



# Ladakh Himalayan Ophiolites (LHO): A Geological Heritage of Northwestern India

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## Abstract

Ladakh has a rich and fascinating sociocultural heritage owing to its unique geographical location and a mixture of varying civilizations. It covers a wide range of geological and geomorphic features of the western Himalaya including high mountain ranges, glacial valleys, saline to freshwater high-altitude lakes, and cold rocky desert. Himalaya is the product of a continent-continent collision between Indian and Eurasian plates and the closure of the Neo-Tethys Ocean during the Late Mesozoic to Early Tertiary. The Neo-Tethys Ocean existed during the Mesozoic Era and completely disappeared along the north dipping subduction zones. The Ladakh Himalayan Ophiolites (LHO) are the remnants of the eastern part of the Neo-Tethys Ocean that were obducted discontinuously along the Indus Suture Zone and incorporated on the Indian continental margin. These include Dras-Thasgam-Suru Valley-Shergol dismembered ophiolitic slices and Nidar-Spong tang ophiolitic complexes. These ophiolitic remnants comprise typical lithostratigraphy, viz., radiolarian cherts, pillow volcanics, gabbros, mafic-ultramafic cumulates, and mantle peridotites. They are scattered in the Ladakh region, accessible by foot and road, and form recognizable picturesque outcrops. They provide insights into the mantle sources, depth and degree of partial melting, melt-rock interaction, mantle wedge melting and metasomatism, and evolution of mantle-derived melts. In strength weakness opportunity threat analysis, the total weighted score (TWS) for the internal factor evaluation matrix is 3.22, indicating that strength exceeds weaknesses. While the TWS for the external factor evaluation matrix is 3.25, suggesting that the opportunity to develop and conserve the proposed geoheritage sites exceeds the threat. Thus, the LHO, with excellent aesthetic sense and good accessibility, are attractive from both scientific and geotourism perspectives. They must be recognized as valuable geoheritage sites worthy of protection and conservation against exploitation

**Keywords** Neo-Tethys Ocean · Indus Suture Zone · Ladakh Ophiolites · Geoheritage

## Introduction

Geoheritage includes geological features, viz., lithological, structural, stratigraphical, geomorphological, paleontological, and economical that provides knowledge about

the Earth's evolution and therefore can be used for research, teaching, or as local as well as global reference outcrop. A section or outcrop of such geoheritage site could be a rare or unique site at which the occurrence of any geological or geomorphological feature is well developed or preserved. India is richly endowed with extensive geological diversity, comprising rocks ranging from Precambrian to Recent thereby evolved unique landscape and landforms. As early as 1970s, Geological Survey of India declared several geoheritage sites of the country as the "National Geological Monuments." These include marble rocks of Jabalpur Madhya Pradesh, Borra caves and Erra Matti Dibbalu sand dunes of Vishakhapatnam, Orvakal Rock Garden of Andhra Pradesh, Vindhyan Basin Stromatolites of Uttar Pradesh and Madhya Pradesh, and Siwalik Fossil Park of Himachal Pradesh. These sites could help understand various earth processes, evolution of life, and reconnect with the Earth's dynamic past. The

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cultural and spiritual values of these geoheritage sites are immense; however, their geoheritage literature is meager with few and far between popular geoscientific literature. Ladakh (land of high passes), situated above 3000 m in the northwest India, has become an ideal outing destination among tourists worldwide. The geological diversity of Ladakh Himalaya was declared as a National Geological Monument by the Geological Survey of India (Rao 2002). It holds a range of geological and geomorphic features such as Paleozoic to Pleistocene rocks and the fossil record, mountain glaciers (e.g., Machoi, Parkachik, Panzella, Drang Drung, Siachen), pristine lakes (e.g., Pangong Tso, Tso Morari, Tso Kar), hot springs (Panamik, Chumathang, and Puga), sand dunes and ophiolites,

