



Geoheritage in Ladakh Himalaya: the Indus Suture Zone Ophiolites, Southeast of Ladakh, India

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Abstract

Physiographically, Ladakh is a diverse region covering a broad spectrum of geomorphic and geological features of the western Himalayas. It has numerous wide glacial valleys, high mountain ranges, saline to freshwater lakes, rocky deserts, and lunar/Martian-like surficial features. The region's extraordinarily complex geological past attracts researchers, educators, and geotourists globally. Many unique geosites give a glimpse of the orogenesis of the mighty Himalayas during the Late Mesozoic to Early Tertiary age. The Indus Suture Zone and ophiolite occurrences in the region are valuable geological archives and have been well known for decades with extensive research accomplished. The Nidar Ophiolite and Zildat Ophiolitic Mélange indicate the Neotethyan oceanic crust obduction onto the continental margin of the Indian plate. The study is based on a survey of the related grey and scientific literature and simplified analysis of the "Strengths Weakness Opportunity and Threats (SWOT)" of the potential geoheritage sites. In this analysis, strengths and opportunities are the positive factors of a geosite that could help in its recognition, conservation, and promotion of the geosites. The Nidar Ophiolite and Zildat Ophiolitic Mélange have the potential of being unique geosite for marine geology, paleoenvironments of the volcano-sedimentary formations, and evolution of the collision and subduction process.

Keywords Nidar Ophiolite · Zildat Ophiolitic Mélange · Himalayas · Ladakh · Geoheritage

Introduction

Geoheritage can be defined as a unit/entity of unique geological phenomena, which may be local, regional, national, or global, that can offer information about the dynamic behavior of our planet and acknowledge its origin through scientific research of the geological feature existing in the present time (Brocx and Semeniuk 2007; Brilha 2016; Reynard and Brilha 2017). Geoheritage is a relatively new term that aims to preserve the unique landforms and geological wonders on this planet (Brocx and Semeniuk 2007; Brocx 2008; Gray 2008; Robinson and Percival 2011; Van der Ancker 2012; Reynard 2012; Ruban 2015; de Wever et al. 2015; Fauzi and Misni 2016; Hose 2016; Crofts 2018;

Gordon et al. 2018). Geoheritage is very diverse and identified/established anywhere, but it was, more importantly, centered in Europe (Wimbledon and Smith-Meyer 2012). Its research has gained momentum in many parts of the world, but it is still a new subject of discussion in Africa, Asia, and the Middle East. However, there are a few instances (Moufti and Nemeth 2013; Errami et al. 2015; Searle 2014; Nemeth and Moufti 2017; Maghsoudhi et al. 2019) in Africa, Arabia, and Iran where research in this field is in the upcoming.

Developing nations play a crucial role in the advancement of geotourism and sustainable socioeconomic growth (El Wartiti et al. 2008; Asrat et al. 2012; Kiernan 2013; Henriques and Neto 2015; Nazaruddin 2017; Czerniawska and Chlachula 2018). In the middle of the twentieth century, there was an awareness to protect the geoheritage sites by having geoparks (Page and Wimbledon 2009). Due to ignorance and a failure on our side to protect and preserve the country's geological features, several of India's national monuments were destroyed in the latter half of the twentieth century (Bhosale et al. 2021). Geoparks are developed to enhance the province's sustainable economic development through geotourism by creating public awareness and

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educating about the geological sciences of the region (Kelley et al. 2019).

United Nations Educational, Scientific and Cultural Organization (UNESCO) started the conservation and identification of geoheritage sites with the help of the International Union of Geological Science (IGUS) in 1993. It is a significant loss for the country to the academic and scientific community if the geoheritage sites are lost or destroyed in time (Ahluwalia 2006; Swarna et al. 2013). Therefore in 2001, UNESCO initiated the idea of a geoheritage park by bringing on board the direct stakeholders like the geoscientists, local inhabitants, and tourism service providers (Prabhakar and Radhika 2022). This initiation had a tremendous impact, and in 2004, UNESCO brought a better scheme called “Global Geoparks Network (GGN).” Geopark is a global initiative of UNESCO promoting geologically significant places and the need to preserve them and raising public awareness wherever there is a need for developing geotourism. There are currently 161 UNESCO geoparks worldwide in 44 member countries, 65 of which are in 8 Asian countries (Lee and Jayakumar 2021). Consequently, today there is more awareness about geological sites, which needs attention to recognize them and declare them as geoheritage sites of the world (Larwood et al. 2013; Gordon et al. 2018; Beraaouz et al. 2019; Migon and Migon 2019).

Today, various agencies at the national and international levels are working together to conserve geoheritage sites (Page 2018). Scientists have identified and suggested several locations in India for their preservation or conservation. Arunachal Pradesh (Abor Volcanics; fossil wood; faunal coal balls; Grover and Mahanta 2018), Andhra Pradesh (the Eparchaean Unconformity at Namalagundu; Phani 2016), Gujrat (Trambau River bed and Kanthkot Fort hill; Bhosale et al. 2021), Maharashtra (Elephanta Caves; Sheth et al. 2016), West Bengal (Bhanratongri hill, Garpanchakot, Jabar hill, Tamakhun old mine, at Puruliya district; Ghosh et al. 2021), and many more to be added to the list. There are 34 National Geological Monuments in India declared by the GSI. These places in India have distinctive physical characteristics that are important both geologically and scientifically. These geological sites and abandoned mining regions can therefore be planned for and protected, which will have a considerable economic impact, especially on tourism and recreational activities (Zwolinski and Stachowiak 2012; Gray 2013). It necessitates identifying, declaring, promoting, maintaining, and branding the sites (Prabhakar and Radhika 2022).

The Himalayan orogen is the outcome of the collision between India and Eurasia and the closure of the Neo-Tethys Ocean (Andjić et al. 2022). The Himalayas are the youngest, highest (Searle and Treloar 2019), and perhaps one of the most spectacular of all the continent–continent collisions on Earth, termed the Himalayan–Tibetan orogeny. The mighty Himalaya occupies a length of 2500 km (Le Fort

1975) which trends from Pakistan in the west, the Tibetan Plateau in the north, to the state of Arunachal Pradesh, NE India. The Indo-Eurasian collision essentially formed the Himalayan–Tibetan orogen during the last 70–50 Ma, a part of the greater Himalayan–Alpine system. The Himalayan–Alpine system ranges from the Mediterranean Sea in the west to the Sumatra arc of Indonesia in the east, covering over 7000 km. This extremely long and complex structure was due to the collision of Indian and Eurasian plates leading to the closure of the Tethys, which was existing between two great landmasses since the Paleozoic: Laurasia in the north and Gondwana in the south (Hsu et al. 1995; Yin and Harrison 2000) and creating a suture zone known as Indus Suture Zone (ISZ) or Indus Yarlung Tsangpo Suture Zone (IYTSZ) between the Indian and the Eurasian plate (Le Fort 1975; Molnar and Tapponnier 1975; Gansser 1977).

