.24 Å of Orthochrysotile and 4.57 Å 4.55 Å, and 1.53 Å of Clinochrysotile.

Antigorite shows a colorless to pale green, anhedral or aggregate fibro-lamellar structure with low relief and straight extinction, confirmed by a d-value of 3.61 Å.

Olivine: This mineral appears in shades ranging from greenish to bluish and has a high refractive index. Olivine is often fractured and filled with serpentine. XRD confirms its presence at d-values of 4.45 Å, 2.50 Å, and 2.44 Å.

Enstatite/Bronzite: Identified by prismatic crystals and parallel extinction, enstatite and bronzite are confirmed by d-values of 3.18 Å and 2.87 Å.

Diopside: Diopside is typically colorless to pale green. It shows weak pleochroism, usually from colorless to pale green. It often appears as elongated prismatic or columnar crystals, and the extinction angle in diopside is typically Inclined. It was confirmed by the d-values of 2.97 Å and 2.95 Å.

Chlorite: Exhibits a greenish color with parallel extinction and a medium refractive index. The mineral is confirmed by d-values of 3.50 Å and 2.50 Å.

Talc: Although not visible under the microscope, talc is confirmed by XRD at d-values of 4.55 Å and 2.49 Å.

Chromite: Chromite appears as opaque to sub-opaque grains. Under reflected light and Cross-Polarized Light, it can show a metallic luster and is typically black or very dark brown. The presence is confirmed by d-values of 2.51 Å.

Magnetite: Magnetite grains are opaque and appear as black spots scattered throughout the section and under crossed polars, magnetite grains remain opaque. The presence is confirmed by the XRD at d-values 2.521 Å and 2.14 Å

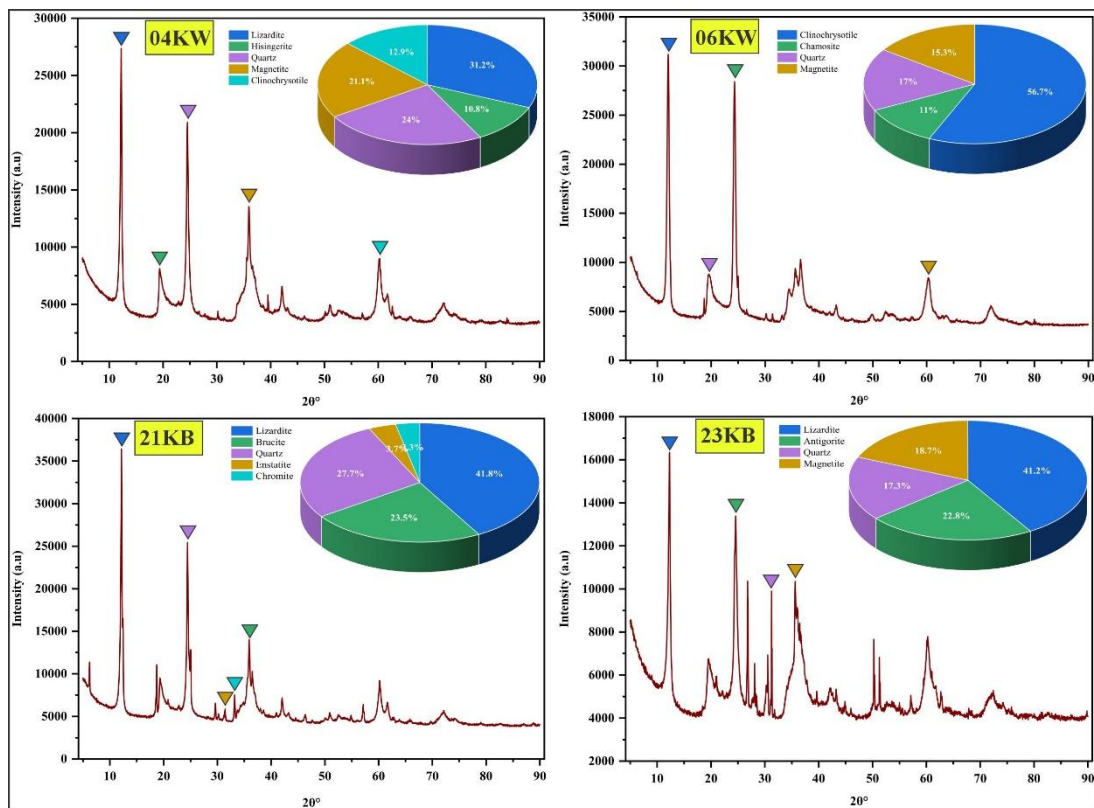


Fig.4.11: X-ray diffraction patterns for the studied serpentinized ultramafic rock samples (Kwatha-Khudengthabi Section) from the ICDD PDF-2 database.

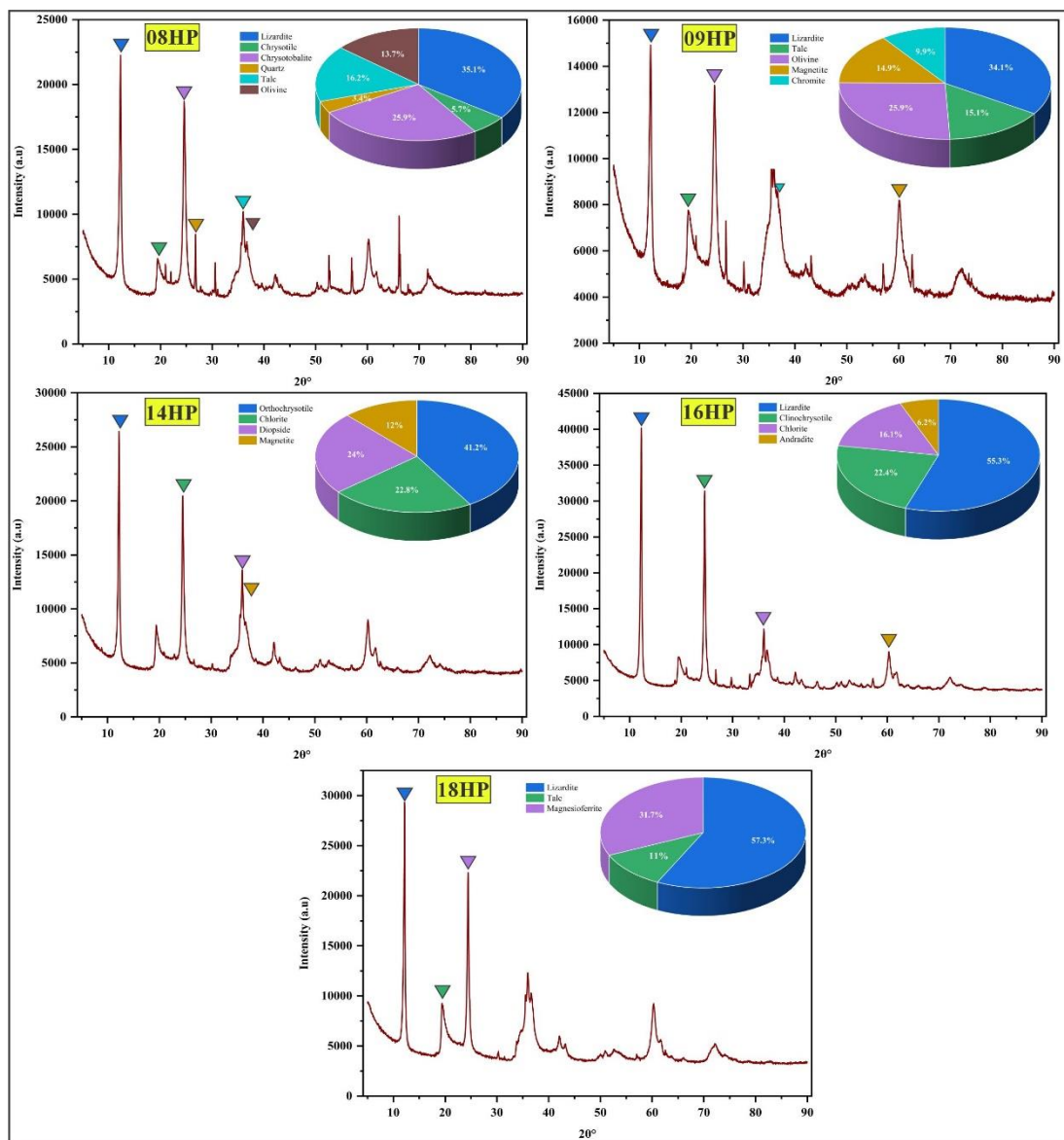


Fig.4.12. X-ray diffraction patterns for the studied serpentized ultramafic rock samples (Haolenphai Section) from the ICDD PDF-2 database.

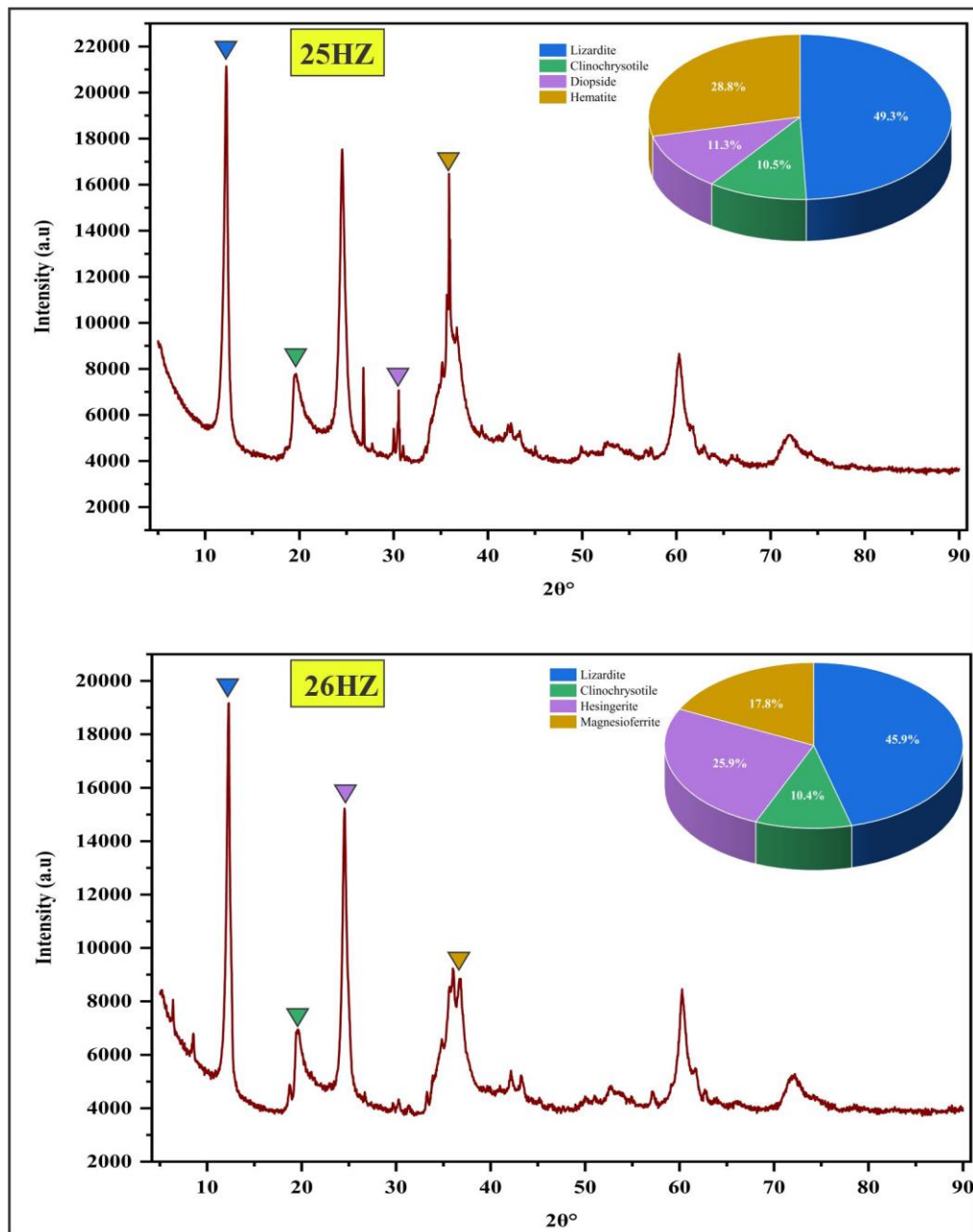


Fig. 4.13: X-ray diffraction patterns for the studied serpentized ultramafic rock samples (Mongjang) from the ICDD PDF-2 database.

Table 4.2: X-ray diffraction data for serpentinized ultramafic rocks.

Sample Sl.No	04KW	06KW	21KB	23KB	08HP	09HP	14HP	16HP	18HP	25HZ	26HZ	Remark
1	-	7.32	-	-	-	-	-	-	-	-	-	Clinochrysotile
2	-	-	-	-	-	7.30	-	-	-	-	-	Lizardite
3	-	-	-	-	-	7.26	-	-	-	-	-	Lizardite
4	7.24	-	7.24	-	7.24	7.24	-	-	-	-	7.24	Lizardite
5	-	-	-	-	-	-	7.24	-	-	-	-	Orthochrysotile
6	-	-	-	7.20	-	-	-	7.20	-	7.20	-	Lizardite
7	4.59	-	-	-	-	-	-	-	-	-	-	Hisingerite
8	-	-	-	-	-	-	-	-	-	4.57	-	Clinochrysotile
9	-	-	-	-	-	-	-	-	-	4.57	-	Clinochlore
10	-	-	-	-	4.56	-	-	-	-	-	-	Chrysotile
11	4.55	-	-	-	-	-	-	4.55	-	-	4.55	Clinochrysotile
12	-	-	-	-	-	4.55	-	-	4.55	-	-	Talc
13	-	-	-	-	-	4.45	-	-	-	4.45	-	Olivine
14	-	-	-	-	4.03	-	-	-	-	-	-	Chrysotobalite
15	-	-	-	3.61	3.61	-	-	-	-	-	-	Antigorite
16	-	3.55	-	-	-	-	3.55	-	-	-	-	Chamosite
17	-	-	-	-	-	-	-	3.50	-	-	-	Chlorite
18	3.34	3.34	3.34	3.34	3.34	-	-	-	-	-	-	Quartz
19	-	-	-	3.18	-	-	-	-	-	-	-	Enstatite
20	-	-	-	3.17	-	-	-	-	-	-	-	Albite
21	-	-	-	-	-	-	-	-	-	2.97	-	Diopside
22	-	-	-	2.95	-	-	2.95	-	-	-	-	Diopside
23	-	-	2.87	2.87	-	-	-	-	-	-	-	Enstatite
24	-	-	-	-	-	-	-	2.68	-	-	-	Andradite
25	-	-	-	-	-	-	-	-	-	-	2.58	Hesingerite

26	2.52	2.52		-	-	2.52	2.52	-	-	-	-	Magnetite
27	-	-	-	2.52	-	-	-	-	2.52	-	2.52	Magnesioferrite
28	-	-	-	-	2.51	-	-	-	-	2.51	-	Hematite
29	-	-	-	-	-	2.51	-	-	-	-	-	Chromite
30	-	-	2.52	-	-	-	-	2.50	-	-	-	Chlorite
31	2.50	-	-	-	-	-	-	-	-	-	-	Olivine
32	-	-	-	-	-	-	2.50	-	-	-	-	Lizardite
33	-	-	-	-	2.49	-		-	-	-	-	Talc
34	-	-	-	-	-	-	-	-	2.45	-	-	Lizardite
35	-	-	-	-	2.44	-	-	-	-	-	-	Olivine
36	2.14	-	-	-	-	-	-	-	-	-	-	Magnetite
37	1.53	-	-	-	-	-	-	-	-	-	-	Clinohrysotile
38	-	-	2.36	-	-	-	-	-	-	-	-	Brucite

4.5 Petrogenetic Significance and Tectonic Implications

The petrographic characteristics of the studied ultramafic rocks reveal important insights into their petrogenesis and tectonic evolution. A clear distinction emerges between deformation features and alteration features. Deformation-related microstructures, such as porphyroclastic textures, kink banding in pyroxenes, undulose extinction, and grain-size reduction, record intense tectonic strain within the mantle peridotites. These features are diagnostic of high-stress deformation and suggest derivation from a depleted mantle source subjected to strong shearing, consistent with a supra-subduction zone environment. By contrast, alteration features—including serpentinization of olivine, bastite formation after orthopyroxene, chloritization, and secondary magnetite development along fractures—reflect later hydration and metamorphic overprint associated with fluid infiltration during obduction.

Taken together, these petrographic observations indicate a two-stage evolutionary history. First, the mantle peridotites experienced high-strain deformation and spinel-stability field equilibration within a mantle wedge, pointing to their origin in a convergent margin setting. Subsequently, extensive serpentinization and mineral alteration occurred during uplift and emplacement along the Indo–Myanmar suture during the Cretaceous–Eocene collision. Thus, the petrographic evidence not only highlights the petrogenetic processes that modified the ultramafics but also constrains their tectonic setting, underscoring their significance as fragments of supra-subduction zone lithosphere incorporated into the Himalayan–Tibetan orogenic system.

CHAPTER-5

GEOCHEMISTRY

5.1 Introduction

The theme and scope of the present works primarily determine the selected rock samples for the Geochemical study. The Geochemistry of ultramafic rocks in Tengnoupal, Manipur can be effectively examined using the earlier petrographic data. This Geochemical analysis contributes by highlighting key major, trace, and Rare Earth Elements (REE) characteristics of the analyzed ultramafic rocks. Whole-rock studies of major, trace, and REE are crucial in geochemistry, offering insights into various geological processes and histories. These studies serve as a valuable quantitative tool for distinguishing protolith evolution and tectonic settings, while also helping identify magmatic processes such as crystallization, magma mixing, partial melting, and assimilation. Trace elements are essential for understanding magma origin and evolution, identifying source rock, tracking magma differentiation, and revealing tectonic settings through distinct signatures. Rare earth elements provide detailed information on magmatic processes, including fractional crystallization and source characteristics, and are useful for identifying tectonic settings. REEs help differentiate between mantle sources and can indicate metamorphic changes. Relatively immobile elements like Co, Cr, Ni, Nb, Y, Zr, and REEs have been effectively used to evaluate the effects of alteration and low-grade metamorphism (Wood et al., 1976; Coish, 1977). In contrast, other trace elements such as B, Ba, Cs, Cu, Ga, Li, Ni, Pb, Rb, Sr, and V can show significant variations with increasing metamorphism levels (Garcia, 1978).

The geochemical analysis presented here builds upon detailed petrographic observations (Chapter 4), where extensive serpentization of primary olivine and orthopyroxene assemblages was observed. The correlation between petrographic textures and whole-rock chemistry provides a comprehensive understanding of both primary magmatic processes and secondary alteration effects in these ultramafic rocks.

5.2 Major Oxide Elements:

Twenty samples (20 Nos.) of the ultramafic rock samples from various locations within the studied area have been selected and analyzed. Most ultramafic rocks under study exhibit varying degrees of serpentinization from moderate to almost entirely serpentinized. The bulk major oxide composition of the rocks reflects the degree of serpentinization in the rocks (Table 5.1, 5.2, and 5.3). The Loss on Ignition (L.O.I) values range from 8.60 – 14.53 wt.% corresponding with the strong degree of serpentinization and weathering observed in hand-specimen. All the major elements lack correlation to the LOI (Fig.5.1 a-f). The studied rocks exhibit low contents in SiO₂ ranging from 39.94-42.02 % with an average value of 40.84 wt.%. In Kwatha-Khudengthabi sections, the studied rocks are characterized by SiO₂ (39.99-42.01 wt.%), MgO (38.66-42.42 wt.%), and CaO (0-2.44 wt.%); in Haolenphai sections, the SiO₂ (39.94-41.60 wt.%), MgO (37.84-42.60 wt.%) and CaO (0.02-1.79 wt.%); and Mongjang sections the SiO₂ (40.95-42.02 wt.%), MgO (36.13-39.60 wt.%) and CaO (0.58-2.45 wt.%). On the other hand, the ultramafic rocks show a high Mg# number [$Mg\#: 100 \times Mg^{2+} / (Mg^{2+} + Fe^{2+})$] in different locations of the study area (79-88 wt.% for the Kwatha area, 72—90 wt.% Haolenphai and 83-88 wt.% for Mongjang), which indicated that the Mg and Fe contents are stable and not significantly altered further as evidenced by the very low K₂O (≤ 0.01 wt.%), TiO₂ (≤ 0.12 wt.%) and Na₂O (≤ 0.07 wt.%) contents. The Al₂O₃ content varies between 0.54-2.70 wt.% (Kwatha), 0.95-2.78 wt.% (Haolenphai) and 2.29-3.01 wt.% (Mongjang).

From the Normative calculation of the Ultramafic rock, the main normative minerals considered are olivine, hypersthene, and diopside, with accessories minerals like apatite, ilmenite, orthoclase, albite, anorthite, corundum, and magnetite present varying with the amount of iron and chromite in the rocks. In Kwatha, the olivine is present with varying amounts of 53.08 -62.54 wt.%, hypersthene 16.22-29.66 wt.%, and diopside 0-4.69 wt.%; In Haolenphai, the olivine ranges from 50.26 – 57.35 wt.%, hypersthene 20.8 – 30.49 wt.% and diopside 0-155 wt.%; and Mongjang the olivine range from 44.75-57.39 wt.%; hypersthene 18.99 -33.28 wt.% and diopside 0 – 4.13 wt.%. The high amount of olivine and hypersthene is recorded in lherzolite and the low value is in harzburgite. Most of the ultramafic rock samples lack diopside, which

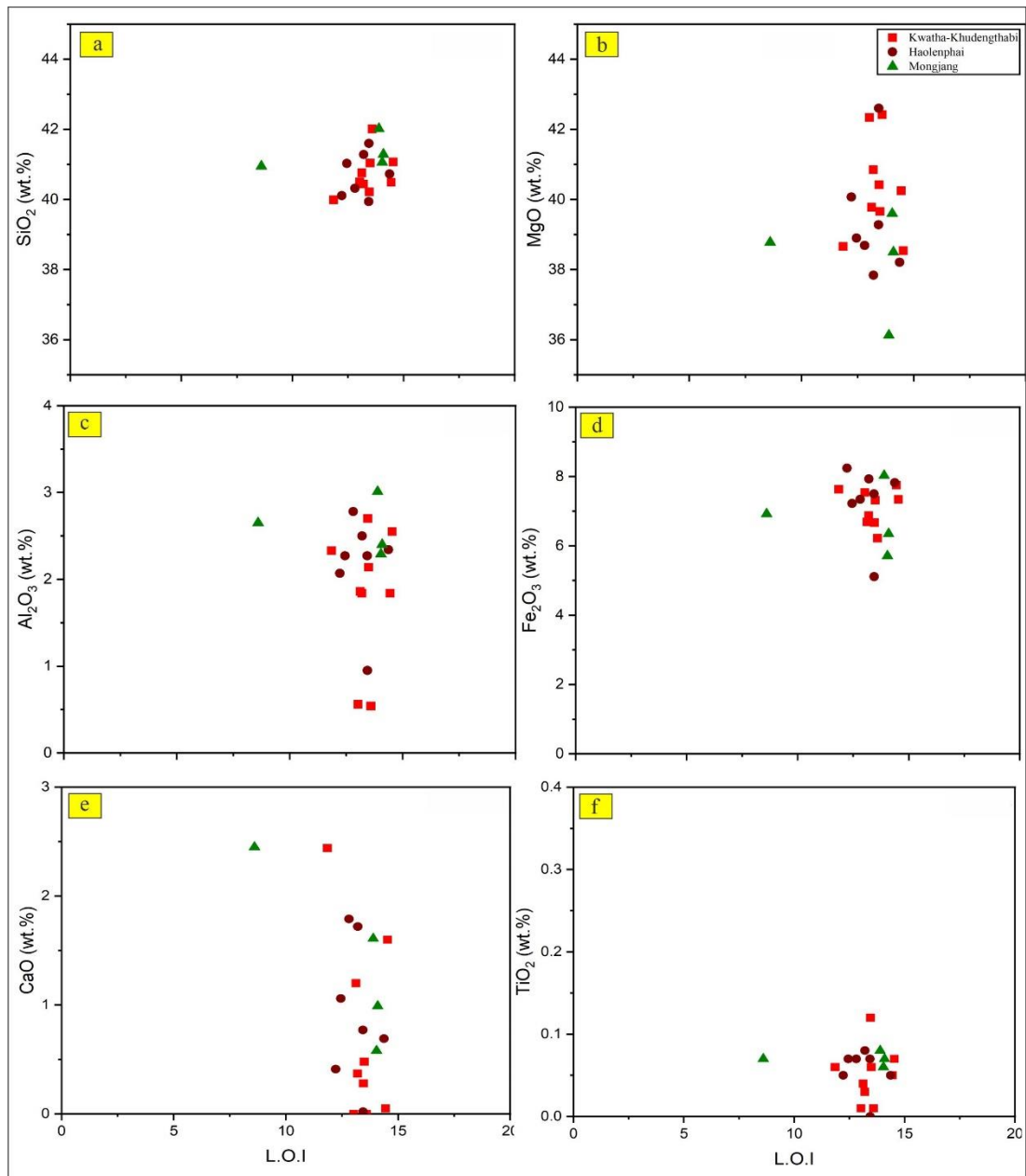


Fig. 5.1: Binary plots of Loss on Ignition (L.O.I.) versus selected major elements of a) SiO₂, b) MgO, c) Al₂O₃, d) Fe₂O₃, e) CaO, and f) TiO₂ of the studied ultramafic rocks. The plots demonstrate element immobility during serpentinization, with CaO showing depletion at higher LOI values indicating leaching during alteration.

suggests that the area experienced a significant degree of partial melting in the mantle causing the depletion of more easily melted components like clinopyroxene. Based on these normative classifications, the majority of the ultramafic rocks in the study area are classified mainly as harzburgite (Fig.5.2).

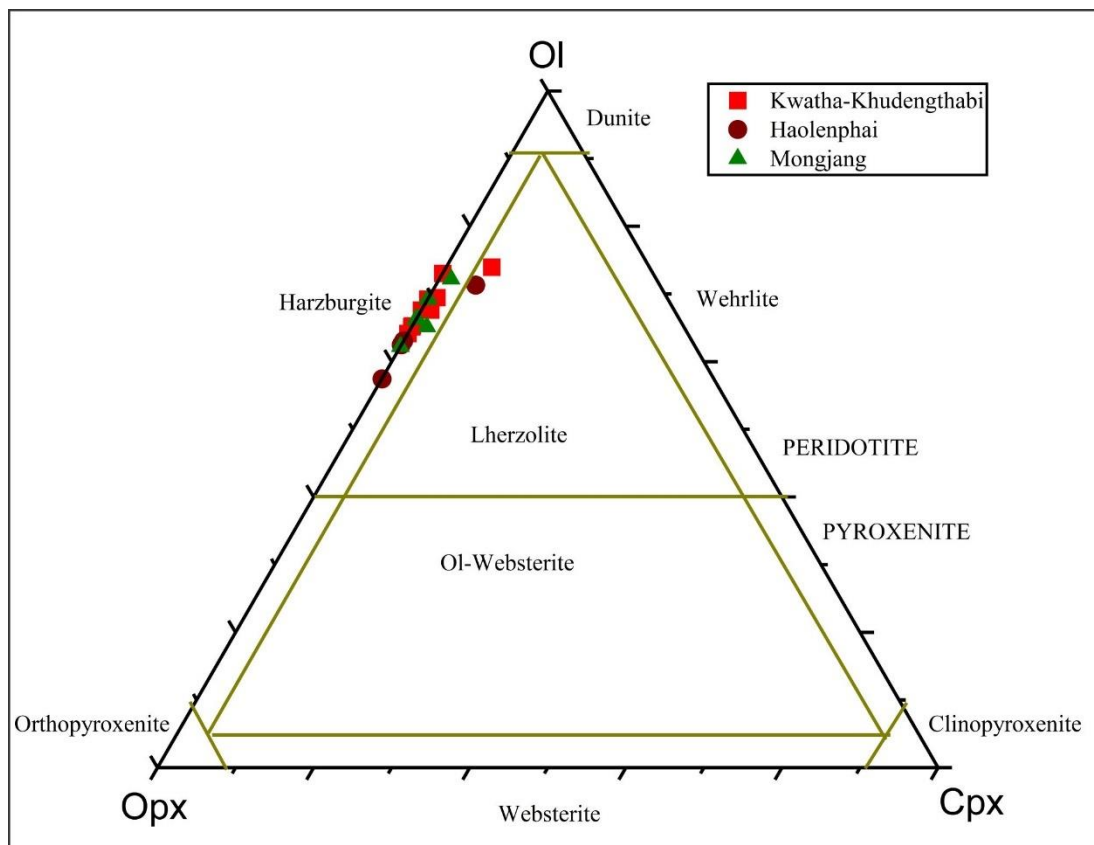


Fig. 5.2: Normative mineral composition of ultramafic rocks plotted on Ol-Opx-Cpx triangle (Coleman, 1977). Samples predominantly classify as harzburgite (>90%), indicating high-degree partial melting with clinopyroxene depletion. Two lherzolite samples (KW1, HZ28) show secondary carbonate alteration.

The normative mineral compositions calculated from whole-rock chemistry correspond well with the mineralogy observed during petrographic analysis. The dominance of normative olivine (44.75-62.54 wt.%) and hypersthene (16.22-33.28 wt.%) matches the observed olivine-orthopyroxene assemblages in thin section, while the scarcity of normative diopside reflects the petrographically confirmed absence or rare occurrence of primary clinopyroxene. The extensive serpentinization textures identified petrographically explain the high LOI values and the preservation of primary Mg/Fe ratios despite alteration. However, only two samples (1KW from Kwatha and 28HZ from Mongjang) were plotted in the fields of lherzolite due to the high contents of CaO and related to the presence of secondary carbonate.