It is now well established that the opening of the Neo-Tethys Ocean resulted due to the rifting of the Cimmerian microcontinent from the northern margin of the Indian plate during the Permian Period (290 million years ago; Dan et al. 2021). Around Late Jurassic (145 million years ago), the Indian plate broke off from the Gondwana supercontinent, resulting in the consumption of the Neo-Tethys Ocean along the north dipping subduction zones (Buckman et al. 2018). The double subduction mechanism is the most favored geodynamic model in the context of the eastern side of the Neo-Tethys Ocean, operated during the Late Jurassic to Eocene

(55 million years ago) until the final collision occurred (Bhat et al. 2021a, and references therein). These north-dipping subduction zones were magmatically active during the Cretaceous Period (66 to 145 million years ago), as evidenced by the geochronological data (Kumar et al. 2007; Jain et al. 2012). During the Late Cretaceous (80 million years ago), the Indian plate drifted northward very rapidly at an average velocity of 160 mm/year, ultimately collided with the Asian continental margin during the Lower Eocene (45 million years ago) and thereby giving birth to the magnificent Himalayan Mountain Belt (Najman et al. 2017). Rocks and fossils preserved in this region document collision and evolution of the Himalayas. This mountain belt is about 2400 km long, extending from Afghanistan-Pakistan in the west to Namcha Barwa in the east, and is part of a long Alpine-Himalayan Mountain Belt (Fig. 1). The Indus Suture Zone (ISZ) is the India-Asia convergence zone characterized by the continental slope deposits, deep-sea sediments, island arc, plutonic complex, molassic deposits, and ophiolitic remnants, ranging in age from Late Permian to Eocene (Jagoutz et al. 2015).

Ophiolites are the obducted fragments of fossil oceanic lithosphere generally found along with the orogenic belts and continental landmasses. A well-preserved stratigraphy of ophiolites