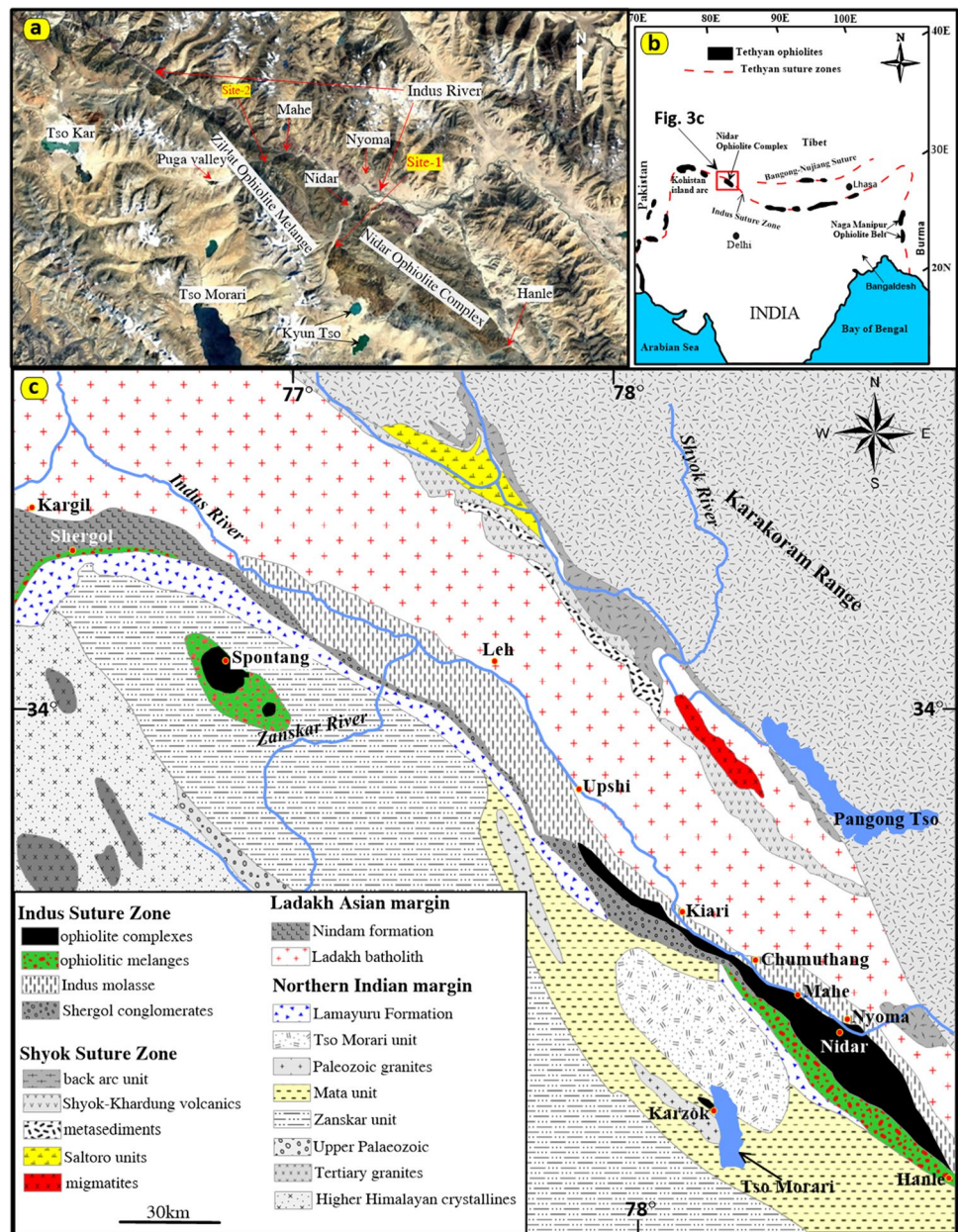
Ophiolite complexes around the globe preserve a highly intriguing geological past of the Earth’s crust and mantle. These geological terrains display beautiful landscapes with deformed and a mixture of all types of rocks, i.e., sedimentary, metamorphic, and igneous, with a general depiction of the geotectonic processes involved. The geology of Ladakh Himalaya exhibits rich geology with beautiful landscapes and high-quality outcrops. The ISZ runs along the Indus River, which flows from the southeastern part of the Ladakh region, originating in the Tibetan plateau. This suture zone is the birthplace of numerous ophiolite complexes and mélanges of the northwest Himalayas. The Nidar Ophiolite Complex (NOC) and Zildat Ophiolite Mélange (ZOM) are part of this suture zone (Fig. 1a–c). These ophiolite complexes are well-known geological formations extensively studied, but their geoheritage value is yet to be explored. Several ophiolite complexes exist in the Himalayas (Fig. 1b), northeast India, and the Andaman and Nicobar Islands. The Naga Ophiolite Belt is the only ophiolite complex declared by the Geological Survey of India as a geoheritage site, but several others in the country have the potential to be geoheritage sites. This paper aims to bring out the geological resources (the NOC and ZOM) in the southeastern part of Ladakh and attempt to create awareness about the importance of preserving these natural monuments, which have both geological and scientific significance.

Study Area

Physiography of Ladakh

Ladakh, the land of many crossings and freezing high barren landscapes, is one of the world’s highest inhabited terrains. It is located in the northern Trans Himalayas and is bounded on three sides by the Zaskar, Ladakh, and Karakoram Mountain ranges (Fig. 2a, b), with the Higher Himalayas

Fig. 1 **a** Location map with prominent places of the study area (source: Google Earth). **b** Occurrence of ophiolite complexes in the Indian subcontinent and Tibetan plateau along the Tethyan suture zones. **c** The geological map of Ladakh Himalaya modified after Virdi (1986) and Maheo et al. (2004) showing the lithostratigraphic units and major rivers of the region



marking its southern border. It is a rain shadow region with about 5-cm annual rainfall only. In the capital city of Leh, the temperature drops to a minimum of $-30\text{ }^{\circ}\text{C}$, while in Dras, it drops to $-50\text{ }^{\circ}\text{C}$. Lack of rain and low temperatures result in sparse foliage, resulting in a desert-like landscape. The temperature rises to about $20\text{--}25\text{ }^{\circ}\text{C}$ in the summer. Over the short, harsh summer, crop cultivation is sustained by melting snow water and skillfully harvesting the water. The Indus River has its source close to Mt. Kailash and flows into India from Tibet at Demchok in southeast Ladakh, a region with wide valleys (Fig. 2c). Numerous geological formations, including the Ladakh batholith, the Indus Formation, and glaciofluvial deposits, are eroded and cut through by this river (Fig. 2d). The Zanskar, Shingo, Shyok, and

Nubra rivers are among the other river valleys in the region. Ladakh has one of the country's largest and most gorgeous natural lakes at about 4300 m above the mean level; Pangong Tso is 150 km long and 4 km wide. Other brackish water lakes in Ladakh include Tso Morari (Fig. 3a, b), Tso Kar (Fig. 3c), and freshwater lakes, including Yaye Tso and Kyun Tso (Fig. 3d).