On the AFM and ACM ternary diagram (Fig. 5.3 a-b), three samples (KW1 from Kwatha, HP12 from Haolenphai, and HZ28 from Mongjang) plotted in the field of ultramafic cumulate while most of the sample from each of the three study area locations is plotted in the field of Metamorphic peridotites, which represent the lower portion of the ophiolite sequence of mantle rocks that have been depleted or residual (Coleman, 1977). The classification as metamorphic peridotites in the AFM and ACM diagrams is consistent with petrographic evidence of recrystallization textures and the development of serpentine mesh textures after primary olivine. The three samples plotting in the ultramafic cumulate field (KW1, HP12, HZ28) correspond to specimens showing secondary carbonate veining observed in hand specimen and thin section, accounting for their elevated CaO contents. Their high Mg# values also supported this conclusion; the average of the studied samples is 87 which is comparable to the primitive 89 (Sun and Mc Donough, 1989) and residual peridotite (Bodinier and Godard, 2004).

The studied ultramafic rocks from all three locations exhibit komatiitic characteristics based on multiple geochemical criteria. The $\text{FeO}^* + \text{TiO}_2 - \text{Al}_2\text{O}_3 - \text{MgO}$ ternary diagram (Fig. 5.4) classifies all samples within the komatiitic field (Jensen, 1976), characterized by high $\text{MgO}/(\text{MgO} + \text{FeO}^* + \text{TiO}_2)$ ratios ranging from 0.82 to 0.91. This

komatiitic classification is rigorously supported by: i) Ultra-high MgO contents

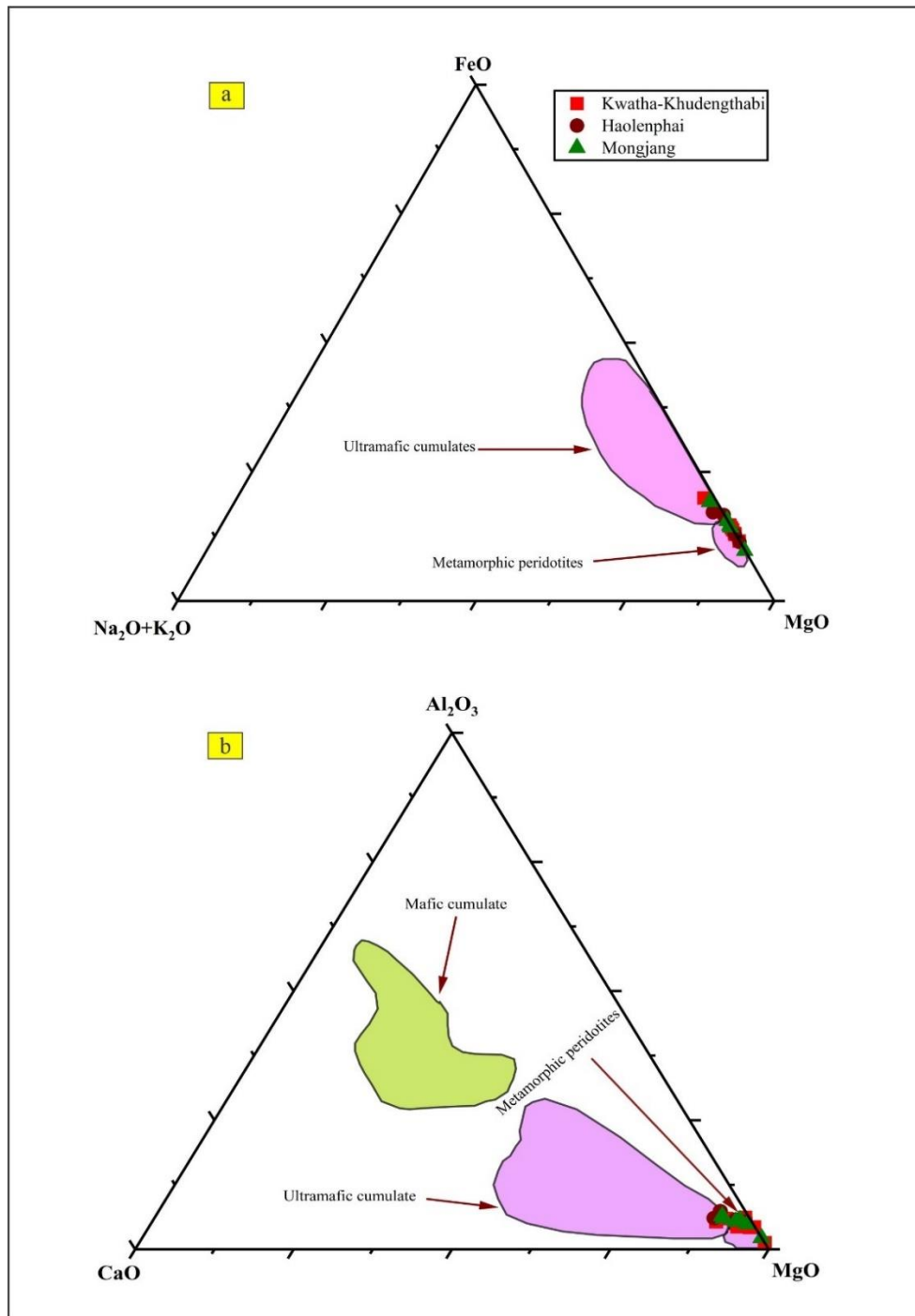


Fig.5.3.: Ternary diagrams (Coleman, 1977): a) AFM [(Na₂O + K₂O)-FeO-MgO] and b) ACM (Al₂O₃-CaO-MgO). Most samples plot in metamorphic peridotite field.

(36.13-42.60) indicating residual mantle origin. Three samples (KW1, HP12, HZ28) in ultramafic cumulate field reflect secondary carbonate alteration.

wt.%) well above the 18 wt.% threshold for komatiites (Arndt and Nisbet, 1982), ii) Very low TiO_2 (<0.12 wt.%) and Al_2O_3 (<3.01 wt.%) contents typical of high-temperature, primitive melts, iii) Exceptionally high Mg# values (72-90) comparable to Archean komatiites from Barberton (Mg# = 85-92; Arndt et al., 1977), and iv) Strong enrichment in compatible elements Ni (2176-4074 ppm) and Cr (628-3816 ppm), reflecting olivine-dominated crystallization sequences characteristic of komatiitic magmas. The combination of these geochemical features provides compelling evidence for komatiitic parentage of these ultramafic rocks.

The major whole-rock elements of the ultramafic rocks' samples are plotted with respect to MgO (Fig.5.5. a-b). Both CaO and Al_2O_3 concentrations show negative correlations with MgO levels. However, the CaO content in some samples that have undergone significant serpentinization is quite low and deviates from the established trend.

Variations in Al_2O_3 versus CaO (Fig.5.6) indicate that the ultramafic rocks from the Manipur Ophiolite Complex (MOC) share compositional similarities with abyssal peridotites, with significant influences of serpentinization. Abyssal peridotites originate from the Earth's mantle and are commonly found at mid-ocean ridges. They are created through a process of partial melting of the mantle, with the melt being removed to form the oceanic crust. The remaining mantle, known as the abyssal peridotite, is what's left behind after this process. When the Mg/Si and Al/Si values of the ultramafic samples from the MOC are plotted on a binary graph, it is observed that most samples fall on the mantle array (Fig.5.7). However, few of the samples from Kwatha, Haolenphai, and Mongjang plots below the mantle terrestrial array which represent depleted harzburgite, and their Mg/Si slightly lower imply that these samples lost their Mg during seafloor alteration (Niu, 2004; Uysal et al., 2011, 2016). The position of samples below the mantle terrestrial array correlates with petrographic observations of advanced serpentinization, where mesh textures and bastite pseudomorphs indicate extensive hydration of primary silicates. This alteration

process, while preserving bulk Mg/Si ratios, can cause subtle shifts in element mobility patterns observed geochemically. This array represents the transition from a primitive mantle to a highly depleted harzburgitic composition, a pattern indicative of

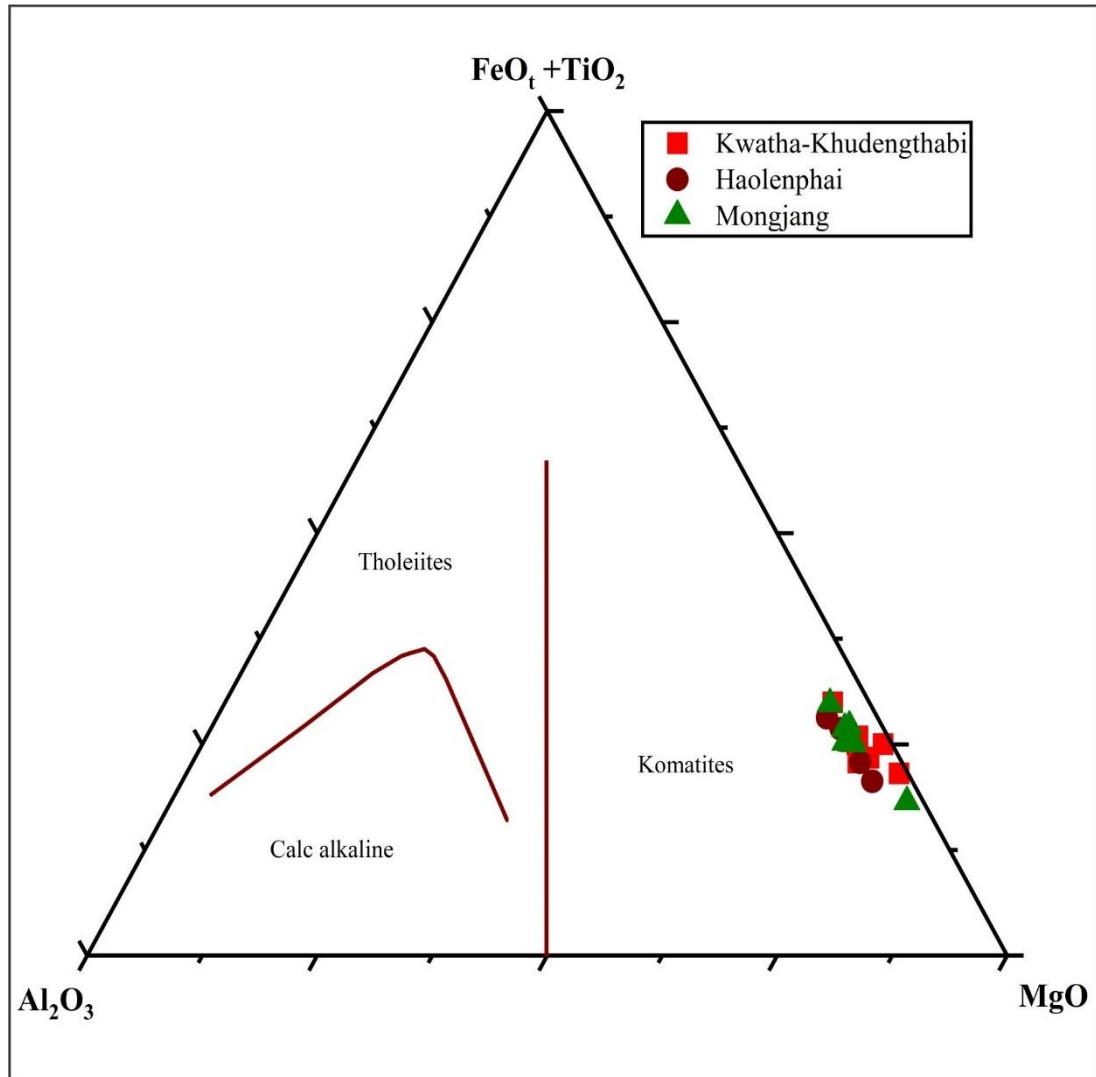


Fig.5.4: Ternary diagram (Jensen,1976), $[(\text{FeO}^* + \text{TiO}_2)\text{-Al}_2\text{O}_3\text{-MgO}]$ showing all samples plot within komatiitic field. High $\text{MgO}/(\text{MgO}+\text{FeO}^*+\text{TiO}_2)$ ratios (0.82-0.91) and ultra-high MgO contents (>35 wt.%) support komatiitic affinity and high-temperature magmatic origin.

magmatic depletion or enrichment (Jagoutz et al. 1979; Hart and Zindler 1986). Most of these ultramafic samples align with the typical range for abyssal peridotites. The samples exhibit a higher Mg/Si ratio, ranging from 0.86 to 1.04, with an average of

0.97. This surpasses the primitive mantle value (PM=0.85). However, their Al/Si ratio, ranging from 0.01 to 0.07 with an average of 0.051, is lower than that of the primitive

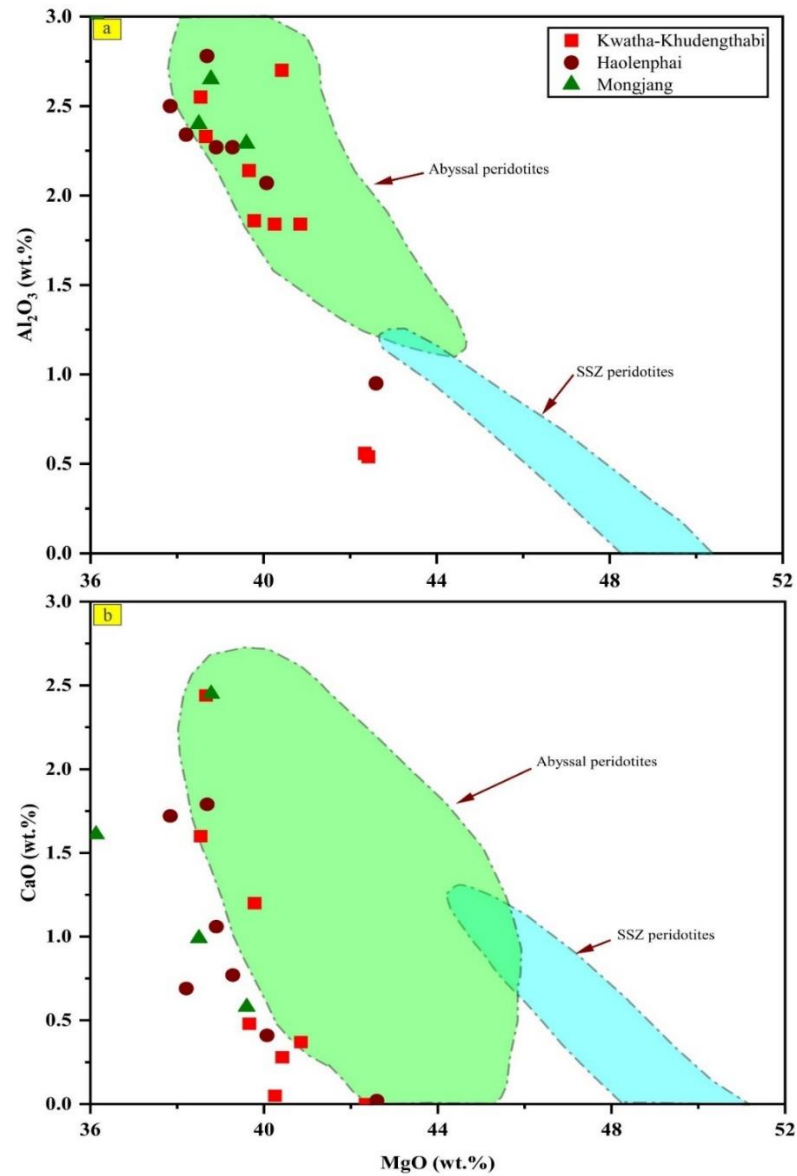


Fig.5.5: Major element variation diagrams: a) Al₂O₃ versus MgO showing negative correlation reflecting progressive depletion during partial melting; samples plot within abyssal peridotite field. and b) CaO versus MgO displaying negative correlation with scatter due to clinopyroxene extraction and secondary mobility during serpentinization. The field of abyssal peridotite is from Niu et al. (1997) and the supra-subduction zone peridotite field is from Parkinson and Pearce (1998).

mantle (PM=0.1). Generally, the Al/Si ratios of the examined ultramafic rocks are significantly lower than the PM ~ 0.1 (McDonough and Sun 1995).

The lower $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios of the studied ultramafic rocks, compared to the PM values, imply that the original rocks from which these ultramafic rocks were formed had undergone a process of partial melting before serpentinization (Niu 2004; Dien et al., 2016; Bhat et al., 2018). Snow and Dick (1995) along with Niu (2004) have suggested that during the process of serpentinization, SiO_2 and Al_2O_3 are immobile, while CaO and large-ion lithophile elements exhibit high mobility. Consequently, Al_2O_3 has been extensively utilized in research as an index of depletion to assess the behavior of major elements (Bhat et al. 2018). Figure illustrates diagrams of major element oxide versus Al_2O_3 , where the compositions of PM and mantle peridotites are compared. MgO displays a negative correlation, this negative correlation of MgO with Al_2O_3 is a commonly observed characteristic in residual mantle rocks (Niu 2004) while TiO_2 , and CaO, exhibit a positive correlation of the studied Ultramafic samples and No correlation is observed in SiO_2 and Fe_2O_3 indicating their mobile nature (Fig.5.8 a-f). Moreover, the ultramafic peridotites under study fall within the mantle peridotites field on the least-mobile major oxide versus Al_2O_3 diagram. The samples from all the locations in Tengnoupal exhibit low content of CaO ranging from 0-2.45 wt.%. Since CaO is highly mobile, its decrease in these samples suggests that the alteration of clinopyroxene involves the leaching of calcium.

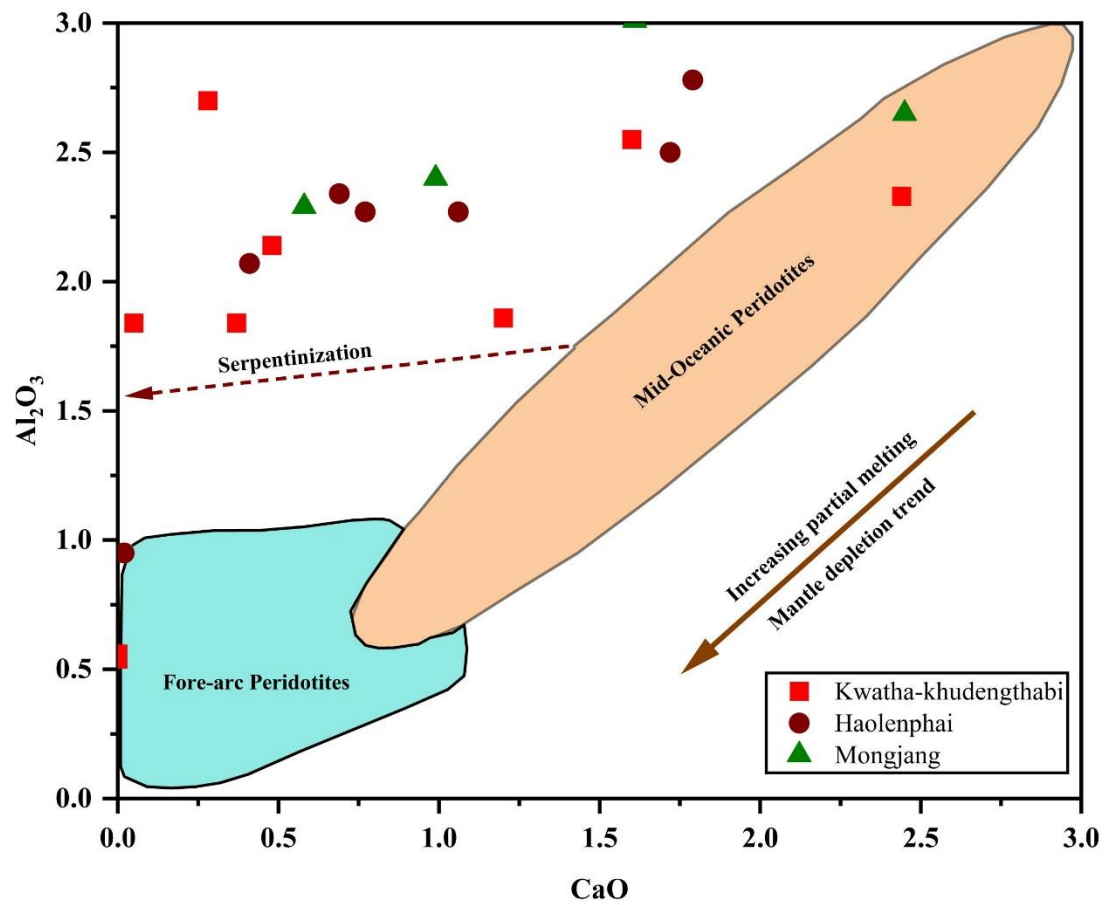


Fig.5.6: CaO vs Al_2O_3 diagram (Ishii et al., 1992) showing samples cluster within abyssal peridotite field. Linear depletion trend indicates coupled CaO - Al_2O_3 extraction during progressive partial melting. Compositional gap from forearc peridotites confirms mid-ocean ridge origin.

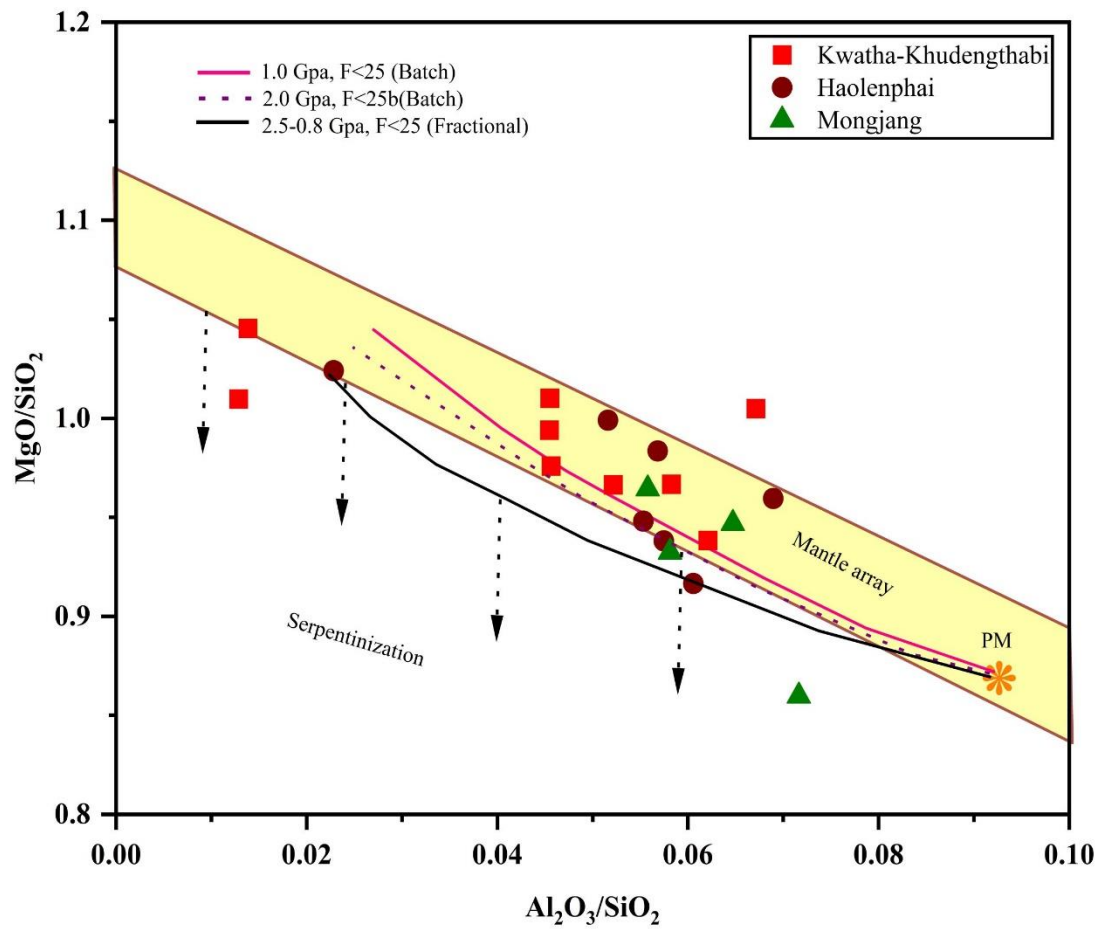


Fig.5.7: A plot of bulk rocks MgO/SiO₂ versus Al₂O₃/SiO₂ of the studied ultramafic rocks. The mantle array field, representing a melt depletion trend, is taken from Hart and Zindler (1986). The ultramafic sample points are shifted to a lower MgO/SiO₂ ratio due to alteration and serpentinization. For comparison, the plot of the composition of the primitive mantle is taken from McDonough and Sun (1995). The serpentinization trend is after Uysal et al. (2016).

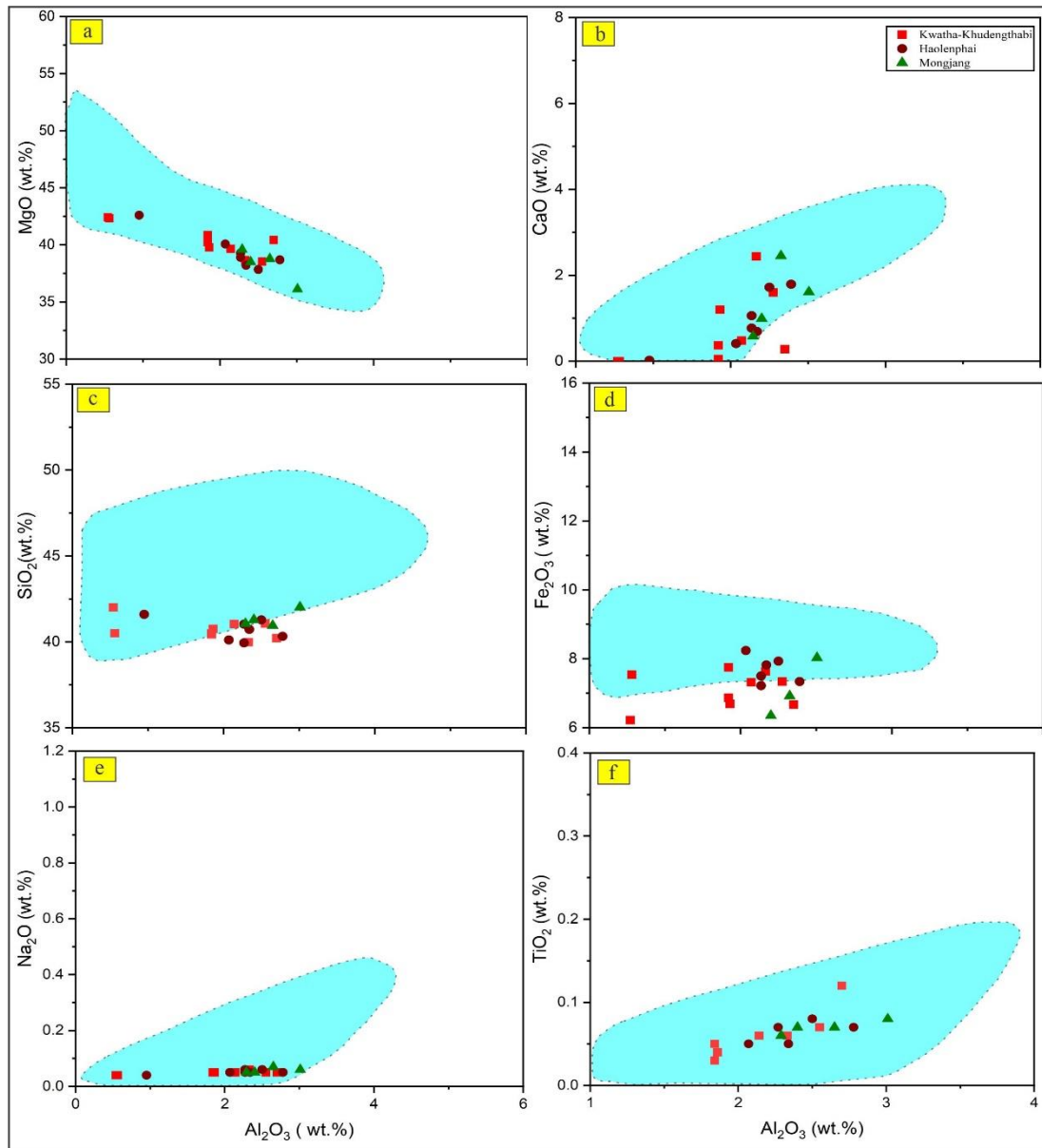


Fig. 5.8: Selected major elements of a) MgO versus Al_2O_3 , b) CaO versus Al_2O_3 , c) SiO_2 versus Al_2O_3 d) Fe_2O_3 versus Al_2O_3 e) Na_2O_3 versus Al_2O_3 and f) TiO_2 versus Al_2O_3 of the studied ultramafic rocks. The light blue fields are of orogenic, ophiolitic, and abyssal mantle peridotites (Bodinier and Geodard, 2004).

Table 5.1: Whole-rocks major elements composition of the Ultramafic rocks in Kwatha-Khudengthabi sections.