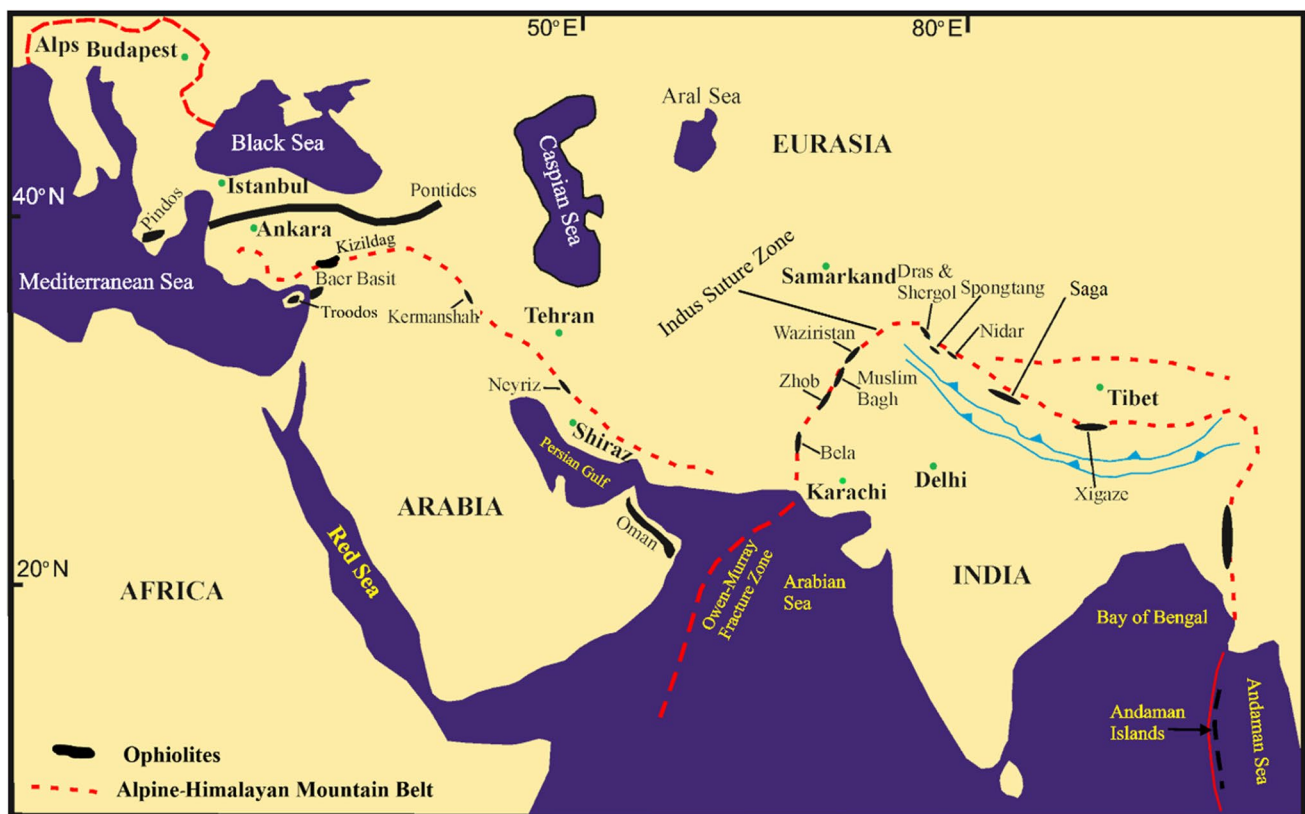


Fig. 1 Distribution of Neo-Tethys ophiolites along the Alpine-Himalayan Mountain Belt (after Dilek and Furnes 2009)

from top to bottom consists of pillow basalts, sheeted dike complex, isotropic gabbros, cumulate gabbros and peridotites, and residual mantle peridotites. They help better understand the ancient oceanic lithosphere's structural and geochemical makeup, crust-mantle processes, melt/fluid-rock interactions, magma differentiation models, and old plate boundary reconstruction (Dilek and Furnes 2009). The diagnostic lithological types with well-preserved oceanic features that characterize most of the world's known ophiolite sequences occur in Ladakh Himalaya (Bhat et al. 2021a, and references therein). The Ladakh Himalayan Ophiolites (LHO) were obducted during Late Cretaceous along the ISZ (Brookfield and Reynolds 1981; Corfield and Searle 2000) and were mostly deformed and dismembered due to Tertiary southward back thrusting (Robertson and Collins 2002). The possible geodynamic situations where ophiolites are generated are the mid-ocean ridges, fore-arc and back-arc regions of subduction zones. Ophiolite complexes are divided into two groups: one mid-ocean ridge (MOR) ophiolites, having geochemical characteristics of normal mid-ocean ridge basalts (NMORB), and second supra-subduction zone (SSZ) ophiolites, having geochemical characteristics of island-arc tholeiites (Pearce et al. 1984). Contemporary MOR-ophiolites lie in major ocean basins, along leaky transform faults and back-arc basins, e.g., Muslim-Bagh ophiolite of Pakistan and Xigaze ophiolite of Tibet. In contrast, the SSZ-ophiolites belong to island arcs, e.g., Troodos ophiolite of Cyprus, Kizildag ophiolite of Turkey, Neyriz ophiolite of Iran, Semail ophiolite of Oman, and Dras-Shergol-Nidar-Spong tang ophiolites of Ladakh Himalaya (Fig. 1; Dilek and Furnes 2009).

The geodiversity of Ladakh Himalaya has the potential to educate the masses about the dynamics and evolution of the earth, paleoclimate, and natural catastrophic events. However, the geoheritage literature and geoscientific component of Ladakh Himalaya are insignificant despite being a geological monument. Therefore, the current challenge for geoscientists is to interpret geoheritage sites meaningfully and present lucid writing that is understandable to ordinary people. In this paper, we focus on the geological heritage potential of LHO, their conservation imperative for tourism, and safeguarding future research activities for the upcoming generations.