Ladakh lies in the Trans-Himalaya region with mesmerizing and scenic beauty, attracting tourists and geoscientists worldwide. The landscape represents lunar/Martian morphology, with the best exposures of igneous, sedimentary, and metamorphic rocks and fluvial, glacial, and lacustrine deposits (Phartiyal and Nag 2022). Regionally, it extends from the Siachen Glacier in the Karakoram range to the north, and to

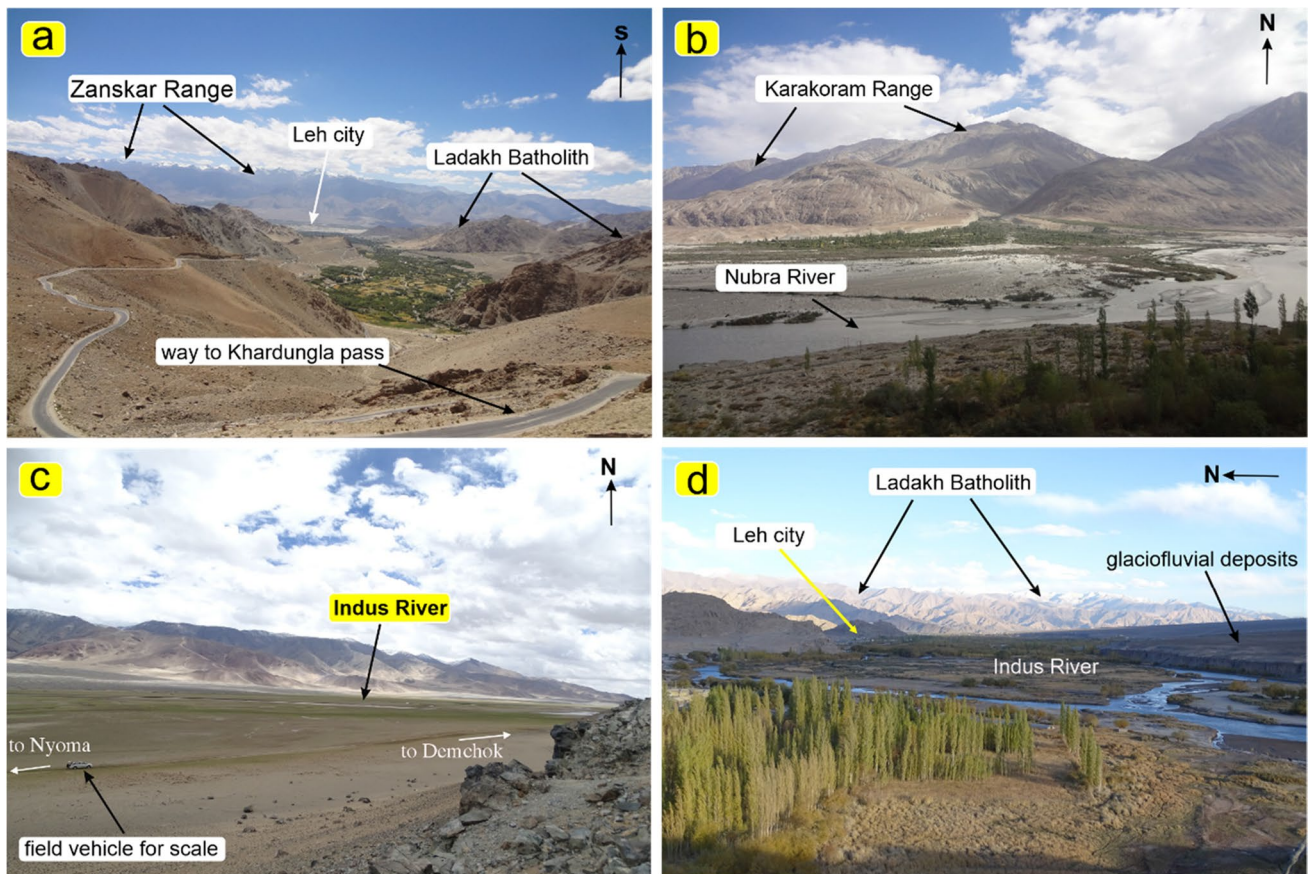


Fig. 2 Panoramic views of landform forms from Ladakh: **a** a view of Leh city and Zanskar range in the background; **b** Nubra River flowing along Shyok Suture Zone and alongside the Karakoram Range; **c** Indus River flowing through Dungti village, making an entry from the

Tibetan plateau to southeastern Ladakh Himalaya, India; and **d** Indus river flowing through the western part of Leh city and Ladakh batholith in the background

the south, it extends to the Great Himalayas (The Himalayan Central Crystalline Axis). It is an excellent ellipsoid with an area of 59,146 km² and a high altitude of ~3500 to 5700 m above mean sea level. The Ladakh Himalaya consists of high mountain ranges (Zanskar, Ladakh, and the Karakoram ranges), deep gorges, and broad river valleys like Indus, Shyok, and Zanskar. The Indus River and its tributaries drain the entire area, with their orientations such as northwest to southeast and northeast to southwest, generally following the structural lineations of the Ladakh Himalaya.

Ladakh is an arid to semi-arid region, affecting India's summer monsoon and the westerlies (Nag and Phartiyal 2015). It receives an annual rainfall of about 30 mm, but climatic conditions are unpredictable, like the 2010 cloud burst (Juyal 2010; Arya 2011). Much of the area is a rain shadow zone due to the Great Himalayas in the south, the Tibetan plateau in the east to southeast, and the Karakoram range in the north, forming an orographic barrier (Sant 2011). Less annual rainfall and high altitude in the region give rise to arid conditions and extreme cold. The whole

of the Ladakh Himalaya is known as the region of a high-altitude cold desert (Sant 2011).

Culture and Traditional of Ladakh

Ladakh, the land of passes, is the most beautiful and picturesque landscape with snow-capped, barren mountains and meandering rivers. Ladakh is often referred to as "Little Tibet" due to the influences of Tibetan Buddhist culture. This culture has been predominant in Ladakh for a long and people are influenced by the Tibetan way of life. Ladakhi people celebrate many festivals like Losar, Hemis, and Saka Dawa. The everyday activities of an ordinary Ladakhi revolve around gumpa or monasteries. The most attractive feature of Ladakh is the beautiful Buddhist monasteries situated on the isolated hillock in the vicinity of villages; these aesthetically pleasing, architecturally exciting monuments provide the focus for the faith of the highly religious Buddhist people. These historical monuments and monasteries are the primary sites for tourist attractions (Fig. 4a-d).