Major oxides (wt.%)									
Sample	KW1	KW2	KW3	KW4	KW6	KB19	KB21	KB22	KB23
SiO ₂	39.99	40.76	40.44	40.22	42.01	40.50	41.07	40.49	41.04
Al ₂ O ₃	2.33	1.86	1.84	2.70	0.54	0.56	2.55	1.84	2.14
Fe ₂ O ₃	7.63	6.69	6.87	6.67	6.22	7.54	7.34	7.75	7.32
CaO	2.44	1.20	0.37	0.28	0.00	0.00	1.60	0.05	0.48
MgO	38.66	39.78	40.85	40.42	42.42	42.34	38.54	40.25	39.66
K ₂ O	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.06	0.05	0.05	0.05	0.04	0.04	0.05	0.05	0.05
MnO	0.09	0.10	0.12	0.16	0.05	0.08	0.10	0.14	0.13
TiO ₂	0.06	0.04	0.03	0.12	0.01	0.01	0.07	0.05	0.06
P ₂ O ₅	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O+K ₂ O	0.07	0.05	0.05	0.05	0.04	0.04	0.05	0.05	0.05
SUM	91.28	90.48	90.57	90.62	91.29	91.07	91.32	90.62	90.88
LOI	11.85	13.12	13.19	13.45	13.59	13.02	14.53	14.44	13.49
Mg#	79	87	87	87	88	86	85	85	86
MgO/SiO ₂	0.97	0.98	1.01	1.00	1.01	1.05	0.94	0.99	0.97
Al ₂ O ₃ /SiO ₂	0.06	0.05	0.05	0.07	0.01	0.01	0.06	0.05	0.05
CIPW normative minerals									
Apatite	0.02	0	0	0	0	0	0	0	0
Ilmenite	0.11	0.11	0.06	0.23	0.02	0.02	0.13	0.09	0.11
Orthoclase	0.06	0	0	0	0	0	0	0	0
Albite	0.51	0.42	0.42	0.42	0.34	0.34	0.42	0.42	0.42
Anorthite	6.06	4.85	1.84	1.39	0	0	6.73	0.25	2.38
Magnetite	11.06	9.7	9.96	9.67	9.02	10.93	10.64	11.24	10.61
Corundum	0	0	1.09	2.11	0.47	0.49		1.67	1.18
Diopside	4.69	0.86	0	0	0	0	0.94	0	0
Hypersthene	16.22	24	25.65	26.82	30.33	23.07	24.95	29.14	29.66
Olivine	59.4	56.56	57.74	55.99	56.7	62.54	54.1	54.78	53.08
Total	98.14	96.51	96.75	96.62	96.88	97.4	97.92	97.59	97.46
OL	59.4	56.56	57.74	55.99	56.7	62.54	54.1	54.78	53.08
OPX	16.22	24	25.65	26.82	30.33	23.07	24.95	29.14	29.66
CPX	4.69	0.86	0	0	0	0	0.94	0	0

Mg# (Mg number) = $\text{Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+}) \times 100$; L.O.I = Loss on Ignition

Table 5.2: Whole-rock major elements composition of the Ultramafic rocks in Haolenphai.

Major oxides (wt.%)							
Sample	HP8	HP9	HP12	HP13	HP14	HP16	HP18
SiO ₂	41.03	39.94	41.28	40.11	40.73	40.32	41.60
Al ₂ O ₃	2.27	2.27	2.50	2.07	2.34	2.78	0.95
Fe ₂ O ₃	7.22	7.50	7.93	8.24	7.82	7.34	5.11
CaO	1.06	0.77	1.72	0.41	0.69	1.79	0.02
MgO	38.90	39.28	37.84	40.07	38.21	38.69	42.60
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.06	0.05	0.06	0.05	0.05	0.05	0.04
MnO	0.11	0.13	0.11	0.09	0.11	0.08	0.07
TiO ₂	0.07	0.07	0.08	0.05	0.05	0.07	0.00
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O+K ₂ O	0.06	0.05	0.06	0.05	0.05	0.05	0.04
SUM	90.72	90.01	91.52	91.09	90.00	91.12	90.39
LOI	12.45	13.43	13.20	12.22	14.37	12.81	13.44
Mg#	86	85	72	84	84	85	90
MgO/SiO ₂	0.95	0.98	0.92	1.00	0.94	0.96	1.02
Al ₂ O ₃ /SiO ₂	0.06	0.06	0.06	0.05	0.06	0.07	0.02
CIPW normative minerals							
Apatite	0	0	0	0	0	0	0
Ilmenite	0.13	0.13	0.15	0.09	0.09	0.13	0
Orthoclase	0	0	0	0	0	0	0
Albite	0.51	0.42	0.51	0.42	0.42	0.42	0.34
Anorthite	5.26	3.82	6.55	2.03	3.42	7.36	0.1
Magnetite	10.47	10.87	11.5	11.95	11.34	10.64	7.41
corundum	0.24	0.79	0	1.24	1	0	0.85
Diopside	0	0	1.55	0	0	1.19	0
Hypersthene	27.24	24.7	26.3	25.47	30.49	20.8	28.94
Olivine	53.36	56.01	52.09	57.29	50.26	57.18	57.35
Total	97.21	96.75	98.65	98.5	97.03	97.72	94.99
OL	53.36	56.01	52.09	57.29	50.26	57.18	57.35
OPX	27.24	24.7	26.3	25.47	30.49	20.8	28.94
CPX	0	0	1.55	0	0	1.19	0

Mg# (Mg number) = $\text{Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+}) \times 100$; L.O.I = Loss on Ignition

Table 5.3: Whole-rock major elements composition of the Ultramafic rocks in Mongjang.

Major oxides (wt.%)				
Sample	HZ25	HZ26	HZ27	HZ28
SiO ₂	41.29	41.06	42.02	40.95
Al ₂ O ₃	2.40	2.29	3.01	2.65
Fe ₂ O ₃	6.35	5.71	8.03	6.92
CaO	0.99	0.58	1.61	2.45
MgO	38.50	39.60	36.13	38.78
K ₂ O	0.02	0.00	0.00	0.01
Na ₂ O	0.05	0.05	0.06	0.07
MnO	0.10	0.11	0.11	0.09
TiO ₂	0.07	0.06	0.08	0.07
P ₂ O ₅	0.00	0.01	0.00	0.00
Na ₂ O+K ₂ O	0.07	0.05	0.06	0.08
SUM	89.77	89.47	91.05	91.99
LOI	14.09	14.04	13.89	8.60
Mg#	87	88	83	81
MgO/SiO ₂	0.93	0.96	0.86	0.95
Al ₂ O ₃ /SiO ₂	0.06	0.06	0.07	0.06
CIPW normative minerals				
Apatite	0	0.02	0.02	0
Ilmenite	0.13	0.11	0.15	0.13
Orthoclase	0.12	0	0	0.06
Albite	0.42	0.42	0.51	0.59
Anorthite	4.91	2.81	7.92	6.89
Magnetite	9.21	8.28	11.64	10.03
corundum	0.5	1.18	0.01	0
Diopside	0	0	0	4.13
Hypersthene	30.1	30.22	33.28	18.99
Olivine	50.09	51.56	44.75	57.39
Total	95.48	94.6	98.28	98.21
OL	50.09	51.56	44.75	57.39
OPX	30.1	30.22	33.28	18.99
CPX	0	0	0	4.13

Mg# (Mg number) = $\text{Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+}) \times 100$; L.O.I = Loss on Ignition

5.3 Trace elements and rare earth elements:

The study of ultramafic rocks across three distinct locations in Tengenoupal—Kwatha, Haolenphai, and Mongjang sections reveals remarkable geochemical signatures that provide compelling insights into their mantle origin (Table 5.4, 5.5, and 5.6). These rocks are characterized by substantial enrichment of transition metals, which serve as critical indicators of their deep-seated geological formation. In the Kwatha section, these rocks contain Cr (2262-3596 ppm), Ni (2192-2999 ppm), and Co (92-119 ppm). The Haolenphai section presents a slightly varied profile with the concentrations are Cr (628-3189 ppm), Ni (2264-3331 ppm), and Co (54-114 ppm). Meanwhile, the Mongjang area exhibits the most extensive range, the concentrations are Cr (2687-3816 ppm), Ni (2176-4074 ppm), and Co (31-126 ppm). Additionally, samples from all the locations exhibit a notable depletion of large-ion lithophile (LILE) such as Ba, Rb, and Sr. Still, there is a slight enrichment of Ba and Sr in the Haolenphai section ranging from (bdl -13) and (bdl – 6 ppm). Furthermore, the samples consistently demonstrate a notable depletion of high-field-strength elements (HFSE), such as niobium (Nb) and zirconium (Zr), which remain below the detection limit across all samples. In a plot depicting the relation between trace elements versus Al_2O_3 (Fig. 5.9), all the samples fall within the regions defined by the mantle peridotite. The trace elements chromium and nickel play a crucial role in enriching the primitive mantle composition. These elements are particularly compatible with mantle minerals, especially olivine, and spinel, reflecting the deep-seated origin of these ultramafic rocks. A distinctive positive covariation is observed between samarium (Sm) and ytterbium (Yb) versus Al_2O_3 (Fig. 5.9 c-d), a characteristic that aligns with the geochemical signature of tectonically emplaced abyssal peridotites (Bodinier and Geodard, 2004).

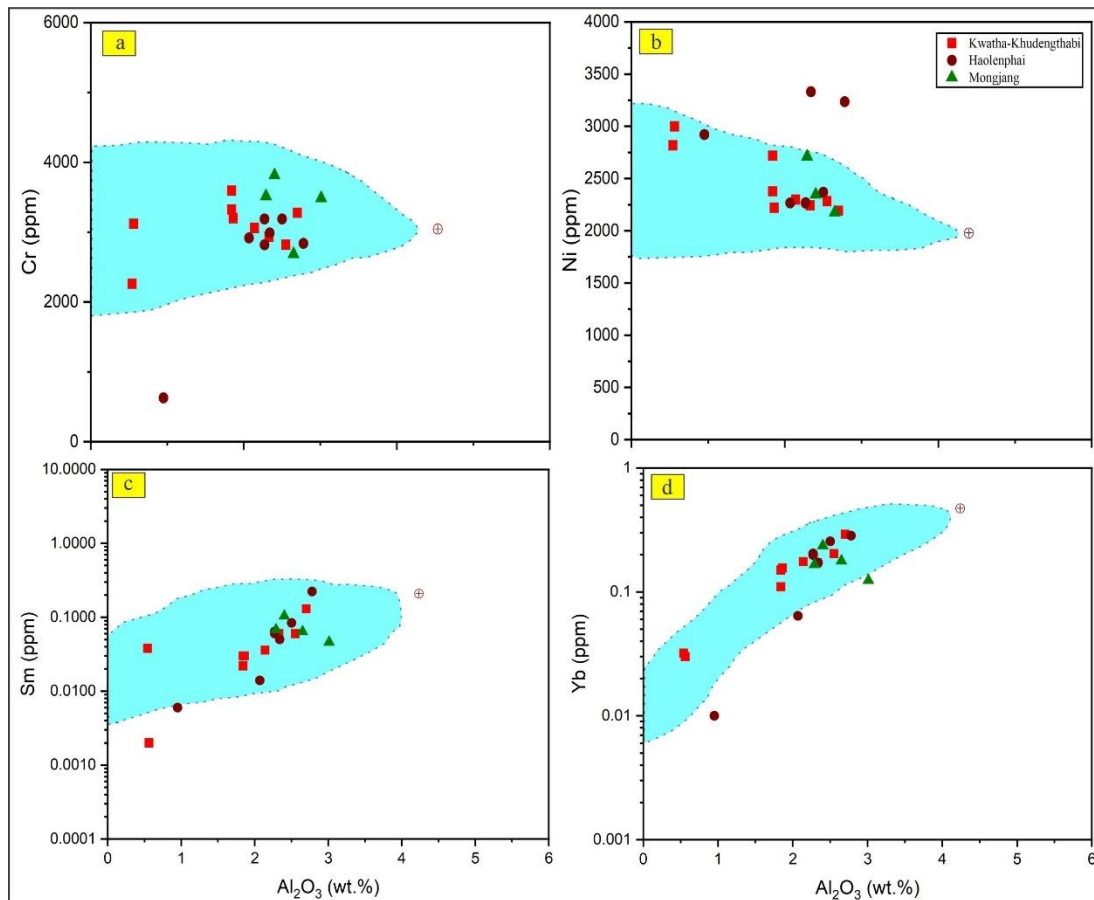


Fig.5.9.: Selected trace elements binary plots versus Al_2O_3 of ultramafic rocks. The fields are of orogenic, ophiolitic, and abyssal mantle peridotites (after Bodinier and Godard, 2004). Primitive-mantle (PM) values are from McDonough and Sun (1995).

The studied ultramafic rocks have deficient and highly varied measures of rare earth elements (REE) content $\text{REE}=0.200\text{--}4.732$ (Table 5.3.1, 5.3.2 and 5.3.3), the spider diagram when normalized to chondrite values (Sun and Mc Donough 1989), producing a spoon-shaped REE pattern (Fig.5.10, 5.11 a, and 5.11 b). The studied ultramafic peridotite in the Monjiang section is more depleted in LREE ($\text{La/Yb}_N=0.067\text{--}0.359$) as compared to Haolenphai LREE ($\text{La/Yb}_N=0.022\text{--}4.491$) and Kwatha LREE ($\text{La/Yb}_N=0.041\text{--}0.526$) except for one sample (KW6). In terms of HREE and MREE, the Mongjiang section show HREE ($\text{Gd/Yb}_N=0.576\text{--}0.667$) and MREE ($\text{Ce/Sm}_N=0.196\text{--}0.287$) in comparison to Kwatha less depleted HREE ($\text{Gd/Yb}_N=0.165\text{--}1.241$) and MREE ($\text{Ce/Sm}_N=0.258\text{--}7.500$) while Haolenphai has even slightly depleted

HREE ($\text{Gd/Yb}_N = 0.439\text{--}1.025$) and MREE ($\text{Ce/Sm}_N = 0.220\text{--}4.083$). Their REE pattern in the Mongjang samples indicates a slight negative Europium (Eu) anomaly with Eu/Eu^* ($0.812\text{--}0.992$) where the size of the Eu anomaly is indicated by the ratio Eu/Eu^* , which can be calculated as $\text{Eu}_N/(\text{Sm}_N \cdot \text{Gd}_N)^{1/2}$, which is the relative normalized abundance of Eu to Sm and Gd chondrite (Fig.5.3.3 b). In Kwatha and Haolenphai, the Eu anomaly is also slightly negative with Eu/Eu^* ($0.576\text{--}5.295$) and Eu/Eu^* ($0.774\text{--}5.095$) respectively (Fig.5.3.2 and 5.3.3 a). However, samples KW1 from Kwatha and HP18 from Haolenphai show positive Eu anomaly. The prominent slight Eu negative anomaly in different locations of the study area is likely due to a primary partitioning event during partial melting while the positive Eu anomaly in a few of the samples from Kwatha and Haolenphai may reflect due to the influence of hydrothermal fluid interactions.

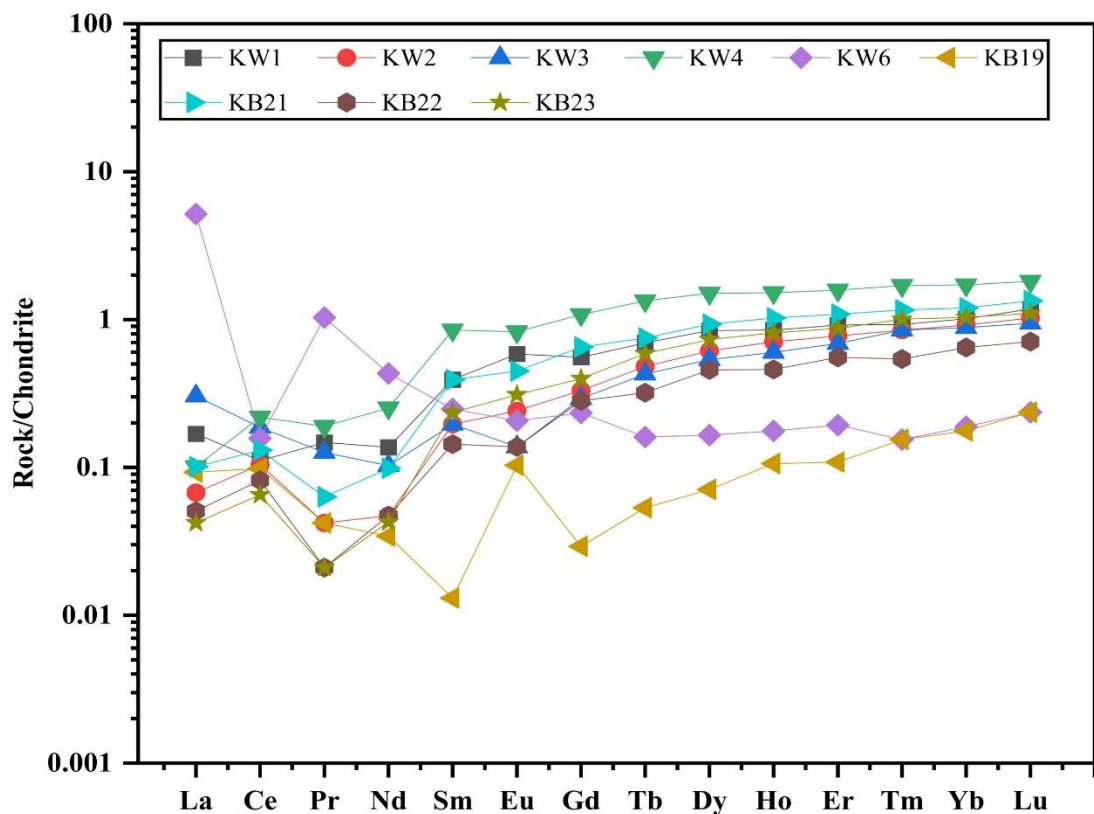


Fig.5.10: Chondrite-normalized REE pattern of ultramafic rocks in Kwatha-Khudengthabi section. Normalizing values are from Sun and McDonough (1989). The field of abyssal peridotites (after Niu, 2004) is shown for comparison.

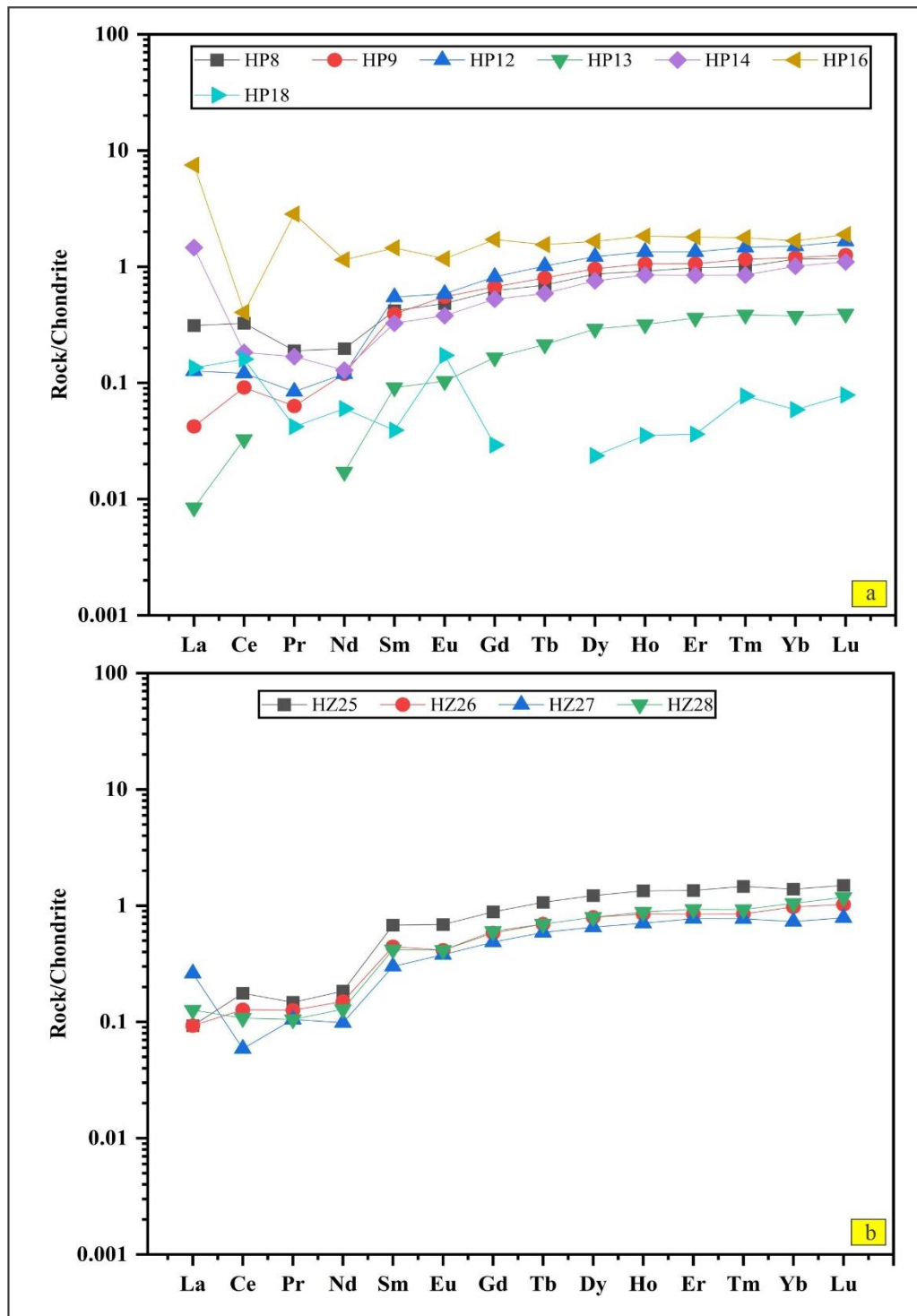


Fig.5.11: Chondrite-normalized REE pattern of ultramafic rocks a) Haolenphai and b) Mongjang sections. Normalizing values are from Sun and McDonough (1989). The field of abyssal peridotites (after Niu, 2004) is shown for comparison.

The spider diagrams normalized primitive mantle of the studied ultramafic rocks pattern is shown in Figures (5.12, 5.13 a, and 5.13 b), according to the primitive mantle of McDonough and Sun (1989). The Lithophile trace elements concentration of the studied ultramafic rocks from different sections of the area are similar to those found in abyssal peridotite from the mid-oceanic ridge (Niu,2004). But differ from those found in forearc peridotites (Ishii et al.1992; Parkinson and Pearce 1998). Specifically, elements from the Kwatha area such as Ce, Rb, U, Y, and Sr show notable positive peaks, while Ba, Sr, La, and Eu are depleted compared to Th, which is consistent with the patterns observed in oceanic abyssal peridotites (Niu, 2004; Paulick et al., 2006). In Haolenphai, there is a noticeable depletion of elements such as Ba, La, and Nd, and In the Mongjang area, elements like Ba, La, Sr, and Y show depletion whereas Sm, U, and Eu show relative enrichments.

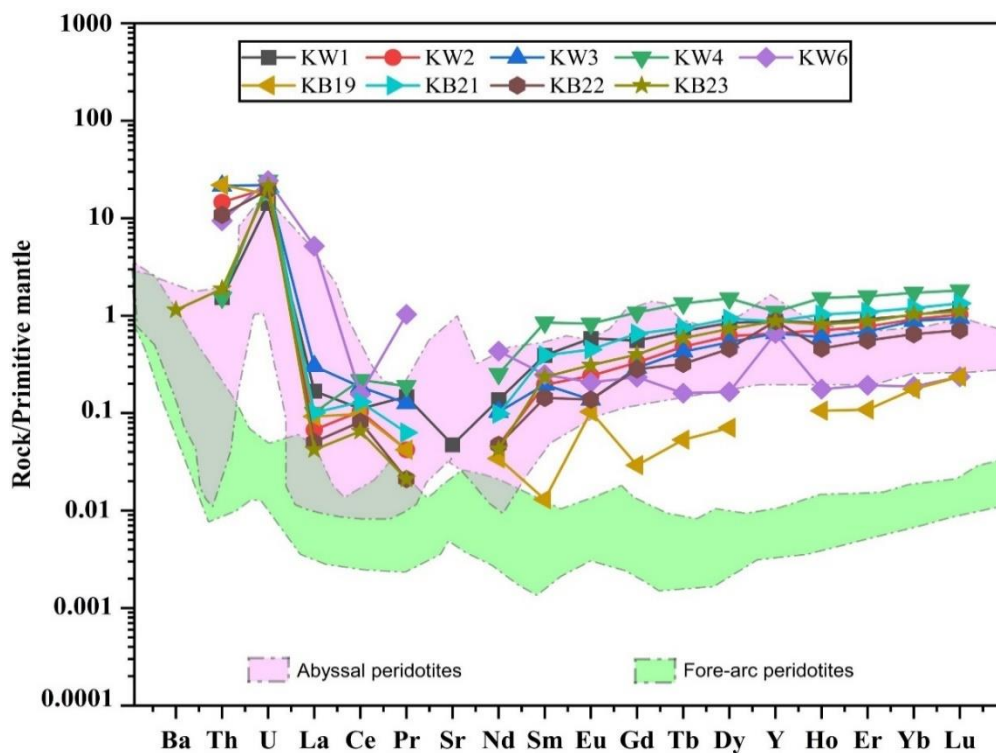


Fig.5.12: Primitive mantle-normalized trace element patterns of the ultramafic rocks in the Kwatha-Khudengthabi section, Normalizing values are from Sun and McDonough (1989). The field of abyssal peridotites (after Niu, 2004) is shown for comparison.

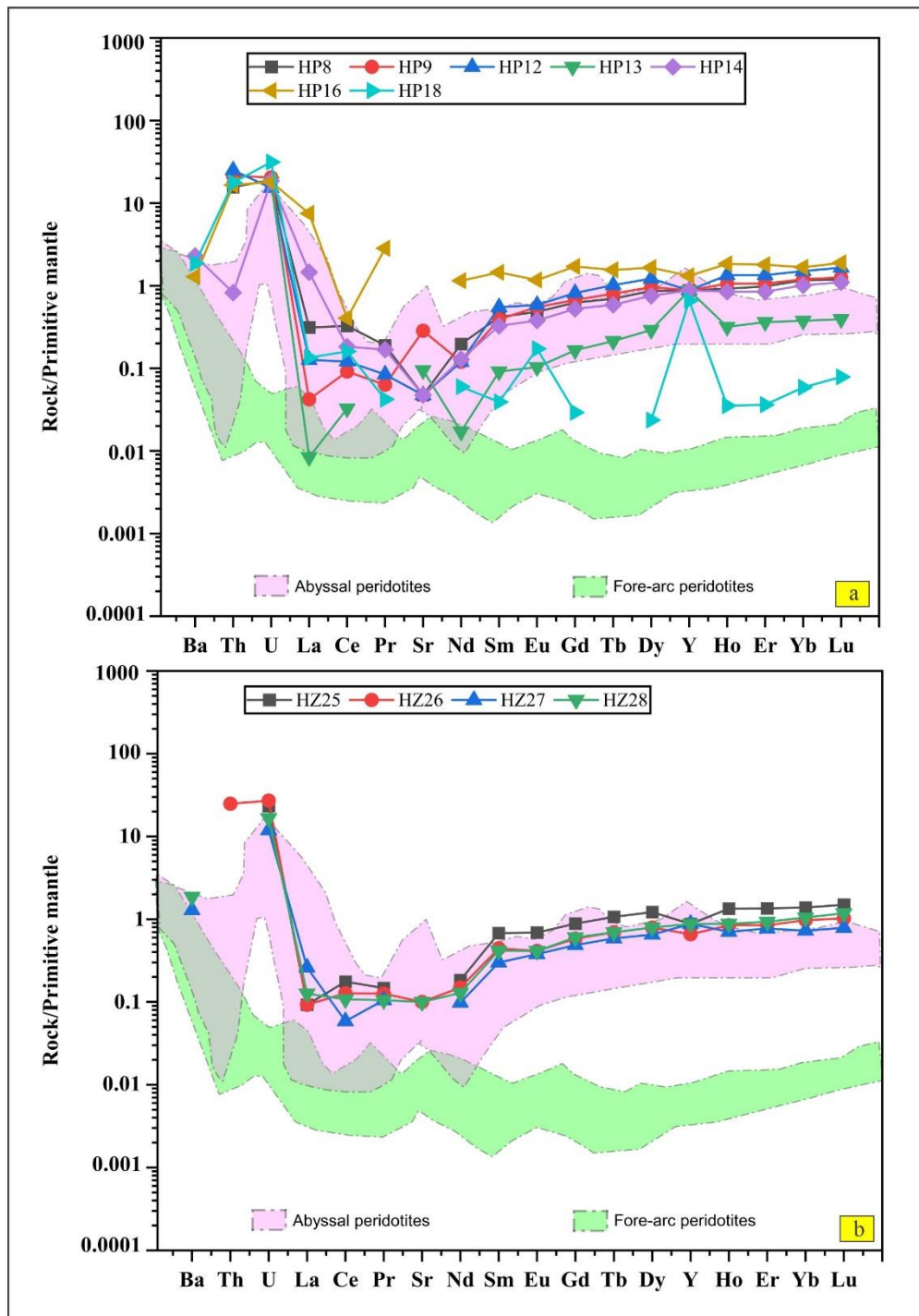


Fig.5.13.: Primitive mantle-normalized trace element patterns of the ultramafic rocks a) Haolenghai, and b) Mongjiang sections, normalizing values are from Sun and McDonough (1989). The field of abyssal peridotites (after Niu, 2004) is shown for comparison.

Table 5.4: Trace and rare earth elements concentration of Ultramafic rocks in Kwatha-Khudengthabi.