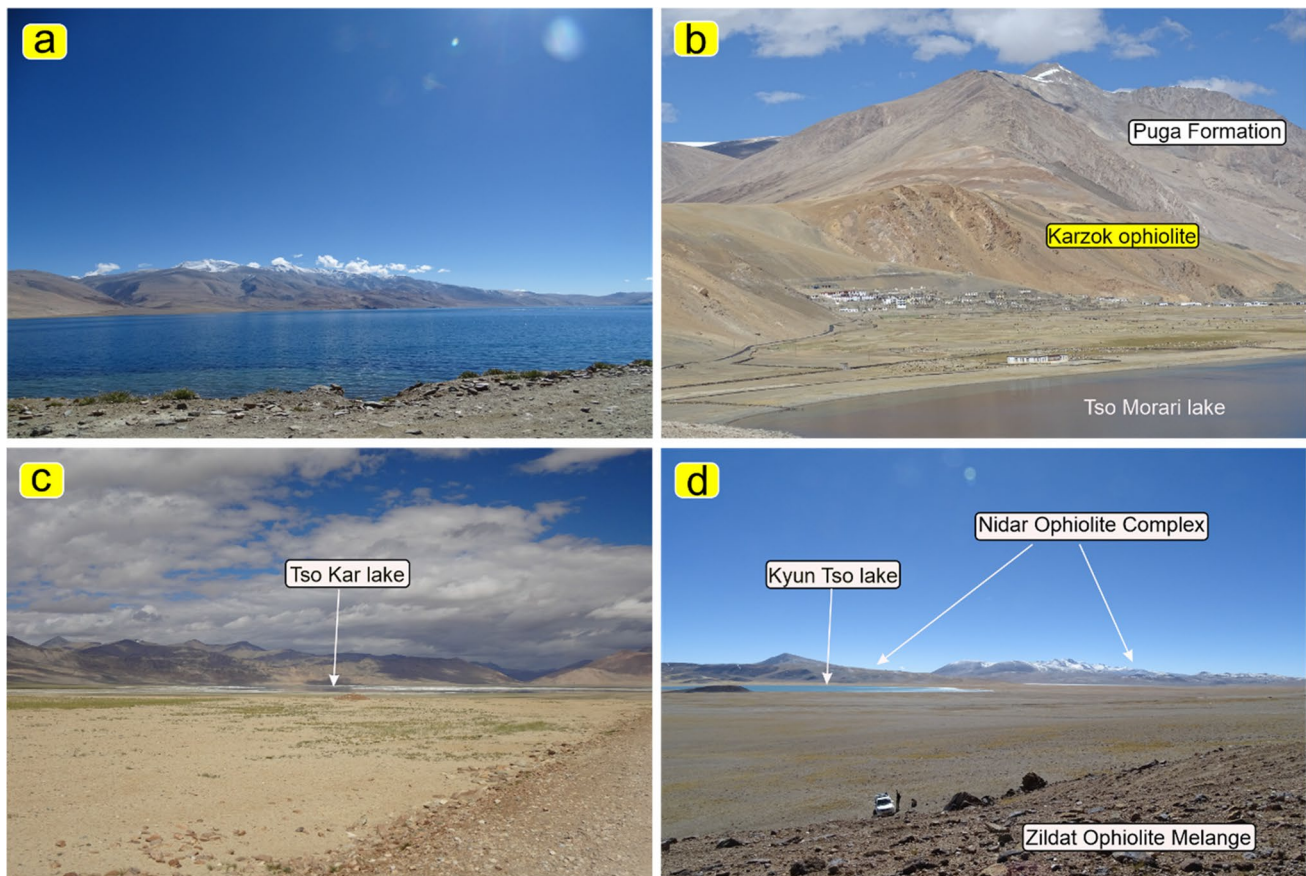


Fig. 3 Field photographs of lakes and landforms from the southeastern part of Ladakh Himalaya: **a** Tso Morari lake and higher crystalline Himalayan rocks; **b** panoramic view of Karzok village with Tso

Morari lake and part of Karzok ophiolite in the background; **c** a panoramic view of Tso Kar salt lake; and **d** Kyun Tso lake (17,000 ft above mean sea level), a glacial lake in the region

Monasteries are places of worship, isolated meditation, and religious instruction. These monasteries have a wealth of artifacts, and Lamayuru is the oldest religious center in Ladakh. The wealth of its possession and its annual summer festival make Hemis the most popular. In contrast, Thiksay rates high in terms of architectural impact, and the beauty of the festival performances at Likir and Phyang with their proximity to Leh are great attractions in their favor, while the accessibility of the Shey, Spituk, and the Sankar monasteries make them suitable for visitors. The Archaeological Survey of India with the government has declared around 11 historical monuments of monasteries and palaces like Leh Palace (Fig. 4b), Lamayuru Monastery (Fig. 4d), Hemis Monastery, Phyang Monastery, Alchi Monastery, and Likir Monastery.

Geological Setting

All the geological features and exposures in the Ladakh Himalaya are rich in magmatic, geomorphic, ancient life (fossils), tectonics, and ancient oceanic crust (Tethys Sea). The geological features are well preserved and exposed

throughout the region, which can be easily assessable. The entire Himalaya, which is around 200 km in thickness, can be divided into six major structural features like the Indus Suture Zone (ISZ) (Molnar and Tapponnier 1975) or also known as the Indus Yarlung Tsangpo Suture Zone (IYTSZ) (Allegre et al. 1984; Girardeau et al. 1984; Searle et al. 1987; Aitchison et al. 2000), the Tethyan Himalaya sedimentary units, Greater Himalaya Sequence (GHS) metamorphic rocks, the Lesser Himalaya fold-and-thrust belt, and the Siwalik molasse (Searle and Treloar 2019). In the north-west Himalaya, there are two suture zones, i.e., the Indus Suture Zone (ISZ) and the Shyok Suture Zone (SSZ) (Thanh et al. 2012). The ISZ marks the subduction of the Indian plate under the Eurasian plate and gives rise to calc-alkaline magmatism (Searle et al. 1987). This suture zone runs from east to west for about 2500 km to the north of the Himalayas (Tahirkheli et al. 1979; Ahmad et al. 1996). It is one of the most mesmerizing regions of the Himalayas due to a broad range of constituent petro-tectonic assemblages, and it is considered a zone of crustal convergence or subduction (Viridi 1987) of the Indian plate under the Eurasian plate.



Fig. 4 **a** The picturesque view of Shanti Stupa located on a hilltop in Chanspa, Leh, constructed by Japanese Buddhist Bhikshu, Gyomyo Nakamura in the year 1991. **b** A view of the Leh palace also known

as “Lachen Palkar Palace” constructed by Sengge Namgyal. **c** Nyoma village Gumpa located at the hilltop. **d** An overview of Lamayuru or Yuru Monastery situated on the Srinagar-Leh highway, Ladakh

This suture zone contains the deep-sea sediments of the northern Indian plate and the southern Tibetan plate, separated by fore arc-trench sediments and overlain by ophiolitic mélanges and molasses.

Remnants of subduction zones and oceanic basins, part of the Tethys, are scattered along the ISZ between India and Eurasia (Hébert et al. 2012). Along this suture zone, a discontinuous belt of Tethyan ophiolites occurs (Robertson and Degnan, 1994; Aitchison et al. 2000; Corfield and Searle 2000; McDermid et al. 2002; Hébert et al. 2012) from Ser-gol–Spong-tang–Nidar between the Zaskar Range and the Ladakh Himalaya (Reuber 1986a, b), through the Dongbo, Purang, Dangxiong and Xiugugabu massifs (Jungbwa-Amlang La ophiolite) in the western, the Saga, Sangsang, Jiding, and Xigaze massifs in the central, and the Zedang and Luobusa ophiolites in the eastern parts. This ophiolite belt reaches the Tsangpo bend in the Namche Barwa syntaxis, the NW–SE trending Lohit ophiolite zone farther east, and then turns southward in the Naga-Manipur ophiolite in the northeast part of India (Mitchell 1993). The Indus River follows the suture zone in the northwest direction (Fig. 1c),

eroding the Ladakh batholith and the Dras volcanics along its path.

Methodology

Based on its size and significance, any given geological formation’s spatial uniqueness as an outcrop is assessed and declared/established as a geoheritage site, which may be regional, national, or international. The geoheritage site assessment and the basic principles of its portrayal are summarized in Wimbledon et al. (1995), Reynard and Brilla (2017), Cetiner et al. (2018), and references therein. The method adopted for evaluating the geoheritage in the south-eastern Ladakh Himalayan ophiolites is based on the potential and characterization of the site. The site’s Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis (Andrews 1971) was performed by taking into consideration the field studies, accessing the significance of the geological formation, evaluating the literature, and conserving the area with the help of the local population.

The NOC and ZOM are described with their uniqueness and geological relevance in assessing the sites' distinctiveness. Assessing these geosites is a crucial step in comprehending the different geological features and their singularity on a local, national, and international scale. With the aid of in-depth field analyses of the outcrops at various locations of the distinct geological formations, such as an upper mantle, crustal, and pelagic sediments exposed in between the higher Himalaya layers, the geoheritage site is chosen. In this present study, the main reason for the characterization of the site is the perfect visibility of all the major geological features. Also, the site should have accessibility for any visits and sampling from the geological formation. Furthermore, the site should discuss in detail the uniqueness considering geoscientists, educators, and geotourists. Finally, emphasis can be given to the aesthetic values of the geosite by having a general perception of the landscape (Kirillova et al. 2014).

Ophiolite Geoheritage Sites

Zildat Ophiolite Mélange (ZOM)

The Zildat Ophiolite Mélange (Fig. 5a) is a part of ISZ, a linear belt emplaced within the molasses of the Hemis Member from the Indus Formation (Paul et al. 2007). This ophiolitic mélange is a disrupted, incoherent rock mass with altered oceanic crust, metasediments, and remnants of ophiolitic fragments with a general trend of NNW–SSE (Fig. 1c). ZOM is found to be associated with blueschist and ultrahigh-pressure eclogites (Fig. 5b) of the subducted Indian continental margin (de Sigoyer et al. 1997; Guillot et al. 1997; and Mukherjee et al. 2003). It has thrust contact with the Tso Morari Crystalline at the southern edge of the mélange near Sumdo. In addition, the ZOM has exotic blocks (Fig. 5c) of limestone of varying sizes, from a few meters to 10 s meters. Essentially, agglomerates, basalts (Fig. 5d), glaucophane schist, pyroclasts, pillow lavas (Fig. 5e), diorites (Fig. 5f), and exotic blocks of limestone make up the ophiolitic

Fig. 5 Field photographs from Zildat Ophiolite Mélange and Puga formation: **a** a panoramic view of Zildat Ophiolite Mélange from Sumdho village; **b** eclogite body occurring in granite gneiss near Sumdho Village at the contact between Puga formation and Zildat Ophiolite Melange, the eclogite body is about 5 m in thickness and 12–15 m in length, the largest eclogite body exposed in the area; **c** exotic blocks of limestone occurring in the ophiolitic mélange; **d** basalt exposed along Sumdho-Mahe road section; **e** pillow basalt with variation in sizes as observed in the field; and **f** A dioritic rock exposure with very coarse grains of pyroxenes, plagioclase

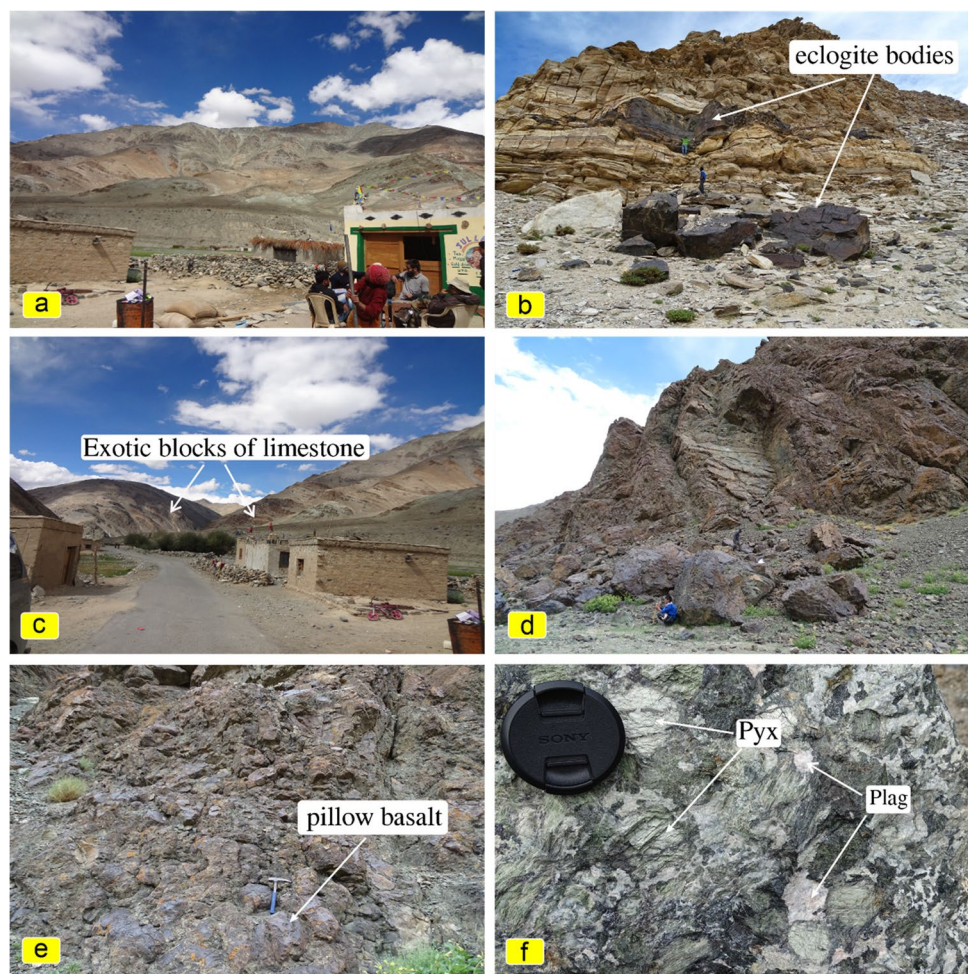


Table 1 SWOT matrix for Zildat Ophiolite Melange (ZOM)