Trace elements (ppm)									
Sample	KW1	KW 2	KW3	KW4	KW 6	KB 19	KB 21	KB22	KB23
Ba	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	8
Cr	2934	3202	3325	3278	2262	311 9	282 0	3596	3062
V	63	71	84	100	26	42	77	89	89
Sc	8	12	13	16	bdl	6	15	14	13
Co	92	108	118	135	94	86	117	119	113
Ni	2243	2220	2718	2192	2818	299 9	228 4	2378	2298
Cu	5	22	17	57	1	4	24	23	27
Zn	42	62	57	81	28	40	46	70	65
Ga	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Pb	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Th	0.1	1.2	1.8	0.1	0.8	1.9	BD L	0.9	0.2
Rb	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
U	0.3	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.5
Sr	1	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Y	4	3	3	5	3	BD L	4	4	4
Zr	bdl	bdl	bdl	2	bdl	bdl	bdl	bdl	bdl
Nb	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Rare earth elements (ppm)									
La	0.040	0.01 6	0.072	0.024	1.22 8	0.0 22	0.02 4	0.012	0.010
Ce	0.068	0.06 4	0.114	0.134	0.09 6	0.0 60	0.08 0	0.050	0.040

Pr	0.014	0.00 4	0.012	0.018	0.09 8	0.0 04	0.00 6	0.002	0.002
Nd	0.064	0.02 2	0.048	0.118	0.20 2	0.0 16	0.04 6	0.022	0.020
Sm	0.060	0.03 0	0.030	0.130	0.03 8	0.0 02	0.06 0	0.022	0.036
Eu	0.034	0.01 4	0.008	0.048	0.01 2	0.0 06	0.02 6	0.008	0.018
Gd	0.114	0.06 8	0.060	0.222	0.04 8	0.0 06	0.13 4	0.058	0.082
Tb	0.026	0.01 8	0.016	0.050	0.00 6	0.0 02	0.02 8	0.012	0.022
Dy	0.214	0.15 6	0.136	0.382	0.04 2	0.0 18	0.23 6	0.116	0.186
Ho	0.048	0.04 0	0.034	0.086	0.01 0	0.0 06	0.05 8	0.026	0.046
Er	0.152	0.12 8	0.114	0.262	0.03 2	0.0 18	0.18 0	0.092	0.144
Tm	0.024	0.02 2	0.022	0.044	0.00 4	0.0 04	0.03 0	0.014	0.026
Yb	0.172	0.15 6	0.150	0.292	0.03 2	0.0 30	0.20 4	0.110	0.176
Lu	0.030	0.02 6	0.024	0.046	0.00 6	0.0 06	0.03 4	0.018	0.028
(ΣREE)_N	8.521	6.39 6	6.275	14.69 1	8.76 6	1.3 19	9.37 3	4.454	7.261
ΣLREE	0.956	0.45 7	0.915	1.612	7.05 1	0.2 80	0.78 6	0.344	0.407
ΣHREE	7.565	5.93 9	5.359	13.07 9	1.71 5	1.0 39	8.58 7	4.109	6.854

ΣMREE	1.670	0.81 5	0.729	3.010	1.12 1	0.1 80	1.59 1	0.611	0.987
(La/Sm)_N	0.430	0.34 4	1.549	0.119	20.8 62	7.1 01	0.25 8	0.352	0.179
(Sm/Lu)_N	0.332	0.19 2	0.208	0.469	1.05 1	0.0 55	0.29 3	0.203	0.213
(La/Yb)_N	0.167	0.07 4	0.344	0.059	27.5 26	0.5 26	0.08 4	0.078	0.041
(Ce/Sm)_N	0.283	0.53 3	0.950	0.258	0.63 2	7.5 00	0.33 3	0.568	0.278
(Gd/Yb)_N	0.548	0.36 1	0.331	0.629	1.24 1	0.1 65	0.54 3	0.436	0.385
Eu/Eu*	1.257	0.94 8	0.576	0.864	0.85 9	5.2 95	0.88 6	0.685	1.013
Ce/Ce*	0.705	1.96 1	0.951	1.581	0.06 8	1.5 68	1.63 5	2.502	2.193

Table 5.5: Trace and rare earth elements concentration of Ultramafic rocks in Haolenphai.

Trace elements (ppm)							
Sample	HP8	HP9	HP12	HP13	HP14	HP16	HP18
Ba	bdl	bdl	bdl	bdl	16	9	13
Cr	3188	2817	3189	2916	2987	2839	628
V	78	74	90	77	67	78	6
Sc	12	14	13	13	9	10	bdl
Co	114	99	108	114	71	54	114
Ni	2269	2264	2369	2265	3331	3236	2921
Cu	23	20	22	21	19	6	32
Zn	64	47	58	48	49	30	38
Ga	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Pb	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Th	1.3	1.8	2.1	BDL	0.1	1.4	1.5
Rb	bdl	bdl	bdl	bdl	bdl	bdl	bdl
U	0.4	0.4	0.3	0.4	0.4	0.4	0.7
Sr	1	6	1	2	1	bdl	bdl
Y	4	4	4	4	4	6	3
Zr	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Nb	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Rare earth elements (ppm)							
La	0.074	0.010	0.030	0.002	0.346	1.778	0.032
Ce	0.200	0.056	0.074	0.020	0.112	0.248	0.098
Pr	0.018	0.006	0.008	0.000	0.016	0.270	0.004
Nd	0.092	0.056	0.056	0.008	0.060	0.536	0.028
Sm	0.064	0.060	0.084	0.014	0.050	0.222	0.006
Eu	0.028	0.032	0.034	0.006	0.022	0.068	0.010
Gd	0.128	0.138	0.168	0.034	0.108	0.352	0.006
Tb	0.026	0.030	0.038	0.008	0.022	0.058	0.000

Dy	0.220	0.244	0.310	0.074	0.192	0.420	0.006
Ho	0.052	0.060	0.076	0.018	0.048	0.104	0.002
Er	0.162	0.176	0.222	0.060	0.140	0.298	0.006
Tm	0.026	0.030	0.038	0.010	0.022	0.046	0.002
Yb	0.198	0.204	0.256	0.064	0.172	0.284	0.010
Lu	0.030	0.032	0.042	0.010	0.028	0.048	0.002
(ΣREE)_N	9.358	9.437	11.952	2.761	9.173	28.412	0.948
ΣLREE	1.444	0.709	1.001	0.150	2.267	13.348	0.436
ΣHREE	7.914	8.728	10.951	2.611	6.907	15.064	0.512
ΣMREE	1.721	1.735	2.073	0.378	1.360	5.484	0.301
(La/Sm)_N	0.746	0.108	0.231	0.092	4.467	5.170	3.443
(Sm/Lu)_N	0.354	0.311	0.332	0.232	0.296	0.768	0.498
(La/Yb)_N	0.268	0.035	0.084	0.022	1.443	4.491	2.295
(Ce/Sm)_N	0.781	0.233	0.220	0.357	0.560	0.279	4.083
(Gd/Yb)_N	0.535	0.560	0.543	0.439	0.519	1.025	0.496
Eu/Eu*	0.946	1.075	0.875	0.841	0.915	0.744	5.095
Ce/Ce*	1.344	1.773	1.171	0	0.369	0.088	2.124

Table 5.6: Trace and rare earth elements concentration of Ultramafic rocks in Mongjang.

Trace elements (ppm)				
Sample	HZ25	HZ26	HZ27	HZ28
Ba	bdl	bdl	9	13
Cr	3816	3516	3489	2687
V		62	89	66
Sc	14	13	11	11
Co	126	124	31	105
Ni	2347	2710	4074	2176
Cu	36	14	26	23
Zn	53	55	47	43
Ga	bdl	bdl	bdl	bdl
Pb	bdl	bdl	bdl	bdl
Th	bdl	2.1	bdl	bdl
Rb	bdl	bdl	bdl	bdl
U	0.5	0.6	0.3	0.4
Sr	bdl	bdl	bdl	bdl
Y	4	3	4	4
Zr	bdl	3	3	bdl
Nb	bdl	bdl	bdl	bdl
Rare earth elements (ppm)				
La	0.022	0.022	0.062	0.030
Ce	0.108	0.078	0.036	0.066
Pr	0.014	0.012	0.010	0.010
Nd	0.086	0.070	0.046	0.060
Sm	0.104	0.068	0.046	0.064
Eu	0.040	0.024	0.022	0.024
Gd	0.182	0.120	0.100	0.124
Tb	0.040	0.026	0.022	0.026

Dy	0.310	0.202	0.166	0.202
Ho	0.076	0.048	0.040	0.050
Er	0.224	0.140	0.128	0.154
Tm	0.038	0.022	0.020	0.024
Yb	0.236	0.166	0.124	0.178
Lu	0.038	0.026	0.020	0.030
(ΣREE)_N	12.194	7.973	6.702	8.363
ΣLREE	1.281	0.941	0.825	0.886
ΣHREE	10.913	7.032	5.877	7.476
ΣMREE	2.439	1.592	1.265	1.564
(La/Sm)_N	0.137	0.209	0.870	0.303
(Sm/Lu)_N	0.454	0.434	0.382	0.354
(La/Yb)_N	0.067	0.095	0.359	0.121
(Ce/Sm)_N	0.260	0.287	0.196	0.258
(Gd/Yb)_N	0.638	0.598	0.667	0.576
Eu/Eu*	0.889	0.812	0.992	0.824
Ce/Ce*	1.509	1.177	0.354	0.934

CHAPTER-6

PETROGENESIS AND TECTONIC EVOLUTION

6.1 Introduction

In the previous chapter, we examined various aspects of the ultramafic rocks, including field observation, petrology, mineralogical, and whole-rocks geochemistry. This chapter thoroughly summarizes the results of this extensive study and integrates the information acquired from these different analyses, providing a cohesive discussion of the key results. The genesis, evolutionary process, and tectonic emplacement are also discussed in this chapter.

6.2 Nature and origin

According to the normative composition of the study ultramafic rocks in the Kwatha, Mongjang, and Haolenphai areas are plotted on Ol-Hy-Di diagrams (Coleman 1977). Where the highly serpentinized fall within the fields of Harzburgite. Based on the ternary diagram of the $\text{Fe}_2\text{O}_3\text{-SiO}_2\text{-MgO}$ (Pfeifer, 1979) and the $\text{CaO-Al}_2\text{O}_3\text{-MgO}$ (Li et al. 2004) (Fig.6.1 a-b). The studied samples from the three locations of the area correspond to a harzburgite protolith with some samples showing minor dunite. The majority of the ultramafic rocks in the study area were shown to belong to the fields of metamorphic peridotite which are associated with ophiolite and a few sample plots in the fields of cumulate based on the ternary AFM and ACM diagram. The high contents of MgO, Mg#, Cr, and Ni and the low concentration of incompatible elements such as Th, Rb, Nb, Sr, and Cs in the samples under study than the primitive mantle likely represent the protoliths' residual nature (Niu, 1997, 2004), which is comparable to the depleted harzburgites and dunites (Zhou et al. 2005; Aldanmaz et al. 2008, 2020). However, high contents of Al_2O_3 (avg-2.3) in some of the samples from Haolenphai reflect a higher content of clinopyroxene than that of the normal harzburgitic ophiolite suggesting that part of the protolith contained fertile components, likely associated with abyssal peridotite of the mid-oceanic ridge. (Coleman and Keith, 1971; Niu 1997, 2004; Niu and Hékinian 1997; Niu et al. 1997). A slight enrichment in Light Rare Earth Elements (LREE) was observed in the

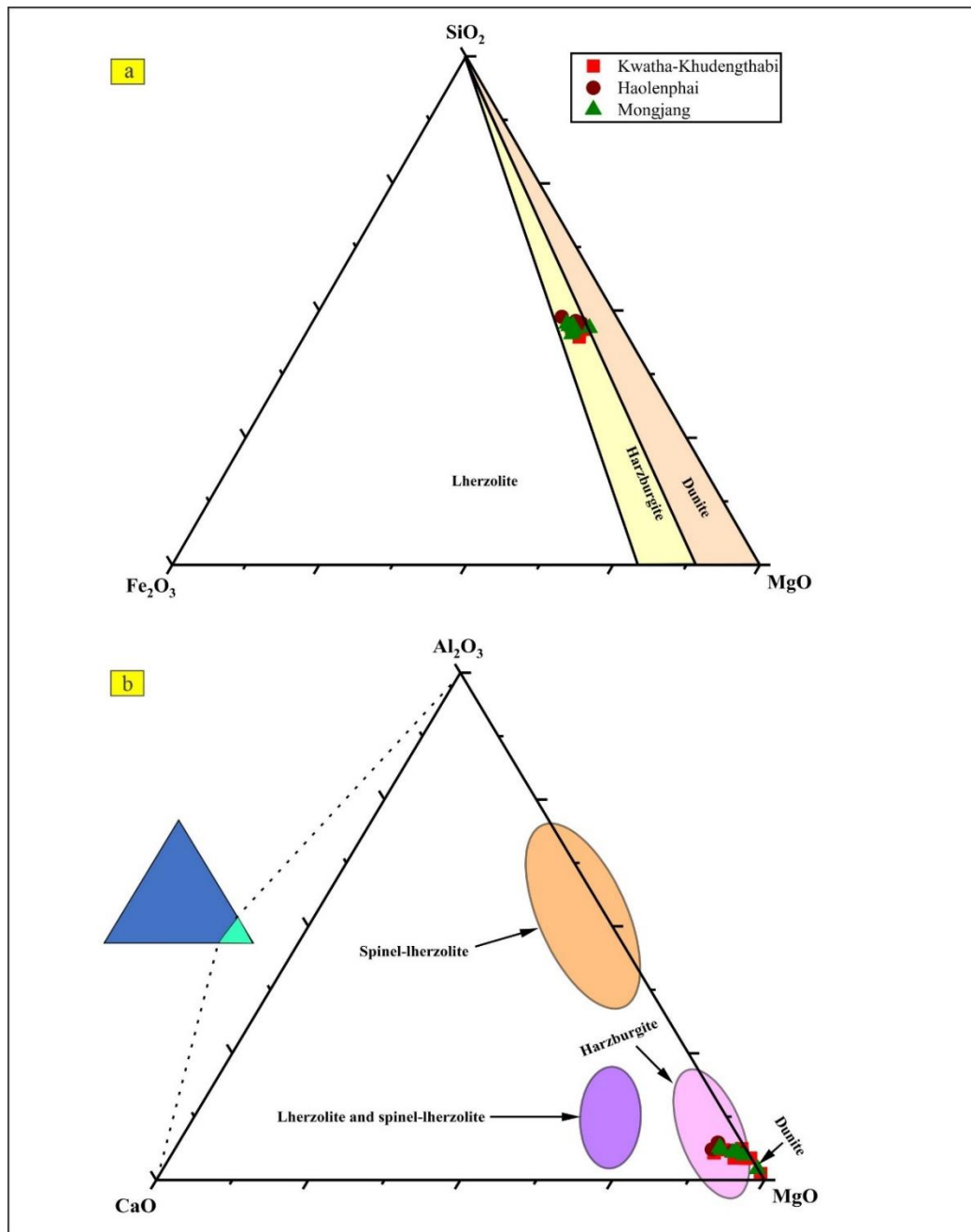


Fig.6.1: (a) SiO₂-FeO*-MgO ternary diagram of the studied ultramafic rocks (after Pfeifer, 1979); (b) relationship between ultramafic rocks and their protoliths in a MgO-Al₂O₃-CaO (wt.%) ternary diagram (after Li et al., 2004).

ultramafic rocks could be ascribed to a hydrothermal metamorphic process involving ocean water, with temperatures ranging from 250 to 400°C and up to 13 weight percent H₂O in serpentinites. This process may aid in utilizing and incorporating LREE (Niu, 2004). Furthermore, the samples exhibit slight enrichment in Large Ion Lithophile Elements (LILE) like Sr and Th. This could be related to fluids produced by the dehydration of an obducted slab (Keppler, 1996) or through interactions with LILE-rich hydrous fluids that come from the subducting slab (Stern et al., 1991, 1996). The Mg/Si and Al/Si ratios appear to provide unambiguous parameters that suggest the original characteristics of peridotite protoliths, as these ratios remain unchanged through the processes of hydration and metamorphism, reflecting those of anhydrous peridotite (Hattori and Guillot, 2007; Saumur et al., 2010). On the other hand, according to Evan (2013), serpentinites within orogenic belts could come from a range of protolith sources, such as cumulates and various varieties of mantle peridotite, like abyssal or mantle-wedge peridotite. In this plot, the data points for all the samples fall beneath and on the 'mantle terrestrial array' trend. This trend corresponds to the magmatic depletion (or enrichment) pathway from a primitive mantle to a highly depleted harzburgitic composition, as described by Jagoutz et al. (1979) and Hart and Zindler (1986). Most ultramafic rock samples (Kwatha, Haolenphai, and Mongjang), generally fall within the range expected for abyssal peridotites. However, there were a few exceptions two samples of KB19 and HP18 from Kwatha and Haolenphai and three samples (KW4, HP16, and HZ27) from Kwatha, Haolenphai, and Mongjang). showed relatively high MgO/SiO₂ ratios (greater than 1) and Al₂O₃/SiO₂ ratios (greater than 0.06). Notably, the two samples were found in the region associated with Cuban peridotites, as illustrated in Figure 6.2.

The ultramafic rocks under study have 0.05–0.07 for Al₂O₃/SiO₂ and 0.95–1.05 for MgO/SiO₂ which are similar to Abyssal peridotite (Niu 2004) and Shergol peridotite (Bhat, 2018). According to Le Maître (1976) average Al₂O₃/SiO₂ and MgO/SiO₂ ratios for harzburgite, lherzolite, and dunite as 0.83 and 0.05, 0.66 and 0.09, and 0.99 and 0.04, respectively. As per Coleman's (1977) proposal, the MgO/SiO₂ ratio can provide valuable insight into the initial composition of peridotite. A low ratio (0.89) indicates the lherzolite composition, while a high ratio indicates the harzburgite and dunite

composition. In the current study of ultramafic rocks most of the samples represent high MgO/SiO_2 in Kwatha, Haolenphai, and Mongjang areas, the average MgO/SiO_2 ratio is 0.96%, indicating a composition of Harzburgite and dunite. Also, The $\text{MgO}/\text{MgO}+\text{FeO}^*$ ratio average for the ultramafic rocks under study is 85 (Kwatha), 84 (Haolenphai), and 92 (Mongjang) which is quite similar to the values of

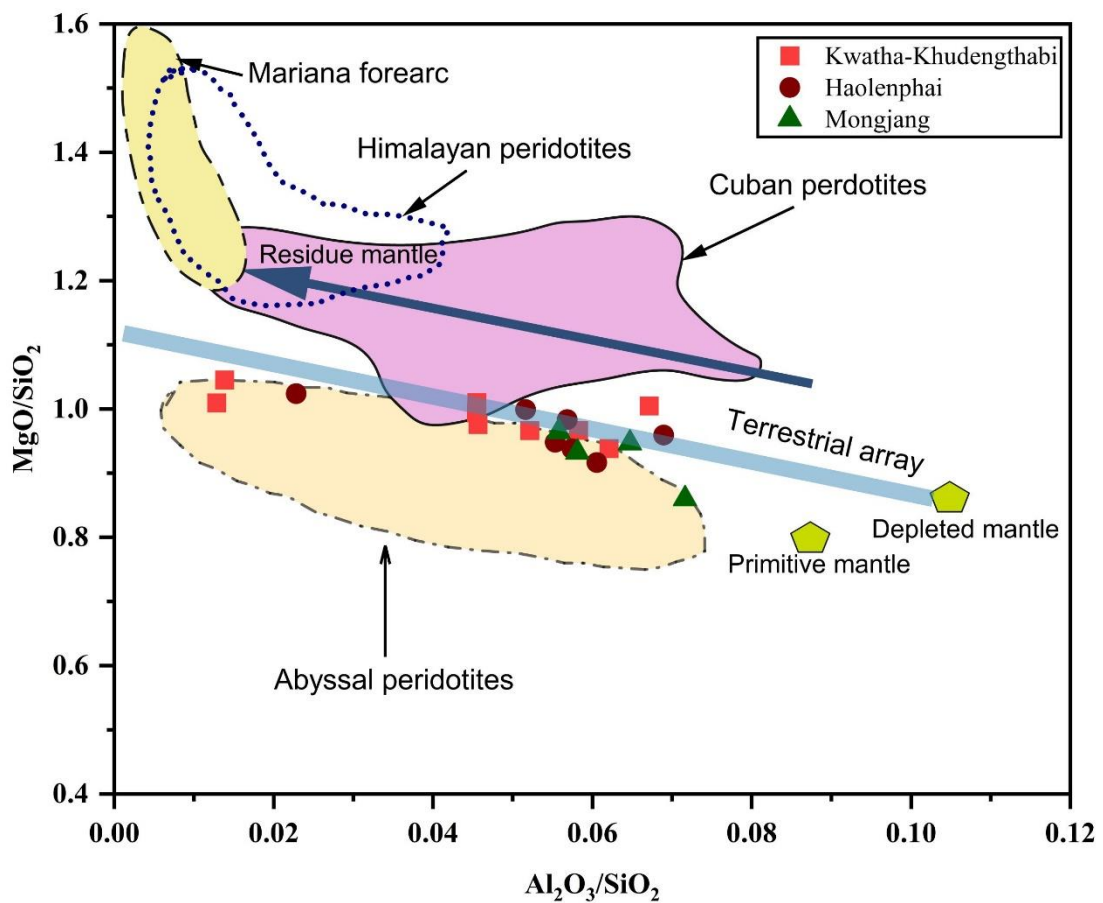


Fig.6.2: MgO/SiO_2 versus $\text{Al}_2\text{O}_3/\text{SiO}_2$ of the studied ultramafic peridotite samples. Depleted mantle, primitive mantle, and abyssal peridotite are from Salters and Stracke (2004a, b), McDonough and Sun (1995), and Niu (2004), respectively. The “terrestrial array” (light blue line) is after Jagoutz et al. (1979) and Hart and Zindler (1986). The “terrestrial array” (light blue line) is after Jagoutz et al. (1979) and Hart and Zindler (1986). The dark blue arrow shows the compositional variation due to the partial melting effect. Fields of abyssal, Mariana forearc, Himalayan, and Cuban peridotites Ishii et al. (1992), Niu (2004), and Hottari and Guillot (2007) are plotted for comparison.

metamorphic dunite (0.86), metamorphic harzburgite (0.85), and lherzolite (0.84).) suggesting that the ultramafic peridotites under analysis resemble metamorphic harzburgite-dunite (Coleman, 1977). The ultramafic peridotites of Haolenphai and Mongjang exhibit a refractory nature than Kwatha as evidenced by their high content of Al_2O_3 (average = 2.47 Haolenphai), high MgO/SiO_2 , and resemblance abyssal plagioclase peridotites of the mid-ocean ridge setting (Coleman and Keith 1971; Niu et al. 1997; Niu (2004). Ultramafic of Mongjang are more enriched in Al_2O_3 (2.93 weight percent), indicating that they are more refractory than Haolenphai's. The Al/Si ratio (0.04–0.08) of the ultramafic peridotites under study, is higher than the highly depleted mantle residual harzburgites (~ 0.02) but lower than the PM ~ 0.1 (McDonough and Sun 1995), further supports the refractory depleted mantle protolith of the studied ultramafic peridotites. This suggests that the samples are probably refractory peridotite residues from partial melting because aluminium depletes during partial melting and is generally incompatible with mantle minerals (Hattori and Guillot 2007).

The ultramafic samples under investigation largely occupy the spinel-peridotite mantle composition range, as shown in the Dy/Yb versus La/Yb diagram (Fig.6.3). About 30 percent of the abyssal peridotites on the ocean floor are plagioclase peridotites, according to Dick and Bullen (1984). Nevertheless, not every sample examined had plagioclase present. It is likely that the initial plagioclase content was low and was significantly changed during the serpentinization process, given the extremely low concentrations of Ca (0.00–2.45 wt.% %) and Na (0.04–0.07 wt.% %) in these samples. The results further suggest that the REE concentrations in the examined ultramafic rocks, particularly the relatively immobile HREE levels, are similar to those found in peridotites from mid-ocean ridges (abyssal peridotites). These concentrations are at least an order of magnitude higher than those observed in forearc-depleted peridotites from subduction zones. The bulk-rock major and trace elements depletion relative to PM value with Al_2O_3 as a depletion index and the depletion of REE and HSE relative to PM were further reported in various peridotites, including orogenic, abyssal, and ophiolite types (Bodinier et al., 1990; Bodinier and Godard, 2003; Niu, 2004, Bhat 2017), and is interpreted as residues from mantle melting processes.

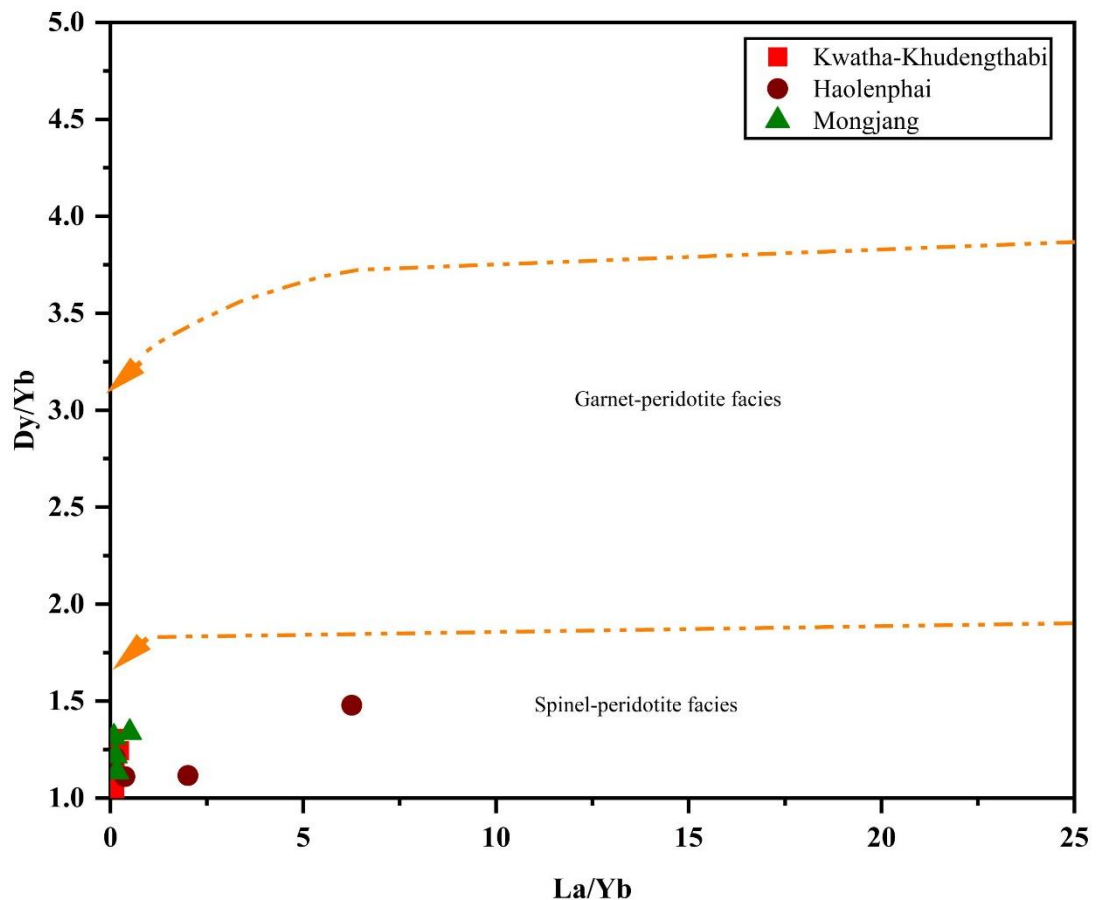


Fig.6.3 Dy/Yb versus La/Yb discrimination diagram demonstrating that the MOC ultramafic rocks formed within the spinel-peridotite stability field at shallow mantle depths, consistent with mid-ocean ridge or shallow subduction zone melting processes. The clustering of samples within the spinel peridotite field excludes deep garnet-bearing mantle sources and supports formation through low-pressure partial melting (modified after Jung et al. 2006).

The bulk-rock Al_2O_3 content in the study of ultramafic rocks remains largely unchanged by the process of serpentinization, thereby preserving their original, primary geochemical signature. This characteristic is significant because it indicates that the Al_2O_3 content serves as a stable marker for the parent rock's composition, unaffected by subsequent alteration. The Al_2O_3 concentrations in these rocks typically range from 0.54 to 3.01 wt.%, which is comparable to the values found in oceanic peridotites (Fig.6.4).