Geoheritage site	Strength	Weakness	Opportunity	Threats
Zildat Ophiolite Melange (ZOM)	<p>i. This geological formation has an excellent aesthetic value due to the unique appearance of the rock types (Fig. 5a, d, and e)</p> <p>ii. It will be a site of outstanding scientific value regarding its geology and occurrence of mantle-crustal rocks between Himalayan rocks</p> <p>iii. The Mahe-Sumdo road section is an essential road to the tourist destinations like the Tso Morari, Noyma, and Puga valley</p> <p>iv. It is located adjacent to some tourist spots like Tso Kar, Puga hot springs, and Tso Morari; developing to a geosite will require minimum effort</p>	<p>i. The local population of the area is not aware of its value</p> <p>ii. No publicity or information disseminated among the general mass about its significance</p> <p>iii. There is no plan so far to declare the geological formation as a geoheritage site</p>	<p>i. Recently, the influx of tourists to Ladakh has increased to many folds. Awareness of its significance will increase the livelihood of the local population and preserve the geosite</p> <p>ii. Since Nyoima and Chumathung are near the geosite, developing the area for geotourism will require the least resources as there is already existing infrastructure for tourism</p> <p>iii. Much of the area in Ladakh is known for its scenic beauty, so declaring and developing the area for the preservation of the site will be easy due to the low density of population and less urbanization</p>	<p>i. The extreme weather conditions, i.e., temperature ranging from -20 to 35 °C, intense frost action, and high altitude (> 500 m), make the region susceptible to landslides and avalanches</p> <p>ii. The region has lower atmospheric oxygen due to its high altitude</p> <p>iii. Much of the region is inaccessible due to weather conditions during the winter season</p>

mélange (Viridi et al. 1977; Frank et al. 1977; Ahmad et al. 1996; Colchen 1999) (Table 1).

Nidar Ophiolite Complex (NOC)

The Nidar Ophiolite is an elongated and narrow belt of the oceanic sequence occurring in the southeastern part of the Ladakh Himalaya. The general trend of the complex is NNW–SSE, giving an impression of an eye-shaped pop-up structure existing south of the Indus River (Fig. 1a, c). The NOC is around 100 km in length, exposed between Hanle village in the southeast to Kiari in the northwest of Ladakh. It has a variable thickness of 2–12 km; the ophiolite sequence is best exposed between Kyun Tso and Nidar village (Nayak and Maibam 2020). The whole sequence is primarily made of three litho units, i.e., the ultramafic, mafic, and volcanic units (Fig. 6a, b; Sachan 2001). The ultramafic sequence in the south has a thrust contact with the Tso Morari Crystalline (Thakur and Mishra 1984; Mukherjee and Sachan 2001; de Sigoyer et al. 2004). This ultramafic sequence comprises harzburgites, lherzolites, and dunites (Fig. 6a) with sporadic intrusions of pyroxenites, chromitites, and diabase dykes (Fig. 7a–c). The ultramafic sequence is overlain by the mafic rocks, with gabbros, plagiogranite, and dioritic dykes (Fig. 7d). Finally, at the top the volcano-sedimentary rocks with pillow lavas, vesicular and amygdaloidal basalts, andesites (Fig. 7e, f), and cherts are present. A volcanic sequence is at the northern end of this dismembered ophiolite sequence marking a thrust contact with the Indus Formation (Table 2).

Discussion

Regional/National Context of Declaring a Geoheritage

With the advancement of digital technology, the planet has become a global village. Also, the influence of western society on India has been quite evident over the last 20–25 years. The country's economic stability has grown with globalization, so people's spending has increased. The economic growth led to a surge of tourists to naturally beautiful and adventurous places like the coastal regions, the mountainous terrains, and the hilly terrains of the country. This social change can be encashed to sustain the Ladakh region's rural population and highlight the region's geological importance. In any geoconservation, educating the local people is critical for promoting awareness of the value of geoheritage, and any typical geoconservation project should include education ingenuity in schools and colleges (Brocx and Semeniuk 2007). Furthermore, such geologically significant areas should be protected from the encroachment of urbanization

Fig. 6 **a** A panoramic view of the lowermost rock unit (the ultramafites) of Nidar Ophiolite Complex as observed in the field. **b** A broader view of all the rock units of the Nidar Ophiolite

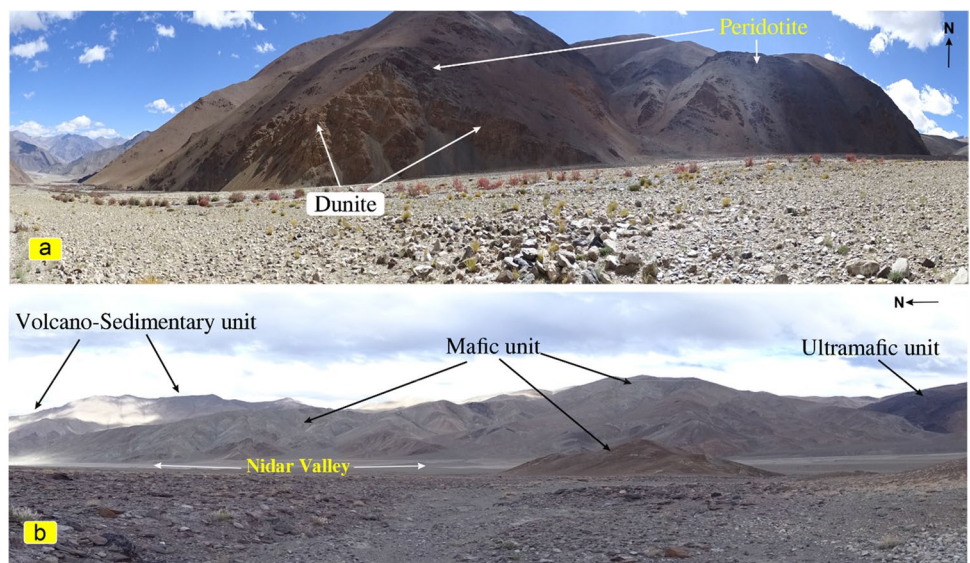
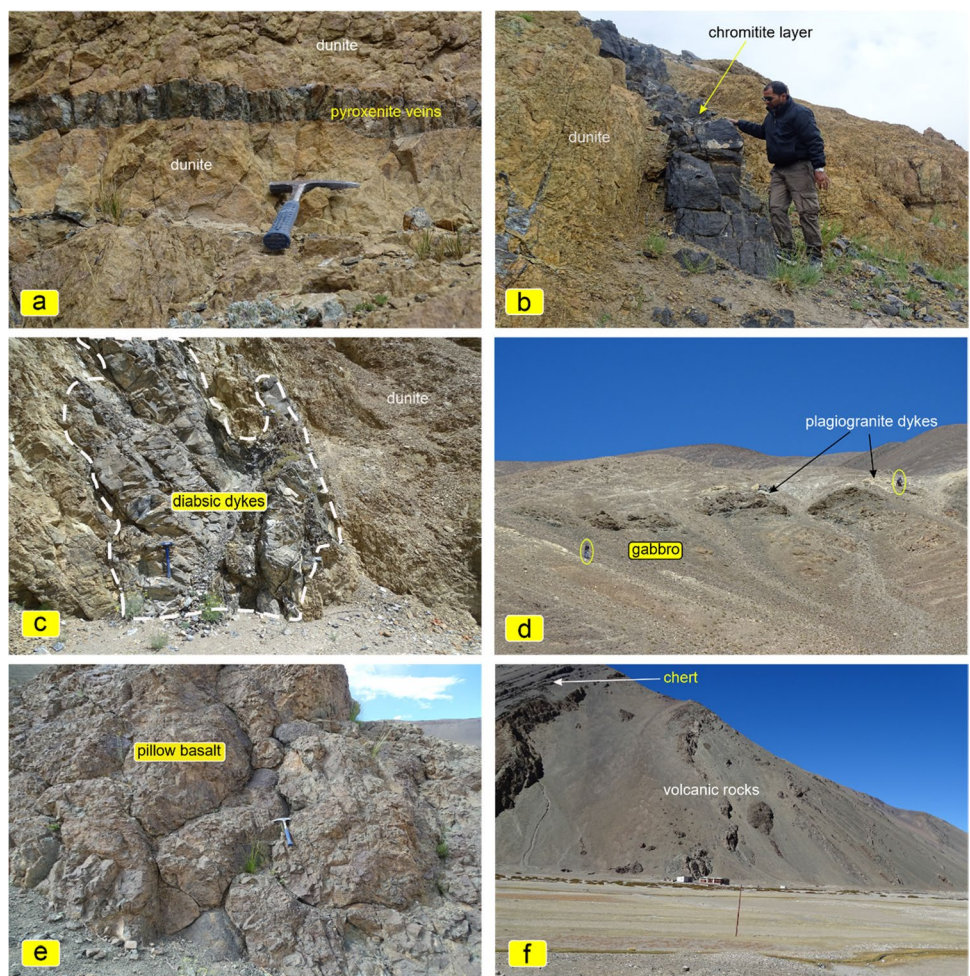