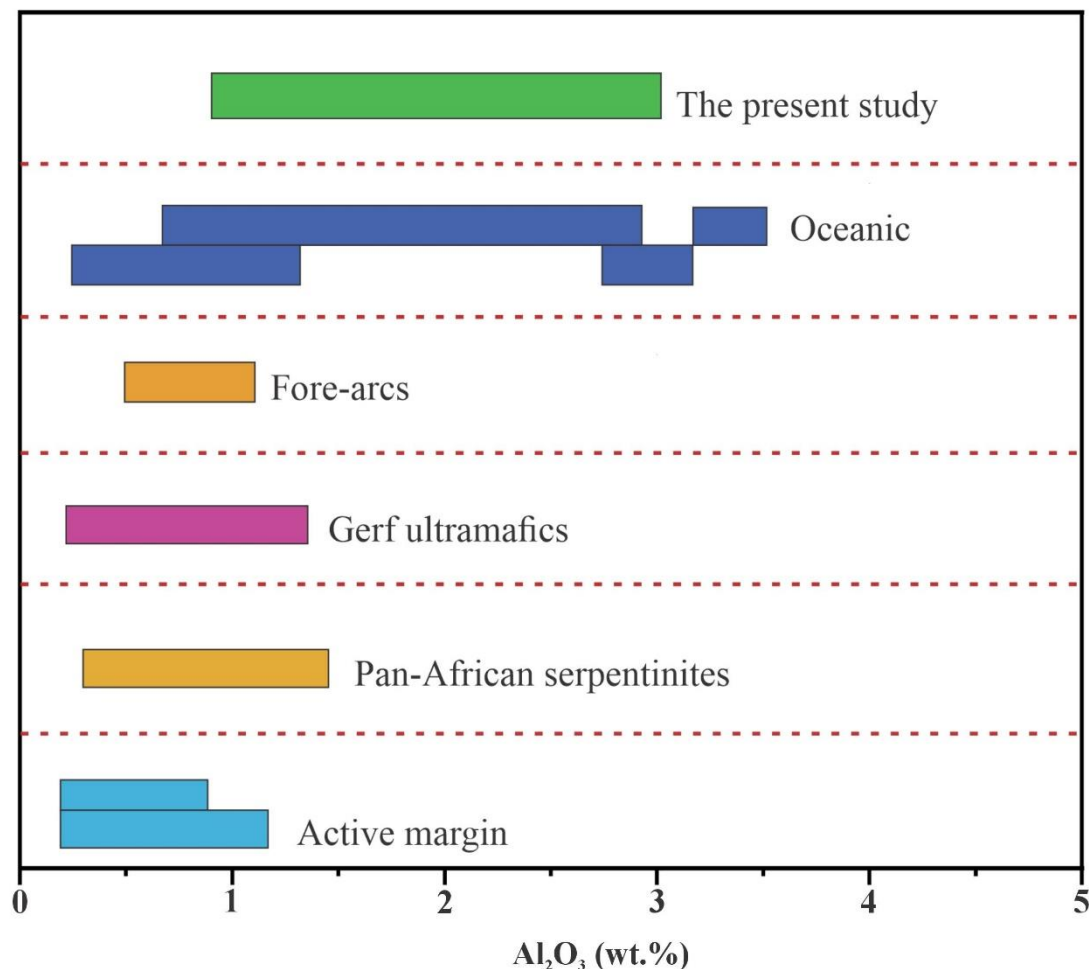


Fig.6.4: Al₂O₃ concentrations (0.54-3.01 wt.%) in MOC ultramafic rocks match oceanic peridotites and differ from continental peridotites, confirming oceanic mantle origin despite extensive serpentinization (comparative data from Floyd, 1991; Abdel-Karim, 2010).

6.3 Cause of Melt-rock Interaction

The Rare earth elements (REE) and high field strength elements (HFSE) have similar behavior and solubility in mafic melts. However, Light Rare Earth Elements (LREE) are more easily mobilized in aqueous solutions than heavy rare earth elements (HREE) and HFSE. As a result, melt-rock interactions transported an equal proportion of LREE and HFSE (Niu, 2004, Deschamp et al., 2013, Tsoungui et al., 2019). The serpentinization process of ultramafic rocks, which requires interaction with a trace element-rich melt before the rocks undergoing serpentinization, is linked to the

observed enrichment of LREE and HFSE in peridotites (Paulick et al., 2006; Kodolányi et al., 2011; Cannaò et al., 2016; Tsoungui et al., 2019). In the binary diagram of Gd/Lu versus Th and Yb versus La/Yb (Fig.6.5 and Fig.6.6), Deschamp et. al. (2013) identified two positive trends: a) trend with melt-rocks interaction (Black) and b) trend with fluid-rocks interaction (dark brown). The studied ultramafic display equal enrichment in LREE and HFSE, which are closely linked with melt-rock interaction trends.

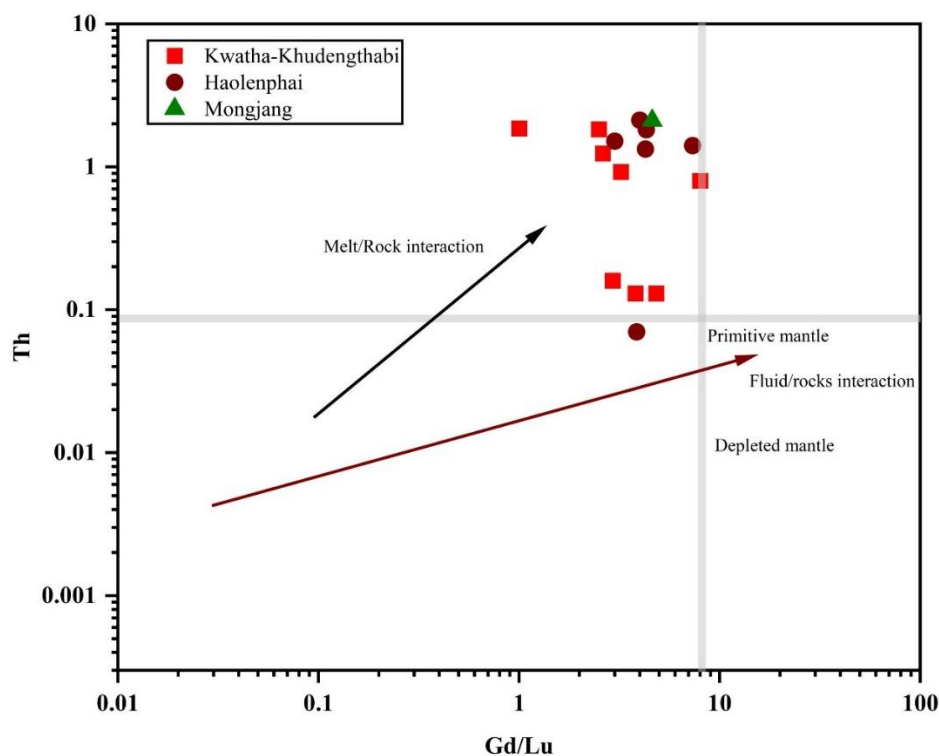


Fig 6.5: Th versus Gd/Lu (ppm) of the studied ultramafic rocks, where melt/rock interaction is represented by a black arrow where fluid/rock interaction is represented by dark-brown arrow trends of mantle peridotite (Paulick et al,2006). The estimated composition of the depleted mantle is from Salters and Stracke (2004) and of the primitive mantle is from McDonough and Sun (1995).

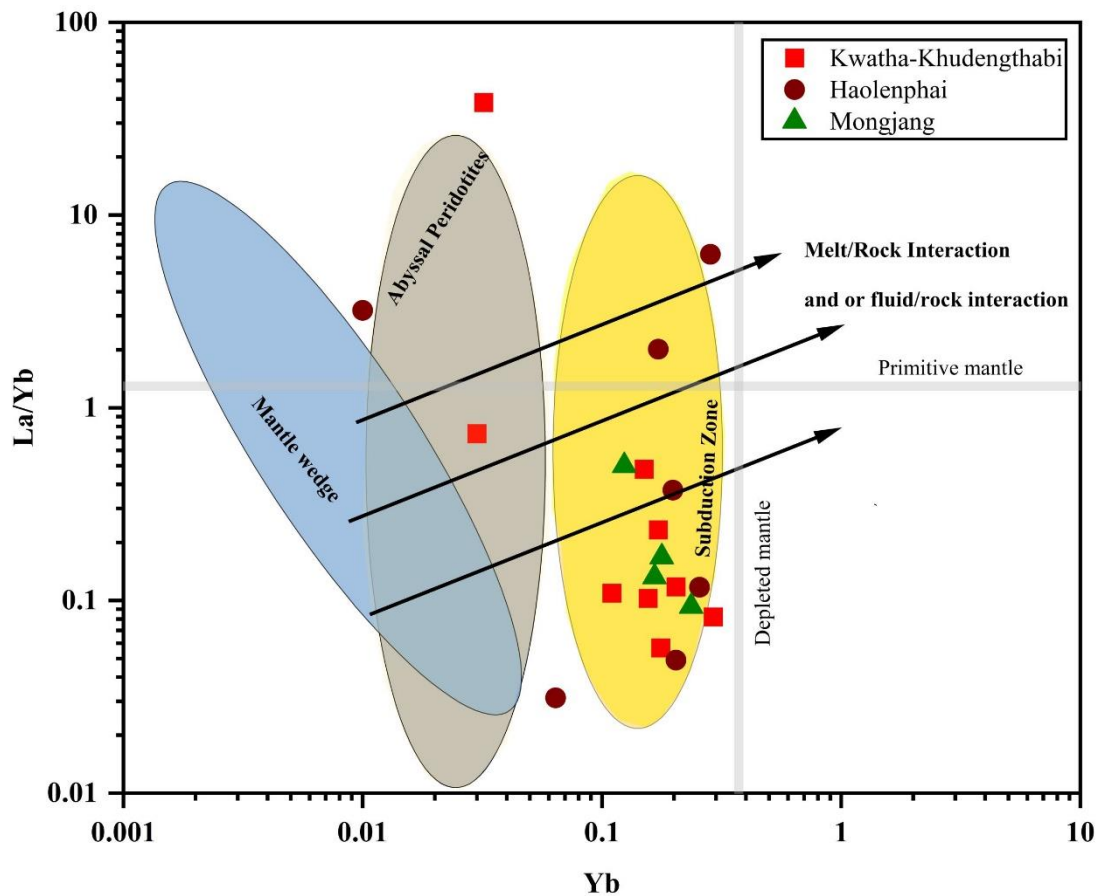


Fig 6.6: La/Yb ratio versus Yb contents (ppm) for the studied ultramafic rocks (after Deschamps et al. (2013)).

According to the binary plots of La/Sm versus Sm/Yb (Fig.6.7), the studied samples show enrichment in HREE relative to LREE, indicating a fertilized character caused by melt-rock interactions before serpentinization. According to Niu (2004), the abyssal peridotites, subducted peridotite, and mantle wedge peridotite that have interacted with melts had a significant enrichment in uranium (U), deviating from the conventional terrestrial pattern. In the Th versus U plot (Fig.6.8), most of the samples (except three samples from Kwatha and one from Haolenphai) are near to the magmatic array. This shows that the high amounts of Th and U are most likely caused by melt/rock interactions. However, it is crucial to note that the concentration of suitable trace elements in peridotite from subduction zones may be due to fluid activity during serpentinization (Niu, 2004). Such melt-rock interactions before

serpentinization are common and have recently been found in peridotite from the Eseka area (Tsoungui et al., 2019) and serpentinized peridotites from the Suru Valley ophiolite slice in the Ladakh Himalaya (Bhat et al. 2017).

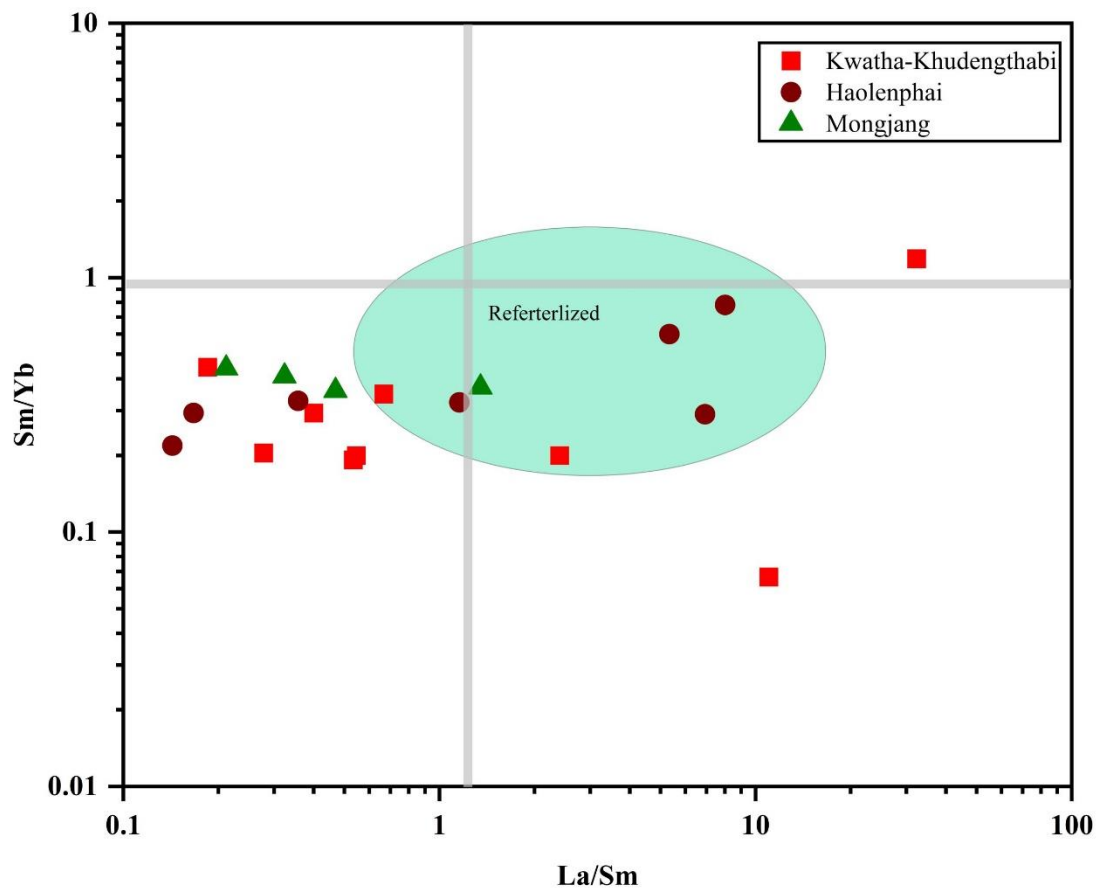


Fig 6.7: Sm/Yb ratio versus La/Sm ratio. The light blue ellipse represents ultramafic peridotite deriving from fertilized protoliths (after Niu,2004).

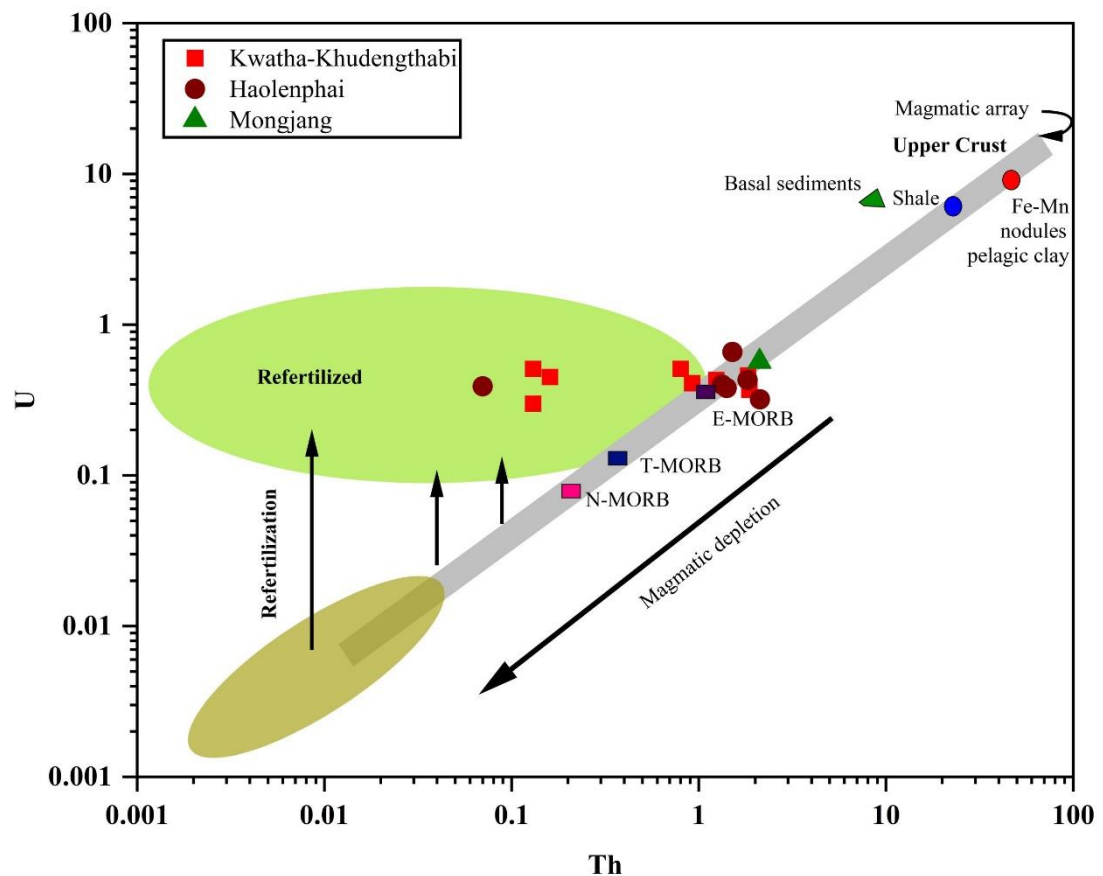


Fig.6.8: U versus Th contents (ppm) of the studied ultramafic rocks, the light green ellipse represents peridotite derived from fertilized protoliths. estimates of the sedimentary pole are after Li and Schoonmaker (2003), and the estimated of MORB compositions are after Klein (2003); the shaded area corresponds to the magmatic array defined by MORB, OIB, IAB, oceanic gabbros, and freshest peridotites; the Black field represents the freshest Tonga forearc harzburgite (Niu, 2004).

6.4 Tectonic implication

Ultramafic rocks typically serpentinized occur normally in three different tectonic settings: a) oceanic ophiolite complexes, where serpentinization is associated with oceanic metamorphism or alteration, b) through dynamic metamorphism at the subduction zone, and c) directly within the mantle. (Bucher & Grapes, 2011; Kamenetsky, 2001). Peridotites in ophiolite complexes and comparable environments undergo low-temperature alteration by retrogression and hydration. Previous workers

(Mével 2003; Kodolányi et al. 2011; Deschamps et al. 2013; Wu et al. 2018) argue that the geochemistry of serpentinites is intimately related to particular tectonic conditions. According to Kodolányi et al. (2011), ocean-floor metamorphism affects trace elements such as Rb and Sr, enriches Pb and Sb through carbonate precipitation, and accumulates U through hydrothermal alteration. Based on the concentrations of the principal oxides of SiO_2 -MgO and Al_2O_3 -CaO (Fig.6.9 a-b), Aumento and Loubat (1971) proposed two diagrams to distinguish between the different types of ultramafic fields: oceanic peridotite, layered intrusions, and low-high temperature Alpine ultramafic rocks. According to the diagram, the studied ultramafic are observed to fall into the low-temperature Alpine category and are close to the oceanic peridotite fields. Additionally, Gulacer and Delaloye (1976) introduced by use of a Ni/Co vs Ni plot (Fig.6.10) for classification. The plot shows that the majority of the ultramafic rocks have high Ni/Co ratios and correspond to the Alpine-type field (Dunite-peridotite). Such high Ni/Co ratios are indicative of ultramafic rocks formed during the early phases of magma production by partial mantle melting (Kogarko, 1973).

Based on the Cr-TiO₂ composition, Pearce et al. (1984) created a schematic to distinguish ophiolites from the supra-subduction zone (SSZ) from those from the Mid-Ocean Ridge basalt (MORB) (Fig.6.11). The majority of the samples analyzed fall within MORB ophiolites and some of the samples are affinity towards SSZ ophiolite classification, suggesting that the ultramafic rocks under investigation are a component of an ophiolitic mantle sequence that was thrust over the continental margin. Thus, the ultramafic rocks under study highlight the influence of various tectonic-magmatic settings. Similarly, the trace element plot between La/Sm versus Sm/Yb shows that all of the samples lie inside the abyssal peridotite area (Fig.6.12).

The present ultramafic rocks are positioned in the overlapping region between abyssal, supra-subduction zone, and mantle wedge serpentinites on the CaO vs. MgO binary plot (Fig. 6.13), trending toward the depleted mantle domain. (Lines follow Deschamps et al., 2013, and the depleted mantle data are based on Workman and Hart, 2005).

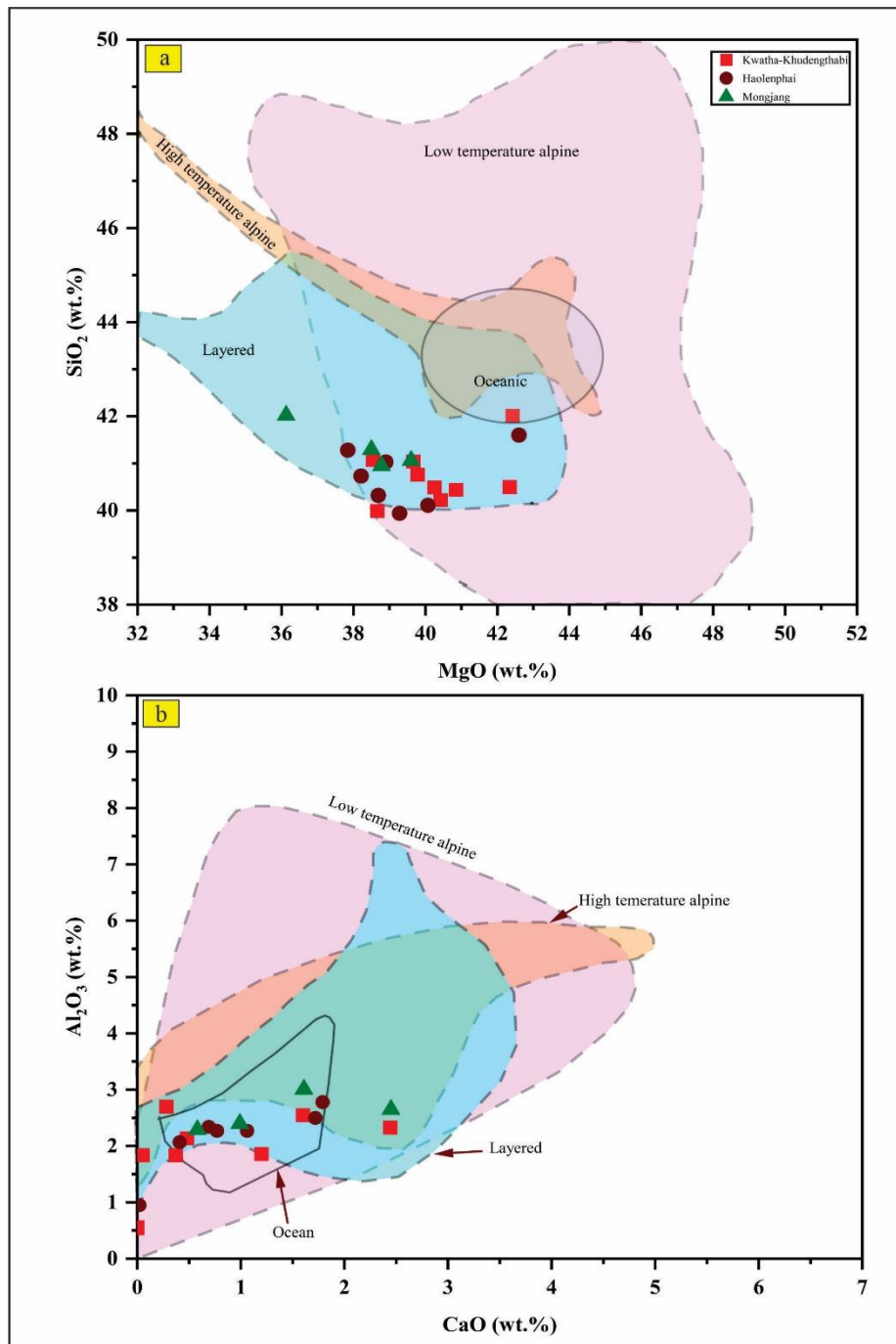


Fig 6.9: a) SiO₂ versus MgO (wt.%) plots of the studied ultramafic rocks. Fields of low and high-temperature alpine, oceanic and layered are taken from Aumento and Loubat, (1971) b) Al₂O₃ versus CaO (wt.%) variation diagram of the analyzed ultramafic rock samples. Fields of low and high-temperature alpine, oceanic, and layered ultramafic are taken from Aumento and Loubat, (1971).

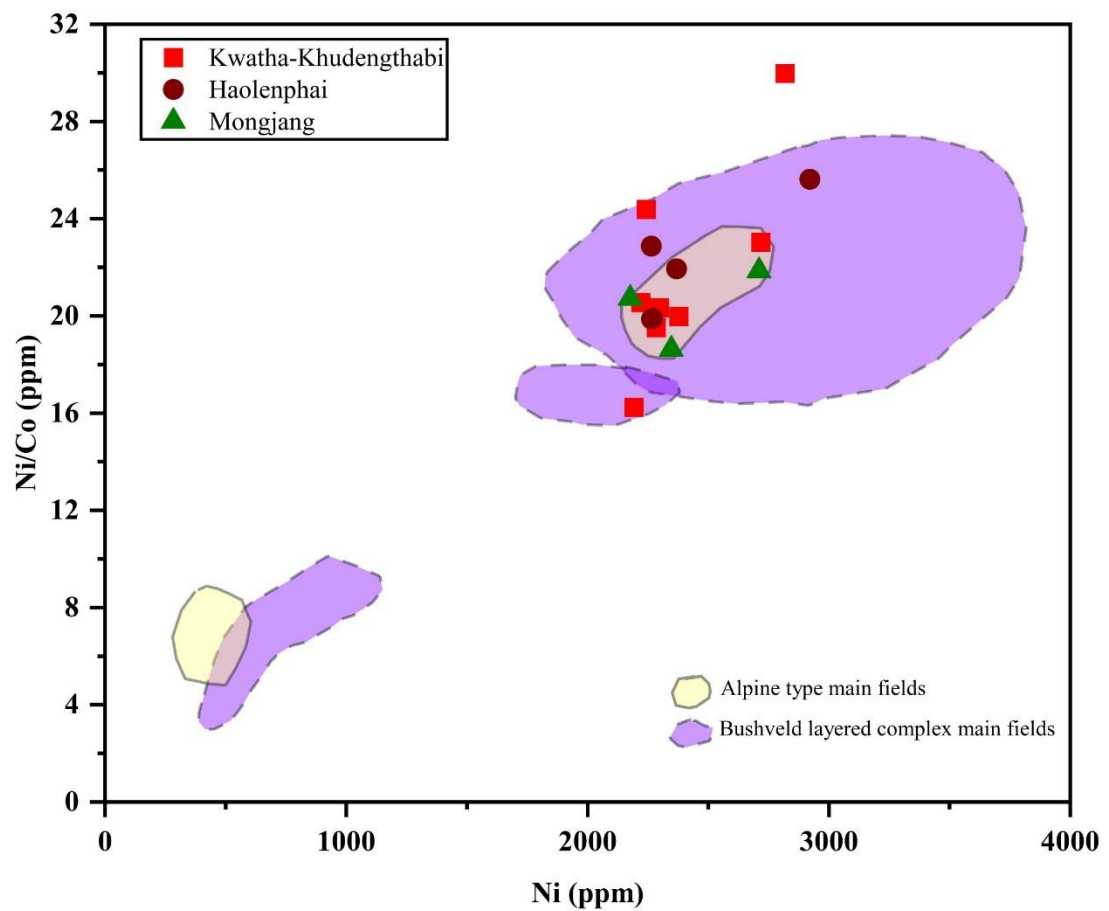


Fig 6.10: Ni/Co ratio versus Ni plot of the studied ultramafic rocks in comparison with ratios of alpine-type and bushveld-layered ultramafic (Gulacar and Delalaye,1976).

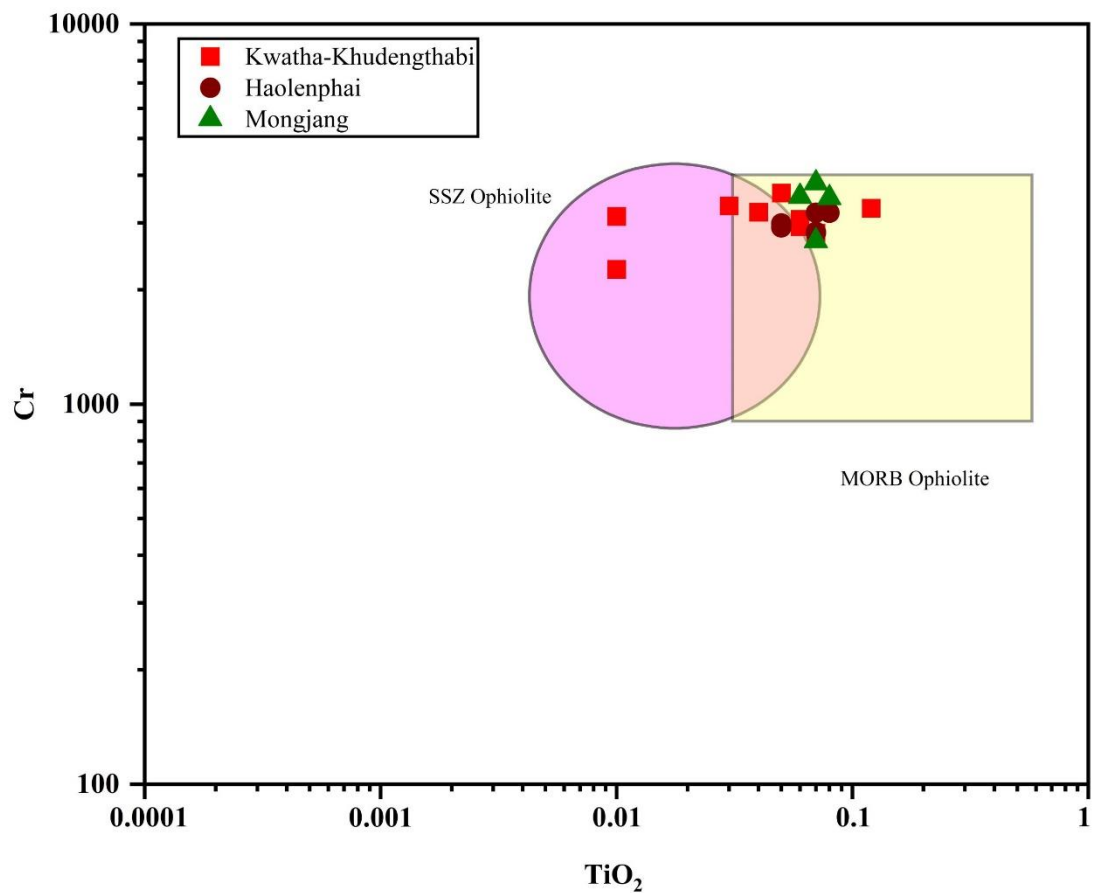


Fig 6.11: Cr-TiO₂ plot for the studied ultramafic rocks, fields are demarcated after plotting ultramafic rocks of different global Tethyan ophiolites (after Pearce, 2008). The 'SSZ' ophiolite mantle residue is generally more residual in nature (less TiO₂) than that of the 'MORB' ophiolites.