Fig. 7 Field photographs from Nidar Ophiolite: **a** pyroxenites vein in dunite is encountered along the Shyrok stream; there are numerous dykes of pyroxenites encountered in the study with varying dimensions in dunite; **b** thickness chromitite dykes in dunite observed in dunite and layers of chromitites with varying sizes observed in dunite; **c** diabasic dykes in peridotites are found occurring with deformations; **d** the gabbroic rocks of this ophiolite sequence with felsic dykes like plagiogranites and diorites; **e** pillow structures with various sizes and pillow breccias are shown; and **f** volcanic rock exposure as observed near the Nidar village



and industrialization (Lemmon et al. 1979). Reynard and Brilha (2018) contend that geoheritage sites should be viewed as priceless resources that require protection from

the encroachment of urbanization and industrialization and passed on to the future generation. There is always a danger to the destruction of these sites due to man’s activities.

Table 2 SWOT matrix for the Nidar Ophiolite Complex (NOC)

Geoheritage site	Strength	Weakness	Opportunity	Threat
Nidar Ophiolite Complex (NOC)	<p>i. It is one of the best- and well-preserved ophiolite sequences of the ISZ</p> <p>ii. An excellent aesthetic site due to its uniqueness in landscape and geology (Figs. 6b, 7f, and 8a)</p> <p>iii. It possesses high scientific value in terms of its preservation and occurrence of mantle-derived rocks</p> <p>iv. This geological wonder is present within tourist hotspots. So, developing this site will be easier</p> <p>iv. Several studies were carried out on ophiolites along the ISZ or IYTSZ (Hébert et al. 2012; Xu et al. 2015 and references therein). Therefore, preserving and making it available for further scientific studies is crucial in understanding the geological phenomena of the region</p>	<p>i. The inhabitants of the area is not aware of its value</p> <p>ii. Location of the site at high altitude with less oxygen in the air</p>	<p>i. During the summer season, tourists increase many folds. Therefore, sensitization programs in the local community about the area's importance will benefit and preserve the geosite</p> <p>ii. Since Nyoma and Chumathung is near to this geosite, these two regions have local hospitality, which will play a vital role in developing the Nidar and Stumdo areas for geotourism</p> <p>iii. Much of the area in Ladakh is known for its scenic beauty, so declaring and developing the area to preserve the site will be an advantage for the local population</p>	<p>i. Without any awareness the site is quarried for construction leading to the destruction of these significant geological formations</p> <p>ii. The flora and fauna of the area are very delicate and scarce. Utmost care should be taken not to disturb the ecosystem</p>

Hence, INTACH (Indian National Trust for Art and Cultural Heritage 2016) suggests that the Government of India enacts a law to preserve, protect, and maintain the geosites, but the government is yet to take any such measures in this regard (Prabhakar and Radhika 2022).

Ladakh is rich in geological records from the upper Paleozoic to Quaternary like magmatism at different geological ages, fossils preserved within rock beds, tectonism, fossilized ancient oceanic crust, and upper mantle, and rapidly changing geomorphic features. All these features are well exposed and can be accessed easily as the region is well connected by road from Leh or other regions. The principal tectonostratigraphic units of the ISZ consist of Lamayuru formation, the Dras formation, the Shergol ophiolitic mélange, the Nindam formation, the Kargil formation, the Indus formation, the Ladakh plutonic complex, and the Khardung formation. These formations occur in the west to the north-western part of Ladakh Himalaya. Two major lithostratigraphic units of the ISZ occur in the southeastern part of Ladakh Himalaya, i.e., NOC and the Tso Morari Crystalline Complex (Thakur 1990). The Indus, Kargil formations, and the Ladakh batholith extend the whole length of the IZS. The Tso Morari Crystalline Complex comprises a belt of metamorphic rocks and granites. At the south of this complex, Mesozoic sediments of the Zaskar Supergroup occur, whereas to the north, it is overlain by a thrust contact with the NOC and the Indus formation (Thakur 1990). Ultrahigh-pressure eclogites occur along the northern margin of the subducting Indian Plate in the Tso Morari crystalline complex, Ladakh (Fig. 5b). Several authors have reported that the age of this UHP eclogite metamorphism at Tso Morari dates India–Asia collision (Leech et al. 2005).

Indus Formation is a sedimentary unit with a thickness of about 5000 m, occurring along the NW–SE direction for more than 500 km. It occurs between the Ladakh plutonic complex in the north, the Shergol ophiolitic mélange, Taglang la Formation, and the NOC in the south. This sedimentary formation primarily consists of a thickly interbedded succession of predominantly conglomerate, sandstone, siltstone, and shale with a subordinate amount of calcareous shale and limestone. The Ladakh plutonic complex is known as the “Ladakh intrusive” or “Ladakh batholith.” This plutonic sequence consists of diorite, and granite, with occasional plutons of gabbro, norite, anorthosite, and pyroxenite (Thakur 1990).

The occurrence of ophiolite complexes in the northern margin of India, the presence of island arc systems within the Indus Suture Zone (ISZ) (e.g., the Dras–Kohistan arc), and the oceanic subduction beneath the Eurasian continent to the north provide vital information on the initiation of subduction, obduction mechanisms, and the emplacement of island arcs and ophiolite obduction onto continental margins (Searle 2019). There are two types of ophiolites found in

the Himalayan belt: (1) ophiolites that are obducted onto the previously existing passive continental margin like the Spontang ophiolite (Searle 1986; Corfield et al. 2001; Pedersen et al. 2001) and (2) ophiolite occurring in the suture zones like the NOC (Mahéo et al. 2004), the Xigase group of ophiolites (e.g., Hébert et al. 2003, 2012; Chan et al. 2015), and the Zedong–Luobusa ophiolites (e.g., Zhou et al. 2002; Malpas et al. 2003) in SE Tibet.

The ZOM and the NOC are important geological units in southeastern Ladakh from several aspects, like part of the ancient oceanic crust and upper mantle, which is a fascinating terrain for geoscientists, students, and nature explorers. These Neotethyan ophiolites are evidence of the existence of the enormous sea “Tethys” before the collision of India with the Eurasian plate at around ca. 60–50 Ma (Dewey and Bird 1970; Gansser 1964, 1980; Frank et al. 1977; Şengör 1979; Aitchison et al. 2000; Hu et al. 2016; Najman et al. 2017; and references therein). Nidar Ophiolite (Fig. 8a, b) possesses a well-preserved boundary between the crust and the upper mantle, where this distinction between the crust and mantle is known through geophysical means. This section is exposed along the Shyrok stream; the “petrological Moho” can be viewed and examined in situ (Fig. 8c). It is very essential to note that these geosites, i.e., the NOC, ZOM, the surrounding geological formations, and features, will offer three major aspects: (i) collision and subduction history of the lithospheric plates (India and the Eurasian plates); (ii) petrogenesis of the diverse rock types of the region; and (iii) the paleoenvironmental conditions involved in giving rise to the landforms.

These ophiolitic sections are very significant relics of a Mesozoic Ocean floor (Maheo et al. 2004; Ahmad et al. 2008) which was almost annihilated due to subduction. It has been subject to variable degrees of metamorphism and exhumed to give rise to various slices of the ophiolites along the Indian continental margin. Furthermore, with their remarkable petrological properties, the most thought-provoking outcrops can be considered for preservations like pillow lavas near Mahe bridge (Fig. 5e); eclogite body along the Tso Morari Crystalline Complex near Sumdho village (Fig. 5b); the dunite channels, the petrological Moho, chromitite, and pyroxenite veins in dunite along the Shyrok stream (Figs. 7a, b and 8b); gabbroic rocks with dykes of plagiogranites and diorites in the Nidar valley (Fig. 7d); volcano-sedimentary rocks at Nidar village (Figs. 7f and 8d, e). It would be difficult to select a site or an outcrop from the above-listed sites as the sequences are highly dismembered, derived from the same oceanic crust, and produced due to the intra-oceanic and alpine types of tectonic developments mainly due to the subduction and exhumation stages (Puga et al. 2009). Besides, the varying extent to which these outcrops were influenced by ocean-floor metasomatism contributed to

Fig. 8 Field photographs: **a** an overview of Nidar Ophiolite and Indus River; **b** panoramic view of the ultramafic rocks and dunite flow channels exposed along the Shyrok stream; **c** an exposure of petrological Moho where the sharp contact between the ultramafic (serpentine) and gabbro is observed; **d** chromite stringers in dunite with discontinuous bands are observed; **e** chert exposure from the topmost rock unit of the Nidar Ophiolite sequence; and **f** volcano-sedimentary unit with interlaying of andesitic to basaltic are found exposed at Nidar village



the formation of diverse types of metamorphic rocks from identical igneous rock types. Another factor that gives rise to the significant mineralogical and petrological discrepancies found in these outcrops is the metamorphic events that occurred during subduction, with metamorphic parageneses originating at different depths in a subducted oceanic slab (Puga et al. 2009).

Considering all of the aspects, the outcrops at various locations of Nidar and Sumdho are the most representative of petrological diversity, a petrological interest on a national and international level, and therefore can be nominated for geoheritage sites. Furthermore, the excellent degree of preservation of their primary structures and/or the local permanence of relics corresponding to their successive parageneses in these outcrops allow researchers to learn more about the main petrogenetic processes that occurred during their formation, in oceanic ridge conditions, at the northern end of the Tethys Ocean, and their subsequent evolution as tectonic slices which got incorporated into ISZ.

International Overview of Ophiolites as Geoheritage Sites

Ophiolite and ophiolite mélanges are found to occur in every continent from different geological ages. This ancient oceanic crust is evident in its uniqueness in petrology which can be linked to the paleoenvironments and tectonic settings, and these geological features are often recognized as geoheritage sites. Ophiolites are usually considered to have geoheritage value, and there are various ophiolite geoparks and geoheritage sites throughout the whole world, like the Monviso ophiolite, Italy (Perego and Vescovi 2005; Balestro et al. 2015, 2016; Rolfo et al. 2015); Troodos ophiolite, Cyprus (Anonymous 2015); Semail ophiolite, Oman (Searle 2014; Hoffmann et al. 2016); Indonesia (Ansori et al. 2022); Albania (Serjani 2002); Greece (Rassios et al. 2016); Malaysia (Muda and Tongkul 2008), and Morocco (El Hadi et al. 2011). The above-listed and other ophiolite sites are considered geoheritage sites mainly due to three geological factors

(Habibi and Ruban 2018): (i) the essential factor is the uniqueness of its total makeup of the sequence like the ultramafic, mafic, and volcano-sedimentary units; (ii) the petrogenetic features provide a vital clue to understanding the evolution of the oceanic crust, subduction, and volcanism; and (iii) understanding of the deep-sea sedimentation and evolution of life. Hence, the ophiolite for the ISZ is a unique site in India, but it has significant and relatively rare ophiolite, which can be a geoheritage site internationally.

Conclusion

Ladakh houses some of the world's most remarkable and unique geological formations, which hold great scientific and aesthetic values. The local populace will be able to rely on aesthetic values as a significant source of income. Furthermore, it attracts geoscientists and nature lovers throughout the globe for its unique geology, landforms, and landscapes. The primary purpose of declaring geoheritage sites is to prevent the destruction of this geological formation. Government can bring in requisite legislation/s and, with the help of the geological institutions, develop these sites systemically, which will be of great value to academics and research apart from the tourism activities and their benefits. These geological marvels can be developed by making a concerted effort to identify them as geoheritage sites and creating the comprehensive literature and logistics needed for preserving and maintaining the site. Creating awareness in the local community is essential, and including them in the process of geoconservation is vital. Such a geoheritage must be preserved from harmful human activities and can be included in sustainable development plans, as UNESCO suggested, as it cannot be restored once lost. Without this action, the country might lose important components of this attractive geological landscape and its distinctive geoheritage.

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Data Availability The datasets used and/or analyzed during the current study are available in the article from the corresponding author on request.

Declarations

Ethical Standard The authors declare that this research article complies with the ethical standards of this journal.

Informed Consent This article does not contain any information that requires informed consent.

Conflict of Interest The authors declare no competing interests.

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