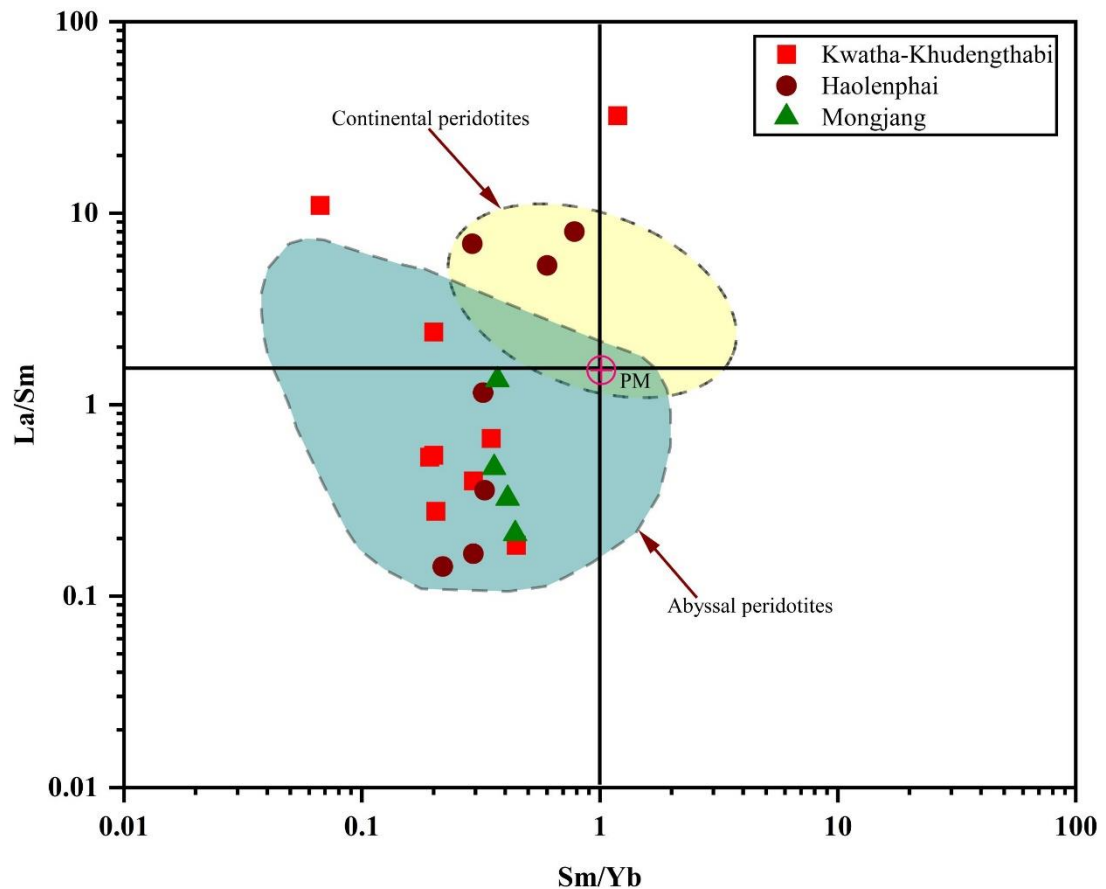


Fig 6.12: Sm/Yb-versus-La/Sm ratio plots of the studied ultramafic rocks (after Whattam et al. (2011)). The abyssal peridotite field is from Niu (2004), and the field of continental peridotite is created from Knippa peridotite xenoliths, Ouachita belt, southern Laurentia (Young and Lee, 2009).

To determine the impact of subduction on SSZ lavas, a Ti/1000 versus V plot (Fig.6.14) is used to study the studied ultramafic-mafic rocks (Servais,1982). Titanium (Ti) is a highly incompatible element whose concentration in melts falls as partial melting increases. Vanadium (V), on the other hand, is generally immobile and reacts incompatibly in the presence of water under higher oxidizing circumstances. As a result, the presence of subducted fluids causes a melting process that depletes Ti while enriching V. Mid-Ocean Ridge Basalts (MORB) have lava compositions with Ti/V ratios greater than 20; island arc tholeiites have ratios between 10 and 20; and boninites have ratios less than 10. The present study rocks have low Ti/V ratios ranging

from 0 – 7.19 ppm (less than 10) placing them in the boninites. This implies that these rocks developed during subduction initiation in greater oxidizing conditions. The high Ti concentration (average = 335.72) of the studied ultramafic rocks closely linked to the value of subducted peridotite supports a subduction-related setting (Fig.6.15 a-d). Furthermore, the high chromium (Cr) levels and spinel protolith compositions indicate that the parent magmas were formed in a subduction zone environment, namely a Supra Subduction Zone setting (Parkinson and Pearce 1998).

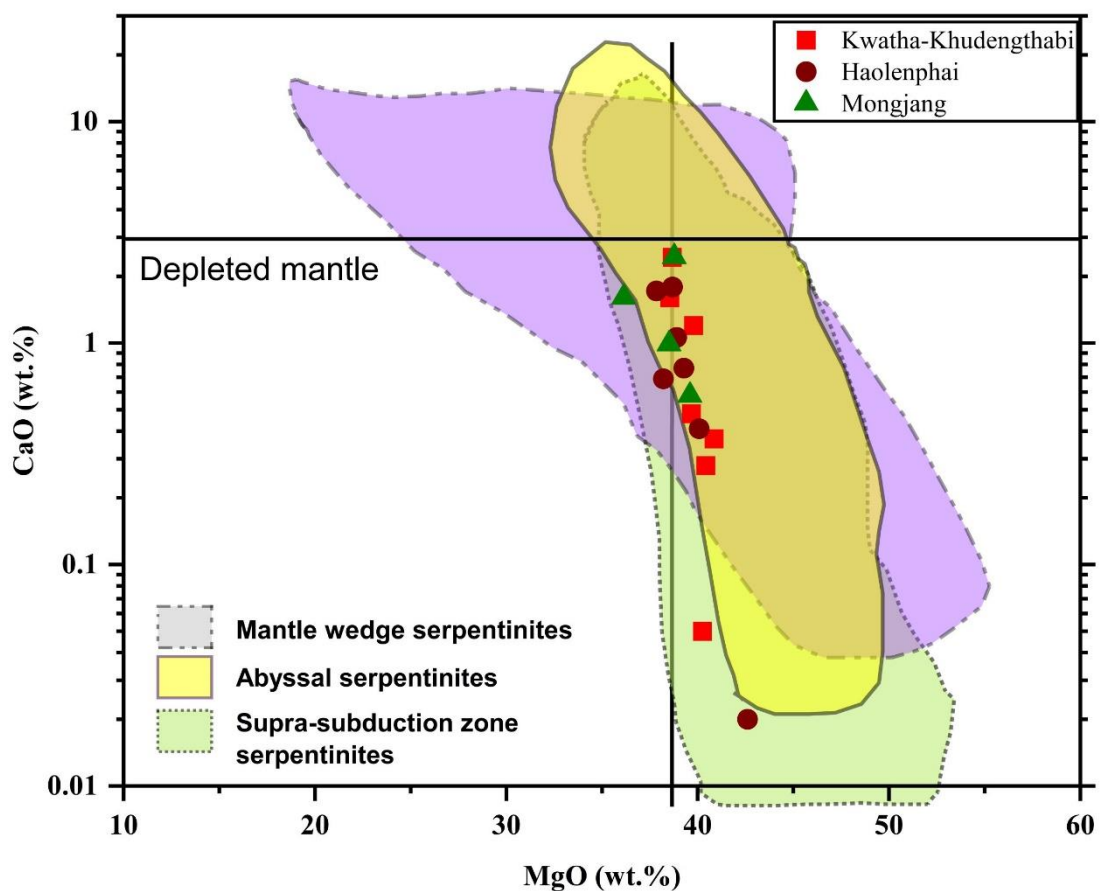


Fig 6.13: CaO versus MgO plots for the studied ultramafic rocks. Mg number lines are taken from Deschamps et al. (2013) and depleted mantle are after Workman and Hart (2005).

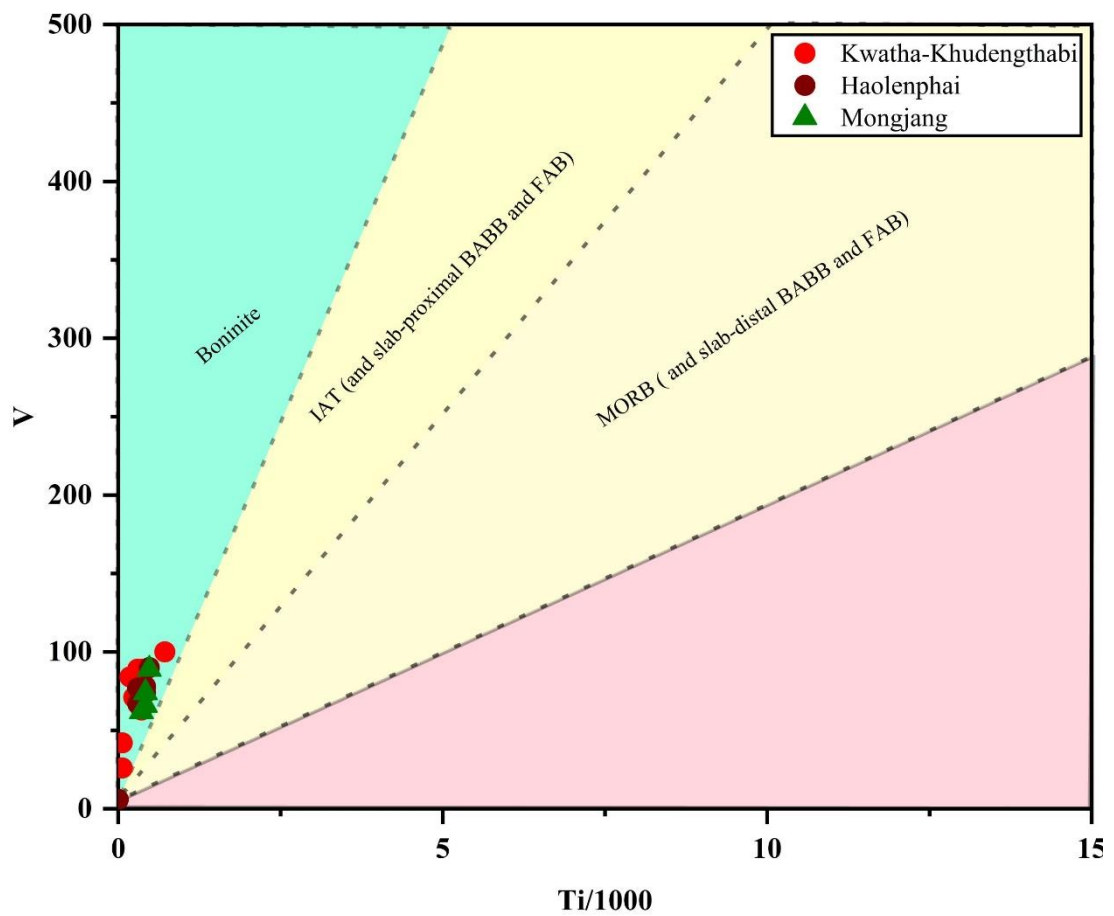


Fig.6.14: Tectonic discrimination diagrams of $Ti/1000$ vs. V plot of the studied ultramafic rocks (Pearce, 2014; Shervais et al, 1982) separating MORB, island arc tholeiite (IAT), and boninite magma types.

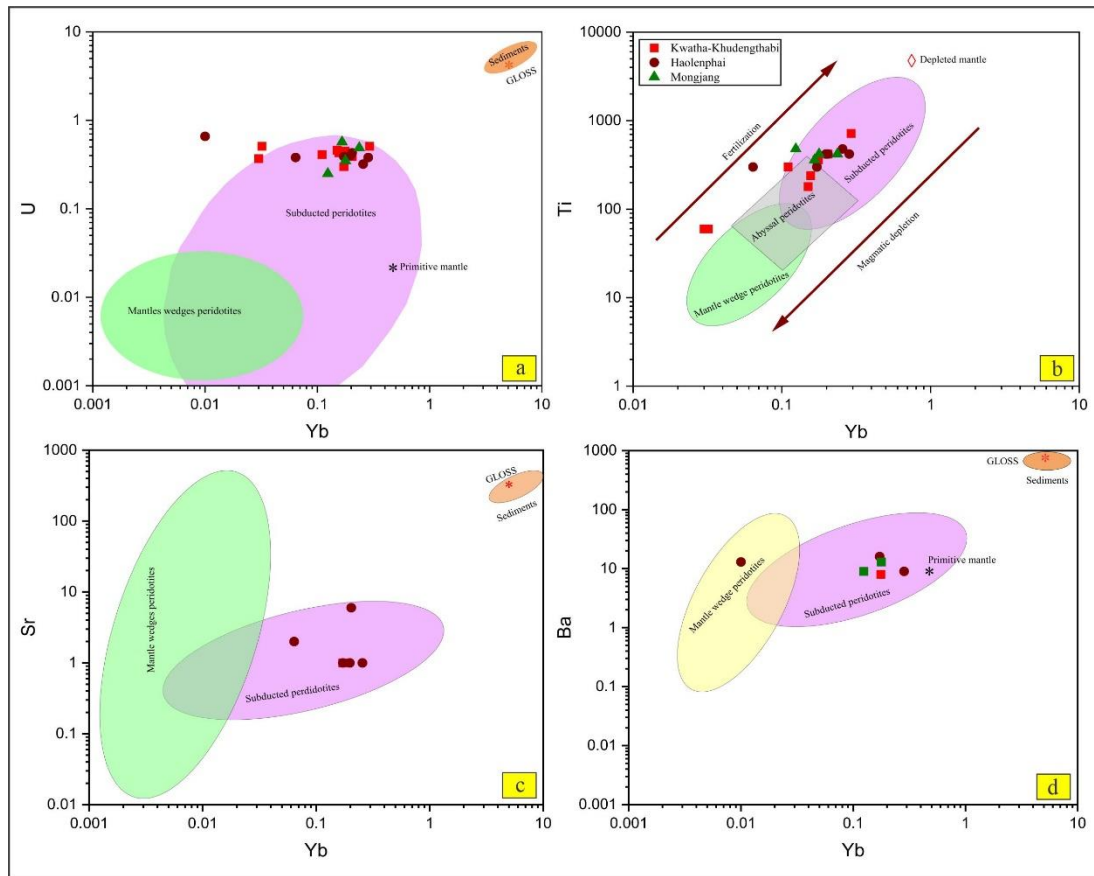


Fig.6.15: a) U (ppm), b) Ba (ppm), c) Sr (ppm), and d) Ti (ppm) versus Yb (ppm) binary plots for the studied ultramafic rocks. Compositions of the primitive mantle, global subducting sediments (GLOSS), sediments are from McDonough and Sun (1995), Plank and Langmuir (1998), and Li and Schoonmaker (2003), respectively.

6.5 Partial melting and Melt extraction

The degree of partial melting of the studied ultramafic peridotites can be determined using whole-rock major oxides and trace element geochemical characteristics, which are primarily controlled by partial melting processes and fluid/melt-rock interactions. The peridotites within the ophiolitic complexes are valuable geological records that offer insights into partial melting processes and subsequent metasomatism and the evolution of the mantle structure and composition throughout ocean basin development and closure (Bodinier, 2003; Brandl et al., 2017). This partial melting

causes depletion of the mantle and removal of major minerals phase. The degree of partial melting can be inferred from whole-rock concentrations of major and trace elements (Niu, 2004). Some major elements like Al_2O_3 , and CaO , and trace elements such as HREE, Cr, Ni, Co, Sc, and Ti tend to have quite similar behaviours during partial melting and related processes. These elements are useful indicators of mantle magmatic processes because they remain relatively stable during seafloor weathering and serpentinization (Niu, 2004; Paulick et al., 2006).

Low heavy rare earth element HREE (Ho, Er, Tm, Yb, Lu) concentrations relative to depleted mid-ocean ridge basalt (MORB) mantle (DMM) (Workman et al., 2005) suggest significant partial melting. By comparing the very low HREE levels in the studied peridotites with DMM melting curves within the spinel stability field, it is indicated that the protolith harzburgites of the studied ultramafic were derived from DM with degrees 5% -15% partial melting. High MgO content and Mg# in mantle-derived peridotites are indicative of significant depletion and correlate with the degree of partial melting. Additionally, low levels of TiO_2 , Al_2O_3 , and CaO compared to the primitive mantle also suggest high partial melting. (Hirose & Kawamoto, 1995, Takazawa et al., 2003, Frey et al., 1985, Khedr et al., 2013). The analyzed peridotites exhibit higher MgO and lower TiO_2 , Al_2O_3 , and CaO contents than primitive mantle sources, reflecting a greater degree of partial melting. In plots of Al_2O_3 , TiO_2 , Fe_2O_3 , and CaO versus MgO (Fig. 6.16), the ultramafic peridotites align with the end of polybaric melting curves, supporting a 3–15% partial melting range, consistent with HREE-based estimates (Fig. 6.20).

To better understand the partial melting of the ultramafic rocks under study, we modeled whole-rock concentrations of Ni and Yb using a non-modal dynamic melting model (Kapsiotis, 2015). Since Ni and Yb are considered fluid-immobile elements—with Ni being compatible and Yb relatively incompatible during melting—the Ni/Yb versus Yb plot helps determine the degree and type of partial melting. In this plot, the studied peridotites suggest approximately 10%–25% closed-system non-modal dynamic melting of the primitive mantle (Fig. 6.17). Elements that remain unaffected by serpentinization, such as Cu and Y, show concentrations that are significantly lower

than those of primitive mantle values. This suggests that the rocks have experienced substantial melt depletion from their original mantle sources.

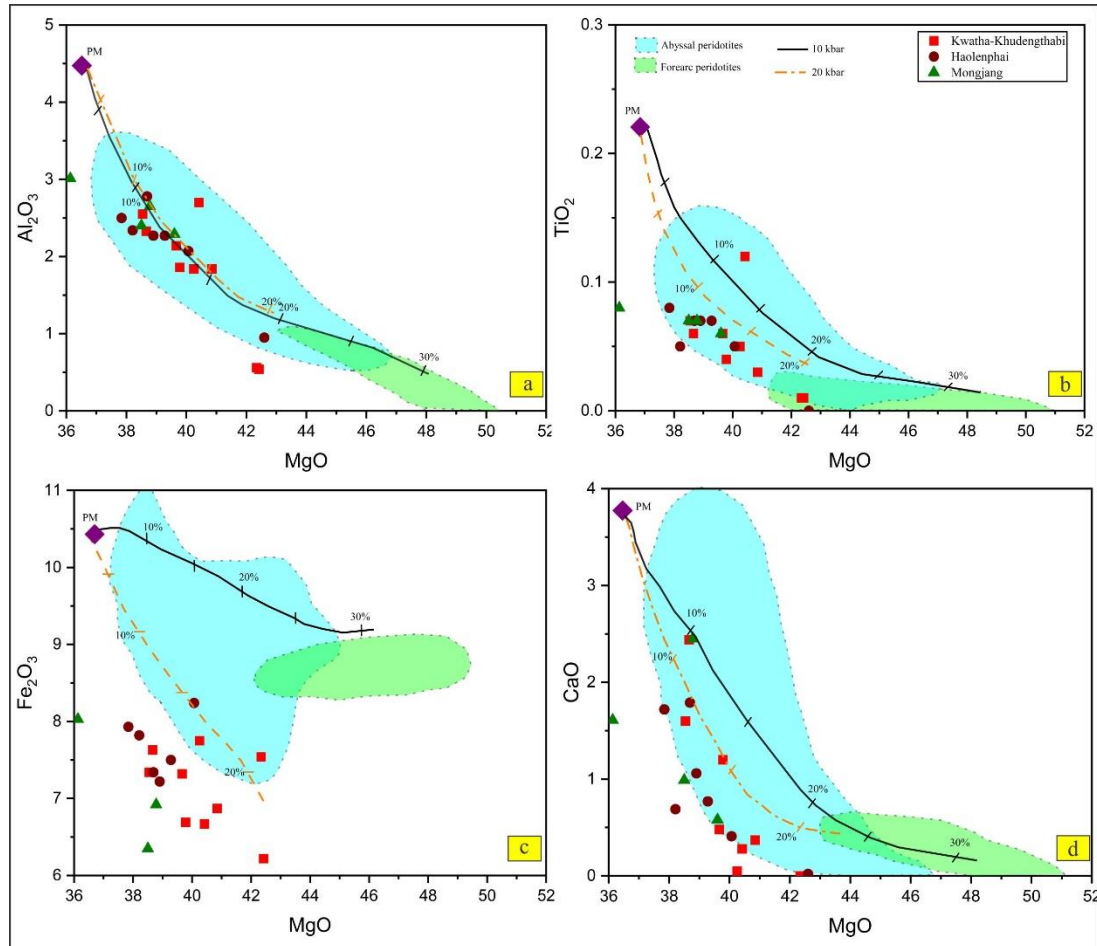


Fig 6.16: Variation diagrams of MgO (wt. %) vs. selected major oxides (wt.%) a) Al_2O_3 b) TiO_2 c) Fe_2O_3 d) CaO of whole-rock abundances from the mantle peridotite. Field of Abyssal and SSZ peridotite fields are from Niu 1997; Parkinson and Pearce 1998. Residual compositions after melting (at 10 and 20 Kbar) of Primitive Upper Mantle (PM; Palme and O'Neill 2004).

Elements least affected by post-melting procedures and low-temperature changes should be used to ascertain the type and extent of melt extraction (Pearce et al., 2000; Niu, 2004). The correlations between whole-rock Yb versus Cr, and Sc (Fig.6.18 a and Fig.6.18 b), reveal that the rock types from Kwatha and Haolenphai have undergone

melt extraction with melting degrees ranging from 5% to 15% and 10% to 15%, respectively. The Ti versus Dy (Fig.6.19) and Cr vs Yb plot also indicates that the peridotites experienced around 5%–10% partial melting of the fertile MORB mantle, and also suggest that the studied ultramafic peridotites are residues after less than 10% melt extraction (around 7%) for lherzolite and less than 20 % (mainly 15%) for harzburgite. Thus, the studied ultramafic rocks in MOC are abyssal or MOR peridotite which are mantle residues derived by partial melting at low pressure that occurs beneath MOR.

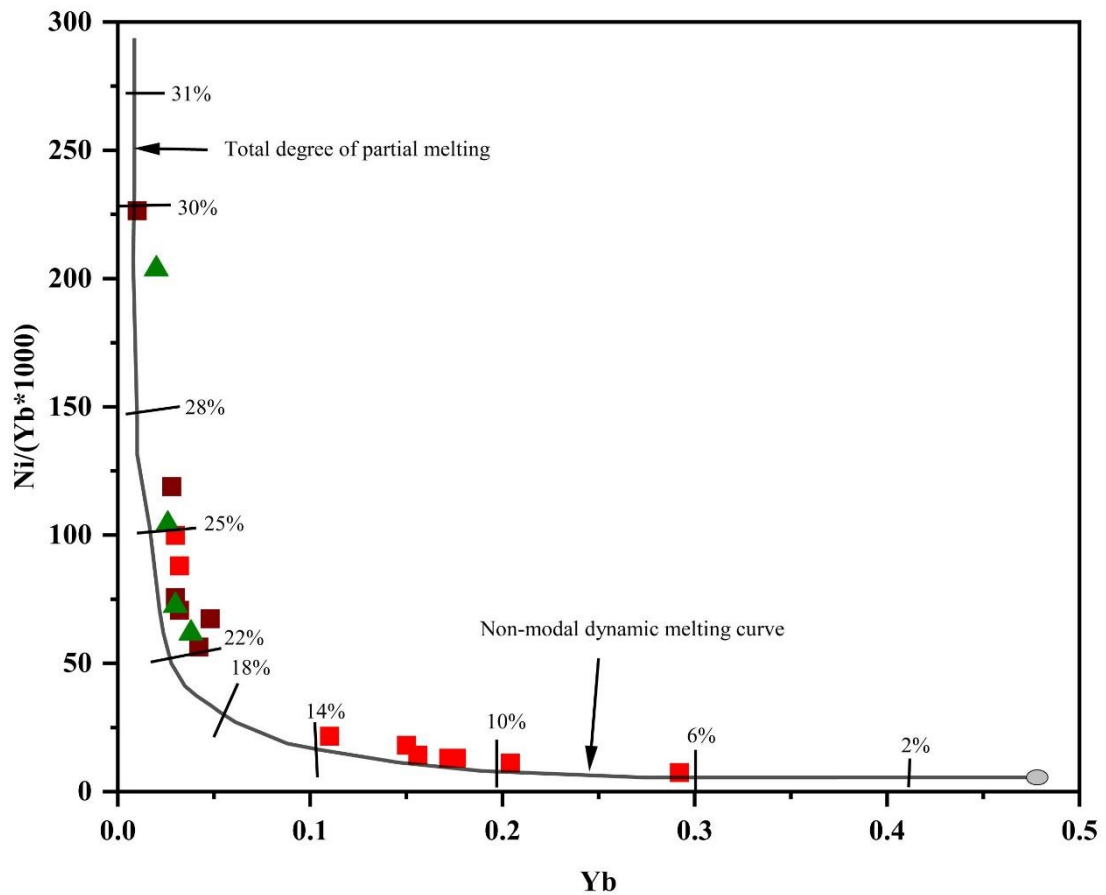


Fig 6.17: Estimation of partial melting degree using bulk-rock chemistry of non-modal dynamic melting of a primitive mantle (PM) source (Palme & O'Neill, 2004) (after Kapsiotis, 2015) for the studied ultramafic rocks. The primitive mantle (PM) compositions are after McDonough and Sun 1995 and Niu 1997.

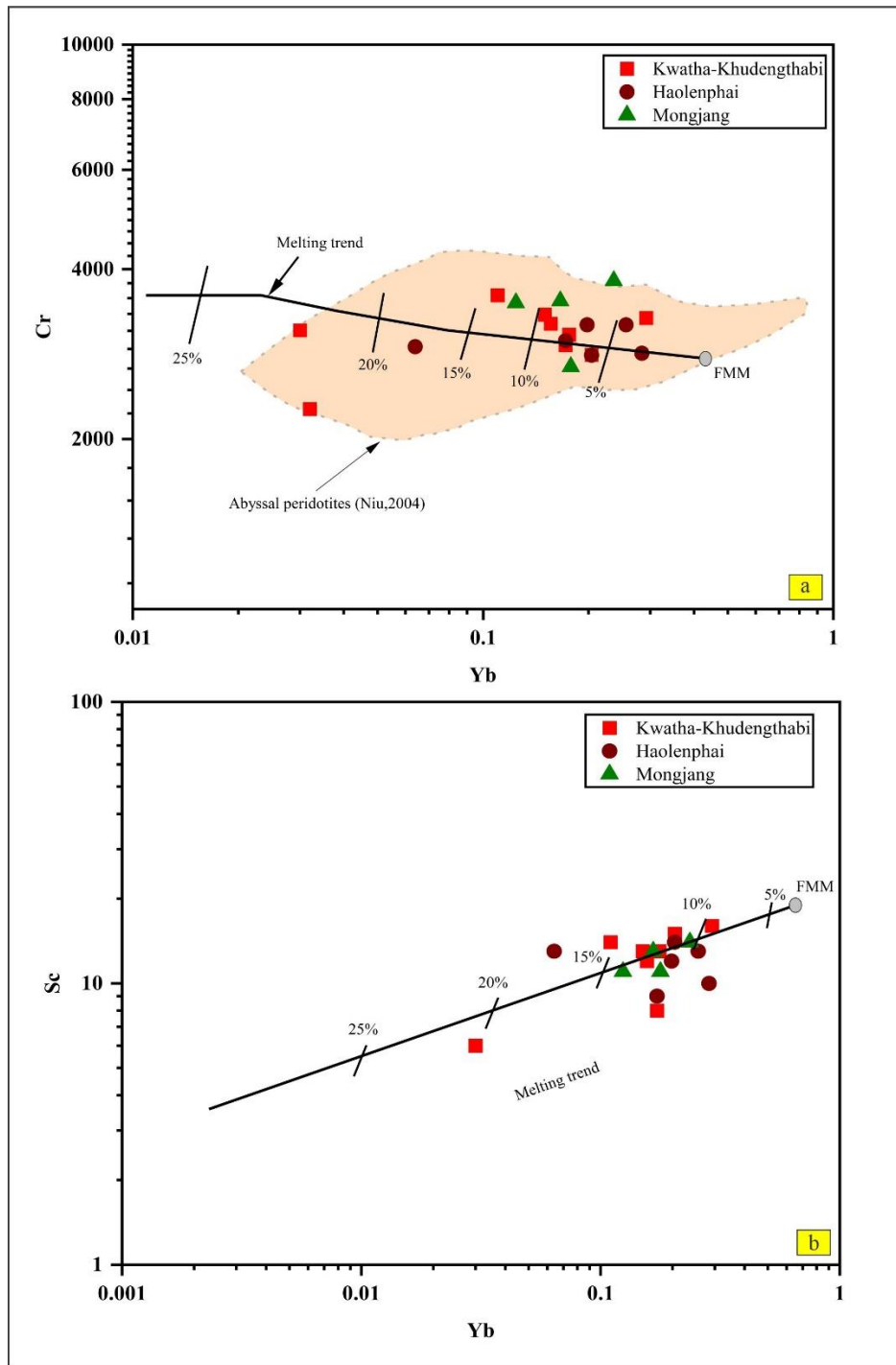


Fig. 6.18: Bivariate a) Yb (ppm) versus a) Cr (ppm) and b) Sc (ppm) of the studied ultramafic rocks. FMM stands for fertile MORB mantle (Pearce and Parkinson, 1993). The melting trends are taken after Pearce and Parkinson (1993) and Lee et al. (2003). Abyssal peridotites fields from the Pacific and Indian Ocean ridges (after Niu, 2004).

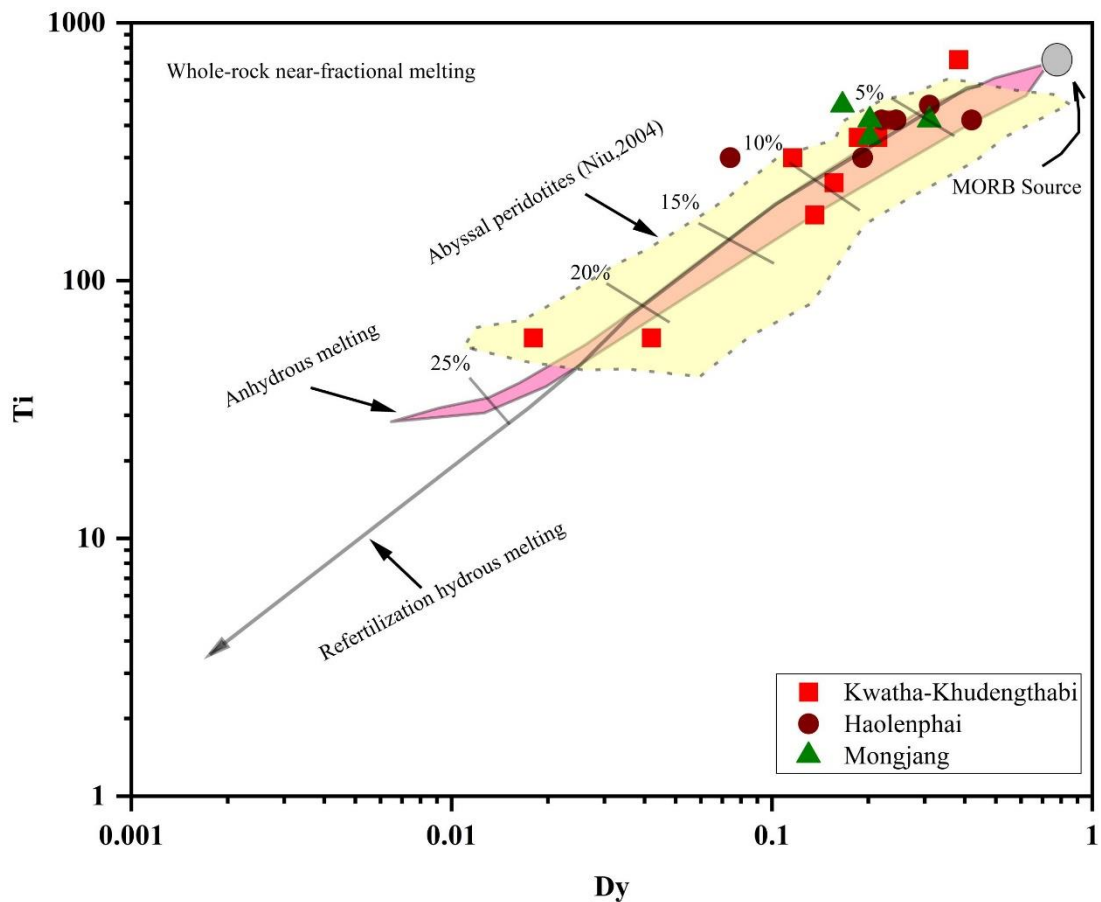


Figure 6.19: Estimation of Partial Melting Degree Using Bulk-Rock Chemistry. (a) The plot shows the relationship between Dy (ppm) and Ti (ppm). The residual peridotite compositions from anhydrous melting (specifically, incremental batch melting at 0.1% intervals) of a MORB source are represented within the MORB melting field (Bizimis et al., 2000). The compositions of residual peridotites resulting from fertilization-hydrous melting of a previously depleted source (residue 9% anhydrous melting) follow the fertilization-hydrous melting trend. These compositions were calculated using the model of Bizimis et al. (2000), with numbers along the lines indicating the percentage of melting (Barth et al., 2008). Based on clinopyroxene (Cpx) chemistry, partial-melting degrees for lherzolites are less than 10%, and for harzburgites, they are less than 20%.

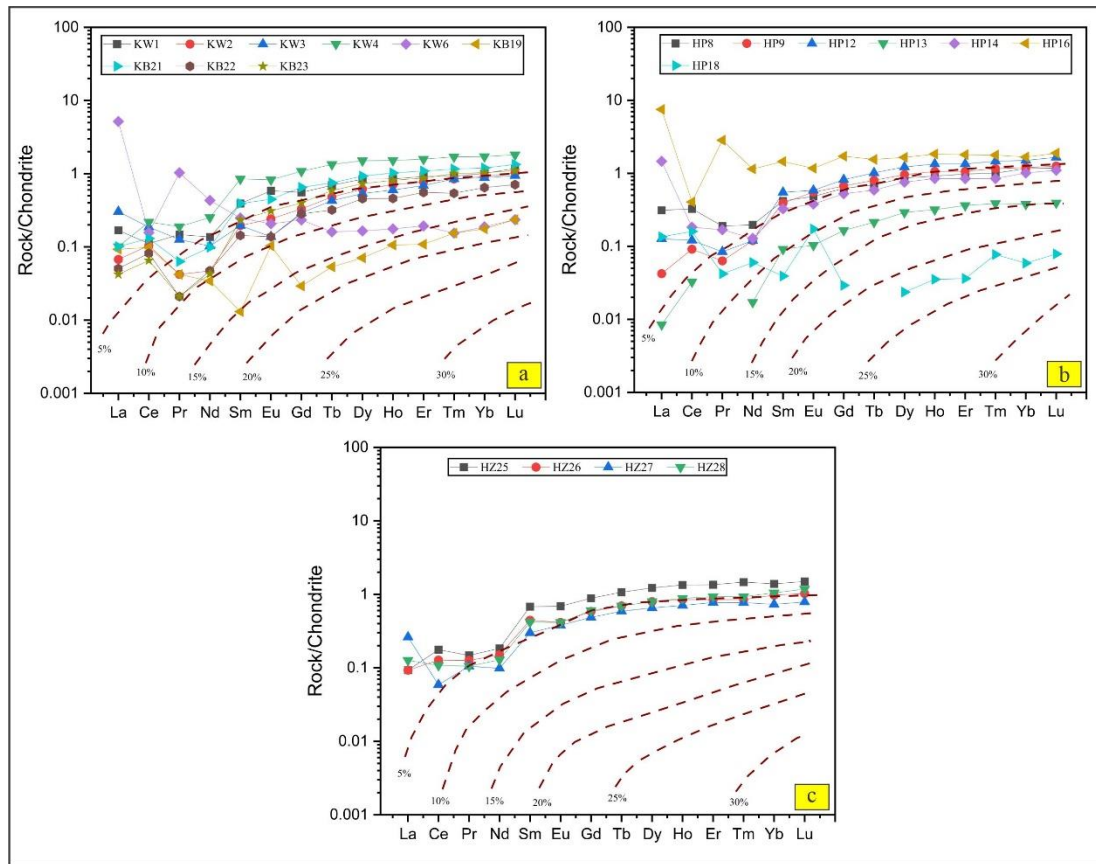


Fig 6.20: Chondrite-normalized REE patterns for the studied ultramafic rocks samples (McDonough and Sun, 1995). Melting curves assuming a source of DM composition in the spinel stability field are from De Hoog et al. (2009).

6.6 Implication of Serpentinite Texture

The petrography, mineral composition, and texture of serpentinite ultramafic under study reveal various serpentinization processes. In the hand specimen, various colors were observed on the surface of the serpentinite which may indicate varying degrees of alteration resulting from prolonged and intense seawater-rock interaction. The original mantle rock was harzburgitic and limited dunite, as evidenced by the common pseudomorphic textures representing bastite developed after orthopyroxene and mesh texture developed after olivine. Bastite generally has a porphyritic texture. Undulose extinction, kinking, subgrains, and deformation lamellae in bastites indicate that the ultramafic peridotite experienced intercrystalline deformation before serpentinization. Bastite pseudomorphs, which have higher chromium and aluminum contents and are most likely due to the alteration of orthopyroxene (Wicks and Plant, 1979), represent the initial phase of serpentinized ultramafic peridotite. These pseudomorphic textures are most likely the product of hydrothermal metamorphism on the ocean floor, where certain mesh or bastite textures may have persisted through later stages of prograde metamorphism and deformation. The serpentinites ultramafic under study are primarily composed of lizardite, chrysotile, and less amount of antigorite (determined in XRD). Based on the whole-rocks composition of the ratio of MgO/SiO_2 versus $\text{Al}_2\text{O}_3/\text{SiO}_2$ and LOI versus SiO_2 diagram of the studied ultramafic rocks correspond to lizardite and chrysotile bearing serpentinites (Figure 6.21 a and 6.21 b). In contrast, samples with higher metamorphic grades clustered closer to the end-member compositions, indicating that the process of metamorphism enhances chemical uniformity. Thus, the ultramafic rocks in the study area correspond to the field of Lizardite and mixed lizardite and chrysotile suggesting that are of low-grade metamorphism. The high lizardite and chrysotile abundances suggest that these minerals formed during low-temperature alteration. Serpentinites' oxygen and hydrogen isotope ratios are commonly used to estimate their formation temperatures. Various workers indicate that oceanic lizardite and chrysotile likely form at temperatures between 130°C to 185°C, while oceanic antigorite forms at approximately 235°C (Wenner and Taylor, 1973). Chrysotile and lizardite minerals are widely distributed in serpentinites, usually found together. They are indicative of temperature conditions that range from the surface to 400°C, with lizardite ranging

from 50 to 300°C through the hydration of peridotite, and chrysotile is found in veins and as a replacement within a range of 0 to 400°C and antigorite, on the other hand, is formed by the recrystallization and hydration of peridotite at temperatures ranging from 250°C to 600°C. (Evans, 2004). According to Hilairet et al. (2007), lizardite and chrysotile may exist in low-temperature oceanic environments of 200–400 °C. According to Bouchet (2008), lizardite, chrysotile, and antigorite can be found at 200°C to 300°C, 200°C to 300°C, and 300°C to 600°C and according to Schwartz (2012) the temperature condition of the three polymorphs of serpentine is Lizardite and chrysotile can be found at less than 300 and antigorite 390-460. Therefore, the mineralogical assemblage of the studied samples which are predominantly of lizardite and chrysotile suggest that they were formed at lower temperatures and have a tendency to co-crystallize within a temperature range of approximately 250–350 °C. The degree of serpentinization often correlates with the presence of magnetite, which can be seen in the color changes of serpentinites. The rock typically appears green, or frequently pale green, in color as the magnetite migrates out of the mesh or hourglass textural units into cross-cutting lenses and veinlets at advanced stages of serpentinization (Wicks and Whittaker, 1977). This indicates that chrysotile veins formed after lizardite as a result of meteoric water activity. Additionally, the texture of magnetite changes with the level of serpentinization. Initially, magnetite appears as small, separate grains, but as serpentinization continues, these grains become larger and form stringers, and eventually, larger cross-cutting lenses and veins. The large, cross-cutting magnetite veins likely formed due to the later tectonic uplift of the oceanic crust, which created space for these veins to develop and be filled with serpentine minerals.

This tectonic activity also helped high-temperature fluids circulate through the veins, leading to the formation of chrysotile veinlets after the early serpentine veins. Thus, the mineral composition of serpentine, which includes the predominant presence of lizardite and chrysotile, suggests that the alteration occurred at consistently low temperatures within a range of 250-350 °C. This suggests that serpentinization in the area originated at low temperatures and moderate pressures (Mevel, 2003). This extensive serpentinization formed a mesh-like texture in which structureless

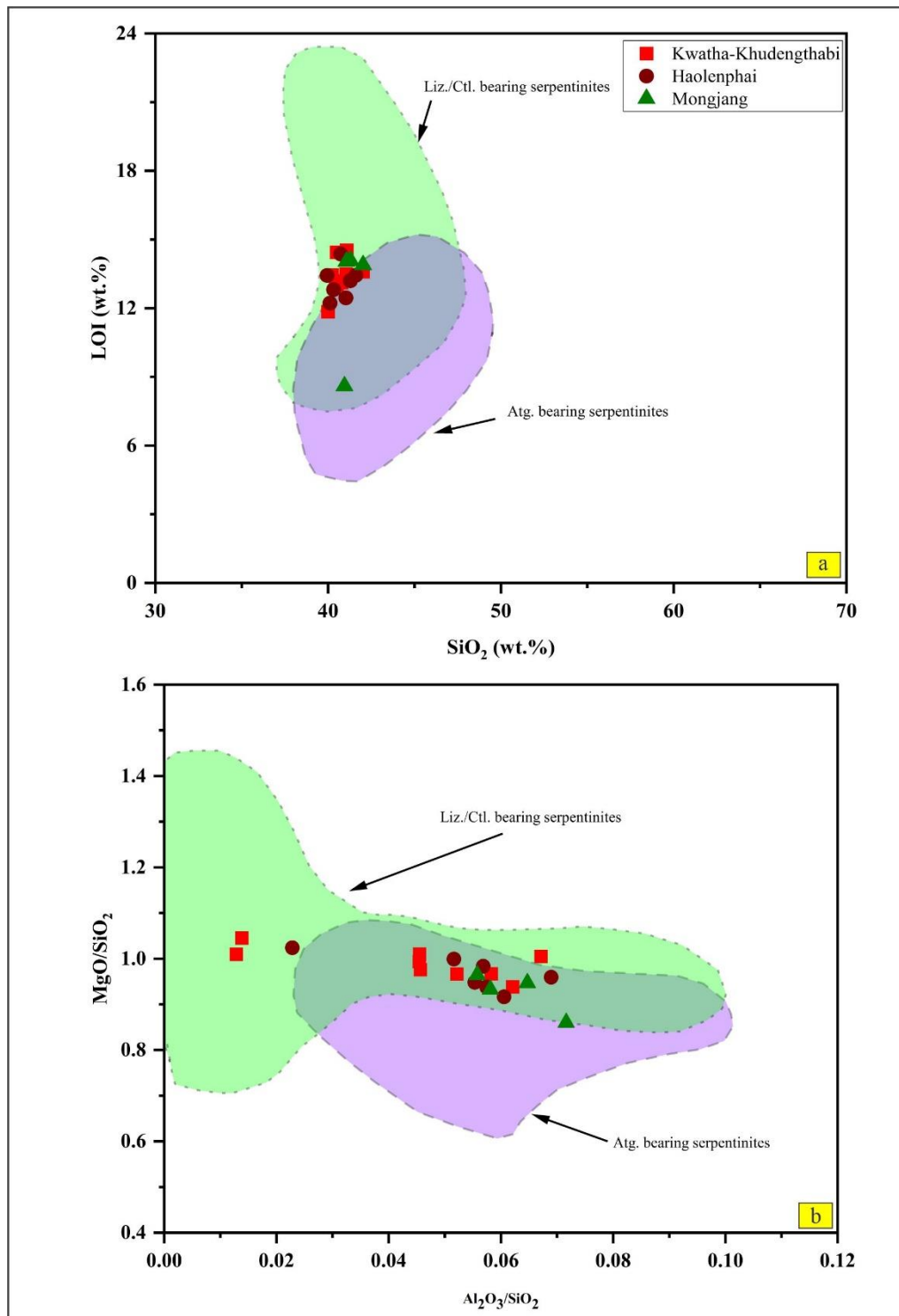


Fig.6.21: a) MgO/SiO₂ versus Al₂O₃/SiO₂ diagram. b) SiO₂ versus LOI diagram. In these diagrams, serpentinites with antigorite are distinguished from serpentinites with lizardite and chrysotile (Deschamps et al., 2013).

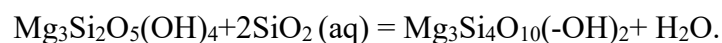
serpentine replaces olivine and lizardite forms pseudomorphs, as well as the formation of an orthopyroxene bastite texture. Furthermore, the high level of serpentinization is indicated by the production of magnetite strings and the disintegration of the original textures.

6.7 Alteration and metamorphism

The alteration and metamorphism of ultramafic rocks include a significant change in their textural, mineralogy, and chemical composition. It may have occurred at the ocean floor, beneath the oceanic crust either during tectonic emplacement or after subsequent exposure. As a result, various sources and compositions of the metamorphic fluids influenced the ophiolitic ultramafic rocks in MOC. Carbonate-rich bearing fluid and H₂O-rich from subducted pelagic carbonate had a crucial role in fluxing the Neo-Tethyan mantle wedge (Kingson, 2023) and hydrothermal infiltration during and after exhumation (Seyfried & Dibble, 1980). The ultramafic rocks that outcrop in the MOC are predominantly serpentinite. The presence of serpentinite indicates that the rocks underwent metamorphism from greenschist to amphibolite facies, most likely in the mantle wedge or during obduction (Fareeduddin1 and Dilek, 2015, Singh et al., 2016, Kingson et al., 2017, Abdullah et al., 2018, Dey et al., 2018, Ao et al., 2020, Ao and Satyanarayanan, 2022). According to O'Hanley (1996), serpentinites are metamorphic rocks that are mostly composed of serpentine minerals - lizardite, chrysotile, and antigorite, with minor phases of magnetite, brucite, talc, magnesium, and calcium silicates. The serpentinites under study are lizardite, chrysotile, and less antigorite, which are typically alteration assemblages formed by serpentinization of ultramafic rocks. Lizardite-chrysotile serpentinites are more prevalent than antigorite. The existence of antigorite suggests prograde metamorphism or serpentinization in a higher P-T regime than lizardite and chrysotile (Moody, 1976). Serpentinites are typically dark or green and contain clay minerals in yellowish to reddish rocks (Mével, 2003). Serpentinization occurs when mafic or ultramafic rocks are hydrated by fluids in various tectonic environments. Serpentinites in the oceans are characterized by downward fluid flow and deep fault formations. Serpentine veins can be seen in fissures in olivine and orthopyroxene, as well as along grain boundaries. These metamorphic veins indicate that the lithosphere has been hydrated by the entry

of seawater-rich fluids into the rocks, resulting in the thermal disintegration of the main minerals olivine and pyroxene.

The most common forms of alteration in ultramafic rocks are serpentinization and talc-carbonate formation. These processes occur only in rocks with mafic to ultramafic compositions, which have higher iron and magnesium levels than other rocks. Serpentine, a mineral that forms at low temperatures, differs from talc, which forms under conditions indicating a higher magnesium concentration during crystallization (Abdel-Rahman et al., 2022). The serpentinized ultramafic rocks examined display different levels of talc alteration that overprint the serpentinite minerals. The transformation of serpentine into talc is a metasomatic process that involves significant mass transfer of Mg, Fe, and Si. This reaction can be expressed as:



This reaction is often regarded as a prograde reaction that takes place in the presence of SiO₂-rich fluids at temperatures ranging from 300 to 350°C (Bach et al. 2004; Boschi et al. 2006, Tsoungui et al., 2019). Talc is found in the studied samples as either a replacement product of the original serpentine matrix. This implies that the serpentinite interacted with a subsequent high-temperature, low pH, and low MgO/SiO₂ fluid. In the study of ultramafic peridotite samples, the majority of the silicate mineral phases have been changed to serpentine minerals, with only a few relicts of clinopyroxene and orthopyroxene (Ao et al., 2020). The high LREE and low HFSE in the secondary and altered rims around the primary clinopyroxene (Ao et al., 2020) are most likely caused by low-temperature secondary processes such as subduction-unrelated serpentinization, carbonation, and amphibolitization (Guice et al. 2018; Rollinson & Gravestock, 2011, Kingson, 2023). Loss on Ignition (LOI) was utilized for observing element redistribution during alterations (Polat & Hofmann, 2003, Deschamps et al. 2013). Higher LOI values in serpentinites from the analyzed areas indicate that the original rocks were more hydrated.

6.8 Tectonic Evolution

6.8.1 Interpretive Complexities and Multiple Scenarios

The tectonic setting of the MOC ultramafic rocks presents significant interpretive challenges, as the geochemical signatures exhibit characteristics that overlap between different tectonic environments. While the data provide important constraints, multiple viable tectonic scenarios must be considered given the inherent complexity of ophiolite formation and the potential for multi-stage evolution or post-emplacement modification.

The geochemical evidence presents apparent contradictions that require careful evaluation. While many samples show clear abyssal peridotite affinities in discrimination diagrams (Figs. 6.12, 6.13), some samples plot within SSZ ophiolite fields (Fig. 6.11), and the consistently low Ti/V ratios (<10) suggest boninitic characteristics more typical of subduction initiation environments (Fig. 6.14). These overlapping signatures could indicate: i) transitional tectonic settings, ii) multi-stage evolution from MOR to SSZ conditions, iii) back-arc basin formation with mixed MORB-arc signatures, or iv) overprinting during serpentinization and obduction processes.

6.8.2 Tectonic Discrimination and Alternative Interpretations

Ultramafic rocks typically serpentinized occur normally in three different tectonic settings: a) oceanic ophiolite complexes, where serpentinization is associated with oceanic metamorphism or alteration, b) through dynamic metamorphism at the subduction zone, and c) directly within the mantle (Bucher & Grapes, 2011; Kamenetsky, 2001). Peridotites in ophiolite complexes and comparable environments undergo low-temperature alteration by retrogression and hydration. Previous workers (Mével 2003; Kodolányi et al. 2011; Deschamps et al. 2013; Wu et al. 2018) argue that the geochemistry of serpentinites is intimately related to particular tectonic conditions.

Based on the concentrations of the principal oxides of SiO_2 -MgO and Al_2O_3 -CaO (Fig. 6.9 a-b), Aumento and Loubat (1971) proposed discrimination diagrams for ultramafic rock types. The studied samples plot predominantly in the low-temperature

Alpine field while showing transitional characteristics toward oceanic peridotite fields, suggesting either formation in transitional tectonic settings or subsequent modification during emplacement processes. Additionally, Gulacer and Delaloye (1976) introduced a Ni/Co vs Ni plot (Fig.6.10) for classification. The plot shows that the majority of the ultramafic rocks have high Ni/Co ratios and correspond to the Alpine-type field (Dunite-peridotite). Such high Ni/Co ratios are indicative of ultramafic rocks formed during the early phases of magma production by partial mantle melting (Kogarko, 1973).

6.8.2.1 Mid-Ocean Ridge (MOR) Scenario

The predominant abyssal peridotite signatures in multiple discrimination diagrams (Figs. 6.2, 6.12, 6.13) suggest possible formation at a mid-ocean ridge during Early Cretaceous Neo-Tethyan opening. The $\text{Al}_2\text{O}_3/\text{SiO}_2$ (0.05-0.07) and MgO/SiO_2 (0.95-1.05) ratios closely match modern abyssal peridotites, and the inferred partial melting degrees (5-15%) are consistent with normal MOR processes. The trace element plot between La/Sm versus Sm/Yb shows that all samples lie inside the abyssal peridotite area (Fig.6.12), further supporting this interpretation.

However, this interpretation faces significant challenges. Some samples plot within SSZ ophiolite classification in the Cr-TiO₂ diagram (Fig. 6.11), and the consistently low Ti/V ratios suggest more oxidizing conditions than typical MOR settings. Additionally, the evidence for melt-rock interaction prior to serpentinization (Figs. 6.5-6.8) may indicate more complex processes than simple MOR melting.

6.8.2.2 Supra-Subduction Zone (SSZ) Scenario

Based on the Cr-TiO₂ composition, Pearce et al. (1984) created a schematic to distinguish ophiolites from the supra-subduction zone (SSZ) from those from the Mid-Ocean Ridge basalt (MORB) (Fig.6.11). Some of the samples analyzed show affinity towards SSZ ophiolite classification, suggesting possible formation during subduction initiation processes. The evidence for melt-rock interaction, as demonstrated by the enrichment patterns in LREE and HFSE (Figs. 6.5-6.7), could reflect hydrous melting processes typical of proto-forearc environments.

To determine the impact of subduction on SSZ lavas, a Ti/1000 versus V plot (Fig.6.14) reveals that the studied rocks have low Ti/V ratios ranging from 0-7.19 ppm (less than 10), placing them in the boninites field. This suggests these rocks may have developed during subduction initiation under more oxidizing conditions. The high Ti concentration (average = 335.72 ppm) of the studied ultramafic rocks closely resembles subducted peridotite values, supporting a possible subduction-related setting (Fig.6.15 a-d).

However, the limitation of this interpretation is the predominant abyssal peridotite geochemical characteristics in most samples and the absence of extremely high degrees of depletion typically associated with forearc peridotites.

6.8.2.3 Back-arc Basin Scenario

The present ultramafic rocks are positioned in the overlapping region between abyssal, supra-subduction zone, and mantle wedge serpentinites on the CaO vs. MgO binary plot (Fig. 6.13), trending toward the depleted mantle domain (Lines follow Deschamps et al., 2013). The heterogeneous signatures across study areas (Kwatha, Haolenphai, Mongjang) could reflect formation in a back-arc basin where both MORB-type and arc-influenced processes operated contemporaneously.

This scenario would explain the transitional characteristics between MOR and SSZ signatures observed in various discrimination diagrams. The variable degrees of depletion and evidence for both anhydrous and hydrous melting processes could reflect the complex mantle dynamics typical of back-arc settings. However, clear arc-related trace element signatures are generally absent from the data, limiting confidence in this interpretation.

6.8.3 Regional Geodynamic Context and Implications

6.8.3.1 Neo-Tethyan Closure and India-Asia Convergence

The MOC ultramafic rocks provide important insights into the complex closure history of the Neo-Tethys Ocean during India-Asia convergence. During the Jurassic and Early Cretaceous periods, extensive rift-drift activity is thought to have occurred, resulting in the detachment of the Indo-Myanmar-Andaman (IMA) massif and the

Sikuleh subcontinent from the Australian continental margin. Following this event, the Indian continent made a tremendous voyage away from Australia near the end of the Cretaceous period (Ramana et al., 1994; Acharya, 1998, Curray, 2005).

The age of the MOC chert was determined to be Early to Middle Cretaceous by Bhattacharjee (1991), based on an analysis of Nassellaria radiolarian fossils. Chungkham and Jafar (1998) also found evidence of early rifting and the creation of the Indo-Myanmar Ocean before the Late Santonian Stage, through a comprehensive study of Coccolith-Globotruncanid biostratigraphy in limestone blocks from the MOC.

The Early Cretaceous (130-120 Ma) period involved rifting and ocean opening between India and Myanmar microcontinents, consistent with the dominant abyssal peridotite signatures observed in the studied samples. The Late Cretaceous (100-80 Ma) marked the onset of convergence and possible subduction initiation, potentially explaining the SSZ characteristics observed in some samples.

6.8.3.2 Comparison with Other Tethyan Ophiolites

The mixed MOR-SSZ signatures in MOC show similarities to those reported from other Tethyan ophiolites. The Yarlung-Zangbo ophiolites (Tibet) also display evidence for multi-stage evolution involving both MOR and SSZ processes, suggesting that transitional or complex evolutionary pathways may be characteristic of Neo-Tethyan closure processes. Similarly, ophiolites from the Ladakh region show comparable complexity, though with more pronounced SSZ signatures in their volcanic sequences.

However, the specific evolutionary pathways likely varied significantly across different segments of the collision zone, reflecting local variations in subduction dynamics, collision kinematics, and microplate interactions. This heterogeneity emphasizes the importance of detailed local studies in understanding the broader regional evolution.

6.8.3.3 Southeast Asian Tectonic Evolution

The MOC represents one component of the complex Southeast Asian orogenic system formed during prolonged India-Asia convergence. Understanding its evolution is

crucial for reconstructing the kinematics of collision, the role of microplate tectonics, and the diachronous nature of Tethyan closure across the region.

The apparent transitional characteristics of the MOC ultramafic rocks may reflect the complex microplate tectonics that characterized Southeast Asia during Mesozoic-Cenozoic convergence. The heterogeneous geochemical signatures could indicate collision and amalgamation of multiple oceanic fragments, each with different evolutionary histories and tectonic characteristics.

6.8.4 Tectonic Evolution Model

As the oceanic crust developed, tholeiitic magmas were produced through a low degree of partial melting (5-15%) of lherzolite and Cpx-harzburgite in a spreading center environment (MORB setting), providing insight into the tectonic setting of the MOC's ultramafic rocks. However, the complex geochemical signatures suggest that a simple single-stage model may be inadequate to explain all observations.

A three-stage tectonic model is proposed for the genesis and obduction of the ultramafic rocks in MOC, as illustrated in the tectonic model diagram (Fig. 6.22):

Stage I: Seafloor Spreading and Basin Formation: The MOC developed during intra-oceanic processes, with ultramafic peridotites formed in the initial stage of the opening of the Neo-Tethyan Ocean between the Indian plate and the Eurasian plate from SW to NE. The geochemical data suggest these may represent remnants of MOR-type melting under a mid-oceanic ridge system, though the possibility of more complex spreading environments cannot be excluded.

Most of the studied ultramafic rocks show depleted characteristics in their respective plots, suggesting formation from a common depleted mantle source, likely spinel lherzolite mantle. Residual peridotites were generated by decompression partial melting (5-15% melting), though the specific tectonic setting (normal MOR, back-arc basin, or transitional environment) remains subject to interpretation.

Stage II: Basin Closure and MOC Evolution: During the Late Cretaceous period, the Indian plate began to move towards the Eurasian plate, initiating the closure of the Neo-Tethys Ocean (Acharyya, 1998). This process led to the formation of oceanic

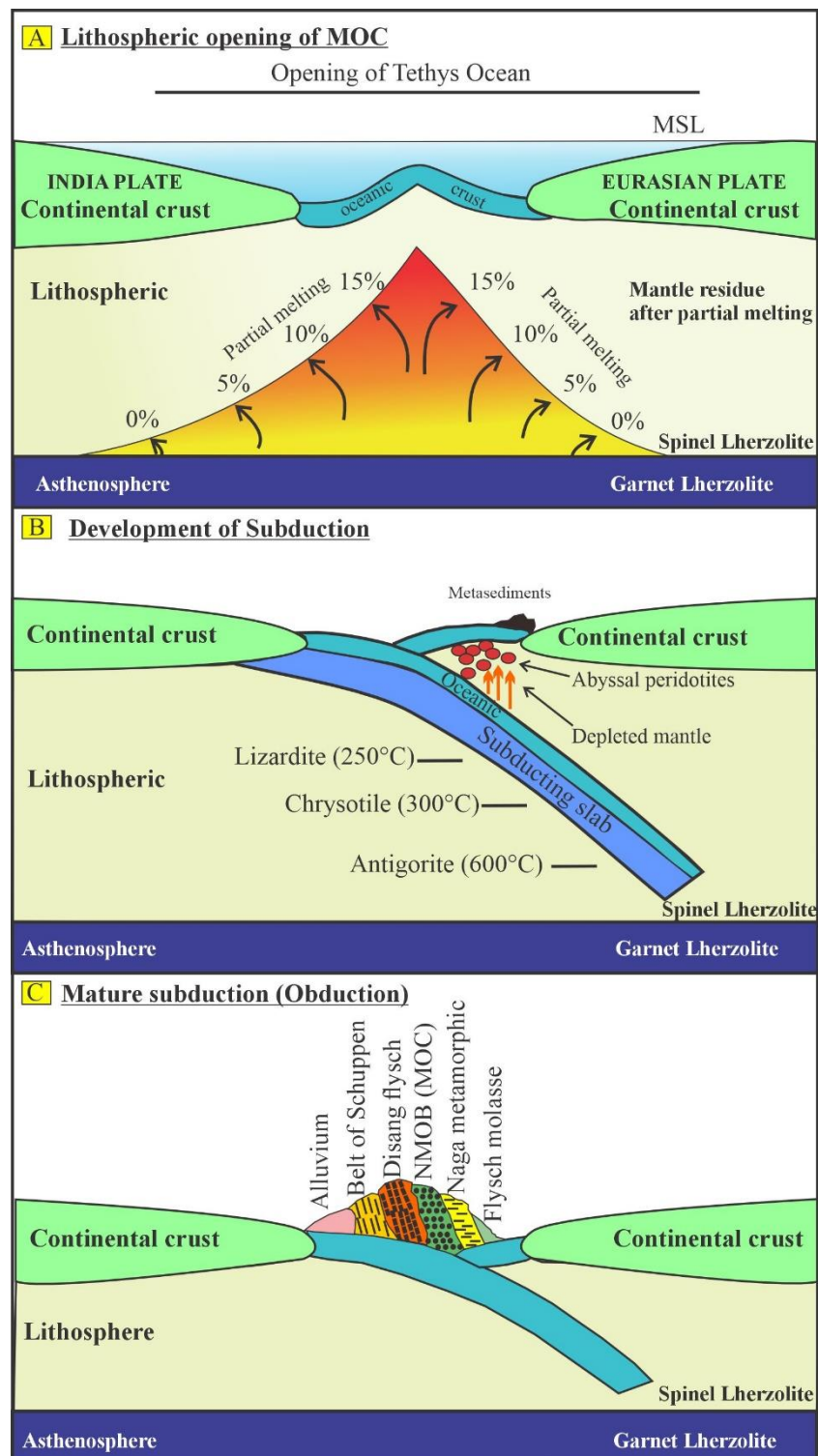


Fig. 6.22: Diagram illustrating the tectonic model for the development of the ultramafic rocks analyzed in the MOC.

ridges in previously weak rift zones, causing ultramafic rocks from the oceanic crust and upper mantle to rise. The previously developed ultramafic peridotites were later modified within changing tectonic conditions as the Tethyan Ocean began to close.

The ultramafic rock samples show characteristics that could indicate formation during an early phase of tectonic transition, though whether this involved subduction initiation, back-arc processes, or other mechanisms remains uncertain. The evidence for melt-rock interaction suggests complex magmatic processes that may have occurred during this transitional period.

Stage III: MOC Obduction: In the Late Cretaceous to Early Eocene period, the Indian plate was actively converging with the Eurasian plate. The final stage describes the obduction of the MOC onto the continental crust, resulting from the collision between the Indian plate and the Myanmar microplate. During this period, the ocean basins and the ophiolite mélange zone were raised above sea level.

The ultramafic peridotites, especially the more refractory varieties, were emplaced during this collision phase. The extensive serpentinization observed in the rocks, with temperature conditions of 250-350°C based on mineral assemblages, likely occurred during this stage through interaction with hydrating fluids during the emplacement process.

The tectonic evolution of the MOC ultramafic rocks involved complex, multi-stage processes during Neo-Tethyan closure and India-Asia collision. The geochemical evidence suggests influence from multiple tectonic-magmatic processes, with the three-stage evolutionary model providing a framework for understanding the complex history of these rocks from their initial formation during oceanic spreading through their modification during convergence to their final emplacement during collision.

CHAPTER-7

CONCLUSION

This comprehensive study of the ultramafic rocks within the Manipur Ophiolite Complex (MOC) in the Tengnoupal district has provided significant insights into the petrogenetic processes, tectonic evolution, and geological history of this segment of the Indo-Myanmar Ranges. Through integrated field mapping, detailed petrographic analysis, X-ray diffraction studies, and whole-rock geochemical investigations, this research has elucidated the complex nature and origin of these ultramafic rocks and their broader implications for understanding Neo-Tethyan closure processes.

7.1 Geological Framework and Distribution

The geological mapping at a 1:50,000 scale revealed three distinct lithostratigraphic units: the Ophiolite Complex, Oceanic Pelagic Sediments (OPS), and the Disang Group. The ultramafic rocks, forming the core of this investigation, are distributed across three main sections—Kwatha-Khudengthabi, Mongjang, and Haolenphai - each displaying varying degrees of alteration and structural complexity. These rocks occur as thrust-bounded slices within a broader ophiolite *mélange* zone, consistent with their interpretation as fragments of oceanic lithosphere tectonically emplaced during India-Myanmar collision.

7.2 Petrographic Characteristics and Alteration Processes

The petrographic investigations revealed that the ultramafic rocks are predominantly harzburgite with subordinate lherzolite, classified into three main types: tectonite, cumulate, and serpentinite varieties. The original mantle peridotites have undergone extensive serpentinization with loss on ignition values ranging from 8.60 to 14.53 wt.%, transforming primary olivine and orthopyroxene assemblages into serpentine minerals while preserving diagnostic textures that provide crucial insights into their evolutionary history.

The most distinctive textural features observed include mesh textures developed after olivine, indicating pseudomorphic replacement during low-temperature hydration

processes. Bastite textures formed through replacement of orthopyroxene preserve original crystal outlines and provide evidence of the protolith mineralogy. Porphyroclastic textures in tectonite varieties record high-strain deformation through kink banding, undulose extinction, and grain-size reduction, suggesting intense tectonic stress prior to serpentinization. Cross-cutting chrysotile veins represent later-stage fluid circulation and demonstrate the multi-phase nature of alteration processes.

The XRD analysis confirmed the presence of three serpentine polymorphs: lizardite, chrysotile, and antigorite, with lizardite and chrysotile predominating over antigorite. This mineral assemblage indicates serpentinization occurred under low-temperature conditions ranging from 250 to 350°C, consistent with oceanic metamorphism or early stages of tectonic emplacement rather than high-grade metamorphic processes.

7.3 Geochemical Signatures and Mantle Source Characteristics

The whole-rock geochemical analysis provided crucial constraints on the origin and evolution of these ultramafic rocks, revealing distinctive signatures that reflect both their primary mantle characteristics and subsequent alteration processes. The major element characteristics include low SiO₂ contents ranging from 39.94 to 42.02 wt.%, coupled with ultra-high MgO contents between 36.13 and 42.60 wt.%, which are well above the 18 wt.% threshold typically used to define komatiitic like compositions. The exceptionally high Mg# values ranging from 72 to 90 indicate highly magnesian compositions comparable to the most primitive terrestrial rocks, while low incompatible element concentrations such as TiO₂ values $\leq$ 0.12 wt.% and Al₂O₃ contents between 0.54 and 3.01 wt.% suggest derivation from a depleted mantle source.

The trace element and rare earth element patterns provide additional insights into mantle source characteristics and petrogenetic processes. High concentrations of compatible elements including Cr ranging from 628 to 3816 ppm and Ni from 2176 to 4074 ppm reflect the olivine-dominated nature of these rocks and their deep mantle origin. Depleted incompatible element abundances relative to primitive mantle values are consistent with formation through partial melting processes. The chondrite-normalized REE patterns display characteristic spoon-shaped profiles with LREE

depletion relative to HREE, and total REE concentrations ranging from 0.200 to 4.732 times chondrite values indicate strong overall depletion consistent with mantle residue characteristics.

The combination of relatively high MgO contents, elevated Mg# values, and enrichment in compatible elements suggests a composition similar to komatiitic systems, indicating derivation from high-temperature primitive mantle melts that crystallized under conditions distinct from typical modern basaltic systems

7.4 Tectonic Setting and Partial Melting Processes

The geochemical data provide evidence for formation through multiple tectonic processes, revealing a complex evolutionary history that cannot be attributed to a single tectonic environment. The ultramafic rocks display strong abyssal peridotite characteristics, with $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios ranging from 0.01 to 0.07 and MgO/SiO_2 ratios between 0.86 and 1.05, values that are entirely consistent with modern abyssal peridotites from mid-ocean ridge environments. Their positioning within the spinel peridotite stability field and compatible element concentrations similar to mid-ocean ridge peridotites further support this interpretation.

However, the presence of supra-subduction zone indicators complicates this simple interpretation. Low Ti/V ratios consistently less than 10 suggest boninitic characteristics typically associated with subduction initiation environments, while evidence for melt-rock interaction prior to serpentinization indicates more complex magmatic processes than simple mid-ocean ridge melting. Some samples plotting in SSZ ophiolite fields in various discrimination diagrams further suggest influence from subduction-related processes.

Multiple independent approaches for estimating partial melting degrees consistently indicate 5 to 15% partial melting of a depleted mantle source within the spinel stability field. These estimates, derived from HREE patterns, major element trends, and trace element modeling, demonstrate remarkable internal consistency and indicate that harzburgites represent more extensively melted residues compared to the subordinate lherzolites. The degree of melting is comparable to that observed in modern abyssal

peridotites from slow-spreading ridges, though the evidence for subsequent melt-rock interaction suggests additional complexity in the melting history.

7.5 Petrogenetic Evolution and Tectonic Implications

The integrated petrographic and geochemical data support a complex multi-stage evolution that reflects the dynamic tectonic history of the Neo-Tethyan region. The first stage involved seafloor spreading during the Early Cretaceous period, during which ultramafic peridotites formed through partial melting of 5 to 15% of spinel lherzolite mantle during Neo-Tethyan oceanic spreading between Indian and Myanmar plates. The predominant abyssal peridotite signatures indicate initial formation in a mid-ocean ridge environment, where decompression melting of ascending mantle produced the observed residual harzburgite and lherzolite assemblages.

The second stage represents a tectonic transition during the Late Cretaceous, when pre-existing peridotites were modified during changing tectonic conditions as convergence initiated between the Indian and Myanmar plates. Evidence for melt-rock interaction during these period and transitional geochemical signatures suggest possible subduction initiation or back-arc basin processes. This stage is crucial for understanding the mixed abyssal-SSZ signatures observed in the geochemical data, as it represents a period when the oceanic lithosphere experienced modification under changing stress regimes and fluid conditions.

The third and final stage involved obduction and emplacement during the Late Cretaceous to Early Eocene period, when the ultramafic rocks were tectonically emplaced onto the Indian continental margin during India-Myanmar collision. Extensive serpentinization occurred during this stage through interaction with hydrous fluids under low-temperature and low-pressure conditions. The mineral assemblages dominated by lizardite and chrysotile, along with the preservation of mesh and bastite textures, provide clear evidence for this low-temperature alteration process that occurred during the final stages of emplacement and subsequent exposure.

7.6 Regional and Global Significance

This study contributes to understanding of:

i) Neo-Tethyan Closure Processes:

The MOC represents one of the few well-exposed records of Neo-Tethyan oceanic lithosphere, providing insights into the complex closure history involving multiple microplates and transitional tectonic settings.

ii) Ophiolite Genesis:

The mixed MOR-SSZ signatures demonstrate the complexity of ophiolite formation, supporting models involving multi-stage evolution rather than simple single-environment genesis.

iii) Mantle Processes:

The detailed record of partial melting, melt-rock interaction, and subsequent alteration processes provides important constraints on mantle dynamics during oceanic spreading and convergence.

7.7 Implications for Himalayan-Tibetan Orogenesis

The MOC ultramafic rocks preserve a record of the eastern termination of the India-Asia collision system, complementing studies from the western and central Himalayas. The evidence for transitional tectonic settings and complex evolutionary pathways may be characteristic of collision zones involving multiple microplates and oblique convergence.

7.8 Future Research Directions

This study establishes a foundation for several compelling research avenues that could further enhance our understanding of the MOC and similar ophiolitic complexes. Geochronological studies involving radiometric dating of zircons from associated mafic rocks could provide precise timing constraints on ophiolite formation and emplacement, helping to resolve questions about the duration and rates of the various evolutionary stages identified in this study. Such age constraints would be particularly valuable for understanding the timing relationships between initial seafloor spreading, tectonic transition, and final emplacement processes.

Detailed structural analysis could elucidate the kinematics of emplacement and relationship to regional deformation patterns, potentially revealing information about the direction and mechanics of thrusting during collision. This would be particularly valuable for understanding how the ophiolitic rocks were transported from their original oceanic setting to their current position within the continental margin. Comparative studies integrating findings from the MOC with other Tethyan ophiolites could provide broader insights into Neo-Tethyan closure processes and help identify regional variations in the closure mechanism across different segments of the collision zone.

Isotopic investigations, particularly Sr-Nd-Pb isotopic studies, could provide additional constraints on mantle source characteristics and crustal interaction processes. Such studies would be especially valuable for distinguishing between different possible mantle sources and for identifying any crustal contamination that may have occurred during emplacement. Furthermore, detailed Electron Microprobe Analysis of preserved primary minerals could yield information about pressure-temperature conditions during initial crystallization and subsequent metamorphism, providing additional constraints on the depth and thermal conditions of formation and alteration.

7.9 Summary

The ultramafic rocks of the MOC represent fragments of Neo-Tethyan oceanic lithosphere that preserve a complex record of mantle melting, oceanic spreading, tectonic transition, and final emplacement during India-Myanmar collision. The geochemical signatures, evidence for 5-15% partial melting of depleted mantle sources, and extensive low-temperature serpentinization collectively indicate formation through multi-stage processes involving both mid-ocean ridge and supra-subduction (transitional) tectonic environments.

This research demonstrates the value of integrated petrographic and geochemical approaches in deciphering complex ophiolite histories and provides important insights into the broader processes of oceanic lithosphere formation, modification, and emplacement during continental collision. The MOC ultramafic rocks thus serve as a

crucial archive of Neo-Tethyan geodynamic processes and contribute significantly to our understanding of the eastern Himalayan orogenic system.

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EDUCATION:

Class	Subject	Institution	Board	Year	Division	Percentage
X	-	Donbosco High School, CCPur	BoSEM	2008	I	63.50
XII	Science	Rayburn College	CoHSEM	2010	II	58.40
BSc	Geology	St. Anthony's College, Shillong	NEHU	2013	I	67.87
MSc	Geology	Nagaland University	Nagaland University	2016	I	70.50

ACHEIVEMENTS

1. Qualified Joint CSIR-UGC National Eligibility Test (NET) for Assistant Professor and Junior Research Fellowship (JRF) in Earth Sciences held on 17-06-2018

PAPER PRESENTED AT NATIONAL/INTERNATIONAL CONFERENCES

1. **Presented paper entitled**, “Textural and mineralogical characterization of serpentinitized ultramafic from Manipur ophiolite belt exposed in and around Kwatha, Manipur, Northeast India”, an international conference on “Advances in Science of the Earth: Relevance to the Society”, organized by School of Earth Sciences Swami Ramanand Teerth Marathwada University, Nanded, Maharashtra, India, 24th -26th November 2022.
2. **Presented paper entitled**, “Petrology and mineralogy of serpentinitized peridotite rocks from Manipur Ophiolite belt of Tengnoupal area, Manipur Northeast India” National Seminar on Research Advances in Geosciences (09-10 May 2023), Organized by Department of Geology, Mizoram University
3. **Presented paper entitled**, “Petrochemical characteristics of Serpentinized Peridotites of Manipur Ophiolite Complex in and around Moreh, District Tengnoupal, Manipur” in the National Conference on Emerging Trends in Environmental Research (NACETER 2023), organized by Department of Forestry & Environmental Science, Manipur University held on 14th and 15th December 2023.
4. **Presented paper entitled**, “Geology and Petrography of Mantle Peridotites in the Tengnoupal Area, Indo-Myanmar Range: Insights from the Manipur Ophiolite Complex” in the International Conference on “Climate Change and Natural Resources Management for Sustainable Development” (ICNS-2024) hosted by the School of Earth Sciences and Natural Resources Management, Mizoram University, from 13th – 15th March 2024.

RESEARCH PUBLICATIONS

1. **Lamzamuán, G., & Devi, S.K.,** (2025). Petrochemical characteristics of serpentinitized peridotites of Manipur Ophiolite Complex in and around Moreh, district Tengenoupal, Manipur. In K. Khelchandra Singh (Ed.), *Conservation of Biodiversity and Environmental Monitoring* (p. 247). Biotech Books. ISBN 978-81-7622-598-4
2. **Lamzamuán, G., Devi, S. K., & Gogoi, L.** (2024). Unraveling the Protolith Origin of Serpentinized Rocks from the Tengenoupal Area, Manipur Ophiolite Complex, Indo-Myanmar Range. *Indian Journal of Science and Technology*, 17(36), 3719–3732. <https://doi.org/10.17485/ijst/v17i36.2279>

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ABSTRACT

PETROGRAPHIC STUDIES AND PETROGENESIS OF ULTRAMAFIC ROCKS IN AND AROUND KWATHA, TENGNOUNPAL DISTRICT, MANIPUR

**AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF
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**DEPARTMENT OF GEOLOGY
SCHOOL OF EARTH SCIENCES AND NATURAL
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**PETROGRAPHIC STUDIES AND PETROGENESIS OF ULTRAMAFIC
ROCKS IN AND AROUND KWATHA, TENGNOUNPAL DISTRICT,
MANIPUR**

BY

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Submitted

**In partial fulfillment of the requirement of the Degree of Doctor of Philosophy
in Geology of Mizoram University, Aizawl**

Abstract

The Ultramafic rocks in the Manipur Ophiolite Complex (MOC) represent a significant geological formation that provides profound insights into the complex processes shaping crustal evolution, mantle dynamics, and tectonic transformations. Ophiolites, as complex geological structures that represent fragments of oceanic lithosphere emplaced onto continental margins, serve as invaluable archives for understanding Earth's geological history. This research aims to conduct a comprehensive study of the ultramafic rocks found within the MOC, using an integrated multidisciplinary approach that combines detailed geological mapping, advanced petrographic and geochemical analysis.

The importance of this research extends well beyond the local geological context, offering new perspectives on global geological processes. By thoroughly examining the ultramafic rocks within the Manipur region, this study contributes to our broader understanding of mantle processes, plate tectonics, and the intricate interactions that shape the Earth's geological systems. The ultramafic rocks of the MOC, primarily consisting of harzburgite with some minor lherzolite, represent fundamental components of the mantle, preserving a geological record that spans millions of years and offers significant insight into the early stages of Earth's tectonic history.

The primary objective of this thesis is to develop a comprehensive understanding of the geological characteristics of the study area. This is achieved through a combination of geological mapping, petrographic analysis, and geochemical techniques aimed at investigating the petrogenesis of the ultramafic rocks. Although previous studies in the MOC region—particularly in the Kwatha area—have explored various aspects of regional geology, ultramafic rocks, which are crucial for understanding regional tectonics and petrogenesis, have received limited attention. This study addresses this gap by conducting an in-depth analysis of these rocks using field observations, petrographic examinations, and geochemical investigations. The ophiolitic complex in the region is characterized by monodominant ultramafic rocks, primarily found as klippe situated between the sedimentary Disang Formation and Oceanic Pelagic Sediments. The main aim of this study is to contribute novel insights to the existing

body of literature and deepen our understanding of the role of ultramafic rocks in regional tectonic evolution.

The following specific objectives have been formulated to achieve the overarching aim of the study:

- i) To carry out a detailed geological mapping of the study area.
- ii) To conduct detailed petrographic investigations of the various rock types, present within the ophiolite suite.
- iii) To perform bulk rock geochemistry studies focusing on major oxides, trace elements, and rare earth elements (REE).
- iv) To understand the genesis and tectonic setting of the rocks based on their chemical compositions.

The objectives will be achieved through systematic field and laboratory studies, as outlined below:

Literature Survey: A comprehensive review of relevant literature will be conducted using books, published journal articles, and other scholarly sources to gather information on the geology and rock characteristics of the study area.

Field Work:

- Geological mapping at a scale of 1:50,000 will be carried out to identify major lithologic units and collect structural data across the ophiolite mélange zone.
- Various rock samples will be collected for mineralogical, textural, and geochemical analysis.

Laboratory Studies:

- Thin sections of collected rock samples will be prepared for petrographic and mineralogical analysis.
- Powdered samples will be prepared for geochemical analysis using techniques like XRD, XRF, and ICP-MS.

The thesis is organized into seven chapters, each addressing a different facet of the research.

Chapter 1 introduces the research work, covering a general account of Manipur state, the scope of the work, aims and objectives, study area, and accessibility, as well as a review of relevant literature.

Chapter 2 explores Manipur's regional geology, presenting the stratigraphic succession and field observations from the study area.

Chapter 3 outlines the research methodology, including both fieldwork and laboratory analysis.

Chapter 4 focuses on the petrography of the ultramafic rocks, examining both megascopic and microscopic characteristics.

Chapter 5 presents the geochemical analysis, including major, trace, and rare earth elements of the studied rocks.

Chapter 6 discusses the findings, exploring the nature and origin of the rocks, melt-rock interaction, tectonic implications, partial melting, melt extraction, alteration, metamorphism, and tectonic evolution.

Chapter 7 concludes the research.

Results and Findings

This comprehensive study of the ultramafic rocks within the MOC has provided significant insights into the petrogenetic processes, tectonic evolution, and geological history of this segment of the Indo-Myanmar Ranges through integrated field mapping, detailed petrographic analysis, X-ray diffraction studies, and whole-rock geochemical investigations.

Geological Framework and Distribution:

The geological mapping at a 1:50,000 scale revealed three distinct lithostratigraphic units: the Ophiolite Complex, Oceanic Pelagic Sediments (OPS), and the Disang Group. The ultramafic rocks are distributed across three main sections—Kwatha-

Khudengthabi, Mongjang, and Haolenphai—each displaying varying degrees of alteration and structural complexity. These rocks occur as thrust-bounded slices within a broader ophiolite mélange zone, consistent with their interpretation as fragments of oceanic lithosphere tectonically emplaced during India-Myanmar collision.

Petrographic Characteristics and Alteration:

The petrographic investigations revealed that the ultramafic rocks are predominantly harzburgite with subordinate lherzolite, classified into three main types: tectonite, cumulate, and serpentinite varieties. The original mantle peridotites have undergone extensive serpentinization with loss on ignition values ranging from 8.60 to 14.53 wt.%, transforming primary olivine and orthopyroxene assemblages into serpentine minerals while preserving diagnostic textures.

The most distinctive textural features observed include mesh textures developed after olivine, bastite textures formed through replacement of orthopyroxene, porphyroclastic textures in tectonite varieties recording high-strain deformation, and cross-cutting chrysotile veins representing later-stage fluid circulation. The XRD analysis confirmed the presence of three serpentine polymorphs: lizardite, chrysotile, and antigorite, with lizardite and chrysotile predominating. This mineral assemblage indicates serpentinization occurred under low-temperature conditions ranging from 250 to 350°C, consistent with oceanic metamorphism or early stages of tectonic emplacement.

Geochemical Signatures:

The whole-rock geochemical analysis provided crucial constraints on the origin and evolution of these ultramafic rocks. Major element characteristics include low SiO₂ contents ranging from 39.94 to 42.02 wt.%, coupled with ultra-high MgO contents between 36.13 and 42.60 wt.%, well above the 18 wt.% threshold typically used to define komatiitic-like compositions. The exceptionally high Mg# values ranging from 72 to 90 indicate highly magnesian compositions comparable to the most primitive terrestrial rocks, while low incompatible element concentrations such as TiO₂ values ≤ 0.12 wt.% and Al₂O₃ contents between 0.54 and 3.01 wt.% suggest derivation from a depleted mantle source.

High concentrations of compatible elements including Cr ranging from 628 to 3816 ppm and Ni from 2176 to 4074 ppm reflect the olivine-dominated nature of these rocks and their deep mantle origin. The chondrite-normalized REE patterns display characteristic spoon-shaped profiles with LREE depletion relative to HREE, and total REE concentrations ranging from 0.200 to 4.732 times chondrite values indicate strong overall depletion consistent with mantle residue characteristics. The combination of relatively high MgO contents, elevated Mg# values, and enrichment in compatible elements suggests a composition similar to komatiitic systems.

Tectonic Setting and Partial Melting:

The geochemical data provide evidence for formation through multiple tectonic processes. The ultramafic rocks display strong abyssal peridotite characteristics, with $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios ranging from 0.01 to 0.07 and MgO/SiO_2 ratios between 0.86 and 1.05, values entirely consistent with modern abyssal peridotites from mid-ocean ridge environments. However, the presence of supra-subduction zone indicators complicates this interpretation. Low Ti/V ratios consistently less than 10 suggest boninitic characteristics typically associated with subduction initiation environments, while evidence for melt-rock interaction prior to serpentinization indicates more complex magmatic processes.

Multiple independent approaches for estimating partial melting degrees consistently indicate 5 to 15% partial melting of a depleted mantle source within the spinel stability field. These estimates demonstrate that harzburgites represent more extensively melted residues compared to the subordinate lherzolites, with degrees of melting comparable to modern abyssal peridotites from slow-spreading ridges.

Petrogenetic Evolution:

The integrated data support a complex multi-stage evolution. The first stage involved seafloor spreading during the Early Cretaceous period, during which ultramafic peridotites formed through partial melting of 5 to 15% of spinel lherzolite mantle during Neo-Tethyan oceanic spreading between Indian and Myanmar plates. The second stage represents a tectonic transition during the Late Cretaceous, when pre-existing peridotites were modified during changing tectonic conditions as convergence

initiated. The third stage involved obduction and emplacement during the Late Cretaceous to Early Eocene period, when the ultramafic rocks were tectonically emplaced onto the Indian continental margin during India-Myanmar collision, with extensive serpentinization occurring through interaction with hydrous fluids under low-temperature and low-pressure conditions.

Conclusion

In conclusion, this study provides important insights into the geological processes that have shaped the ultramafic rocks of the MOC region. The ultramafic rocks of the MOC represent fragments of Neo-Tethyan oceanic lithosphere that preserve a complex record of mantle melting, oceanic spreading, tectonic transition, and final emplacement during India-Myanmar collision. The predominantly harzburgite composition with subordinate lherzolite has undergone extensive low-temperature serpentinization, transforming primary olivine and orthopyroxene into lizardite and chrysotile while preserving diagnostic mesh and bastite textures.

Geochemical characteristics, including ultra-high MgO contents (36.13–42.60 wt.%), exceptionally high Mg# values (72–90), and elevated concentrations of chromium (628–3816 ppm) and nickel (2176–4074 ppm), suggest a komatiitic-like affinity and derivation from a highly depleted mantle source. The chondrite-normalized REE patterns with characteristic spoon-shaped profiles and strong overall depletion are consistent with mantle residue characteristics formed through 5–15% partial melting within the spinel stability field.

The identification of mixed abyssal peridotite and supra-subduction zone geochemical signatures offers valuable evidence for the complex tectonic history of the region. The combination of $\text{Al}_2\text{O}_3/\text{SiO}_2$ and MgO/SiO_2 ratios consistent with abyssal peridotites, alongside low Ti/V ratios indicating boninitic characteristics and evidence for melt-rock interaction, demonstrates a multi-stage evolution involving initial mid-ocean ridge formation, tectonic transition during subduction initiation, and final emplacement during continental collision.

This research significantly contributes to understanding Neo-Tethyan closure processes, ophiolite genesis involving multi-stage evolution rather than simple single-

environment formation, and mantle dynamics during oceanic spreading and convergence. The MOC ultramafic rocks preserve a record of the eastern termination of the India-Asia collision system and serve as a crucial archive of Neo-Tethyan geodynamic processes. This study demonstrates the value of integrated petrographic and geochemical approaches in deciphering complex ophiolite histories and provides important insights into the broader processes of oceanic lithosphere formation, modification, and emplacement during continental collision, contributing significantly to our understanding of the eastern Himalayan orogenic system.