## Geological Setup of Ladakh

Ladakh Himalaya is divided into four tectonostratigraphic zones from south to north, i.e., Zaskar Zone, ISZ, Shyok Suture Zone, and Karakoram Zone (Fig. 2; Searle et al. 1987). The Zaskar Zone (ZZ) comprises weakly metamorphosed Tethys sediments of the Upper Proterozoic to Cretaceous age deposited on the continental shelf of the southern margin of the Tethys Ocean and resting on a basement of Proterozoic Higher Himalayan Crystalline Sequence (HHCS; Gaetani and Garzanti 1991). The ZZ is tectonically separated from HHCS

to the south by the Southern Tibetan Detachment System and from ISZ to the north by Zaskar Thrust. It consists of phyllites, schists, marbles, amphibolites, gneisses, and migmatites with granites and Permian Panjal volcanics. To the north, the ZZ gradually passes into a large dome of greenschist to eclogitic metamorphic rocks known as Tso Morari Crystalline Complex (TMC). The TMC forms a NW–SE trending doubly plunging antiformal structure (approximately 100 km in length and 40 km in width) and represents a distal remnant block of the northern Indian continental margin (Steck et al. 1998). It is composed of Puga Formation—a several thousand meters thick Cambrian (500 million years) sillimanite-kyanite granite gneisses as well as lenses of ultra-high pressure (UHP) metamorphic rocks such as eclogites (Epard and Steck 2008). This formation is intruded by  $479 \pm 2$  million years Polokong granites and towards the south is unconformably overlain by the Tanglangla Formation represented by weakly metamorphosed rocks of the Late Paleozoic to Early Mesozoic age (Fig. 2). Dark-colored irregular bodies of eclogites occur as boudins or lenses enclosed within the Puga Formation. In eclogites, the presence of rare coesite inclusions in garnet yielded a minimum pressure of 27 kbar at  $\sim 600$  °C, reflecting continental subduction to more than 90-km depth (de Sigoyer et al. 2004; Sachan et al. 2004; St. Onge et al. 2013). Recently, Ahmad et al (2022) proposed subducted portion of the Early Permian depleted Panjal volcanics or Late Jurassic to Early Cretaceous ophiolitic mafic rocks from Ladakh as the protolith for the TMC eclogites.

The ISZ is the India-Asia convergence zone and represents a collage of different rock units that records the closure of the Neo-Tethys Ocean from Late Permian to Eocene (Gansser 1980; Searle et al. 1987). It demarcates the northern limit of the ZZ and extends about 2500 km in length and 50–60 km in width in a NW–SE trending zone, delineated by Zaskar Thrust towards the south and Karakoram strike-slip fault towards the north (Thakur 1981). The Shyok Suture Zone separates the Ladakh Batholith—a pre- and post-collisional calc-alkaline magmatism—towards the south from Karakoram Batholith—an Andean-type magmatism towards the north (Thakur and Mishra 1984; Borneman et al. 2015). This zone is interpreted as a relic of the marginal oceanic crust related to ISZ consisting of Shyok and Nubra volcanics, Shyok ophiolitic melange, and Saltoro molasse and flysch (Robertson and Collins 2002; Upadhyay 2009; Bhutani et al. 2009). Based on the geochemical and isotopic signatures, Sivaprabha et al. (2022) proposed an Andean-type arc setting for the Shyok and Nubra magmatic rocks. The Karakoram Zone occurs as a linear belt north of the Shyok Suture Zone, comprising a broad spectrum of rocks ranging in age from the Late Precambrian to Cretaceous (Searle et al. 2011; White et al. 2012). This zone consists of metamorphic, igneous, and sedimentary rock types ranging in age from Permo-Carboniferous to Late Cretaceous (Rai 1987; Sinha et al. 1999).

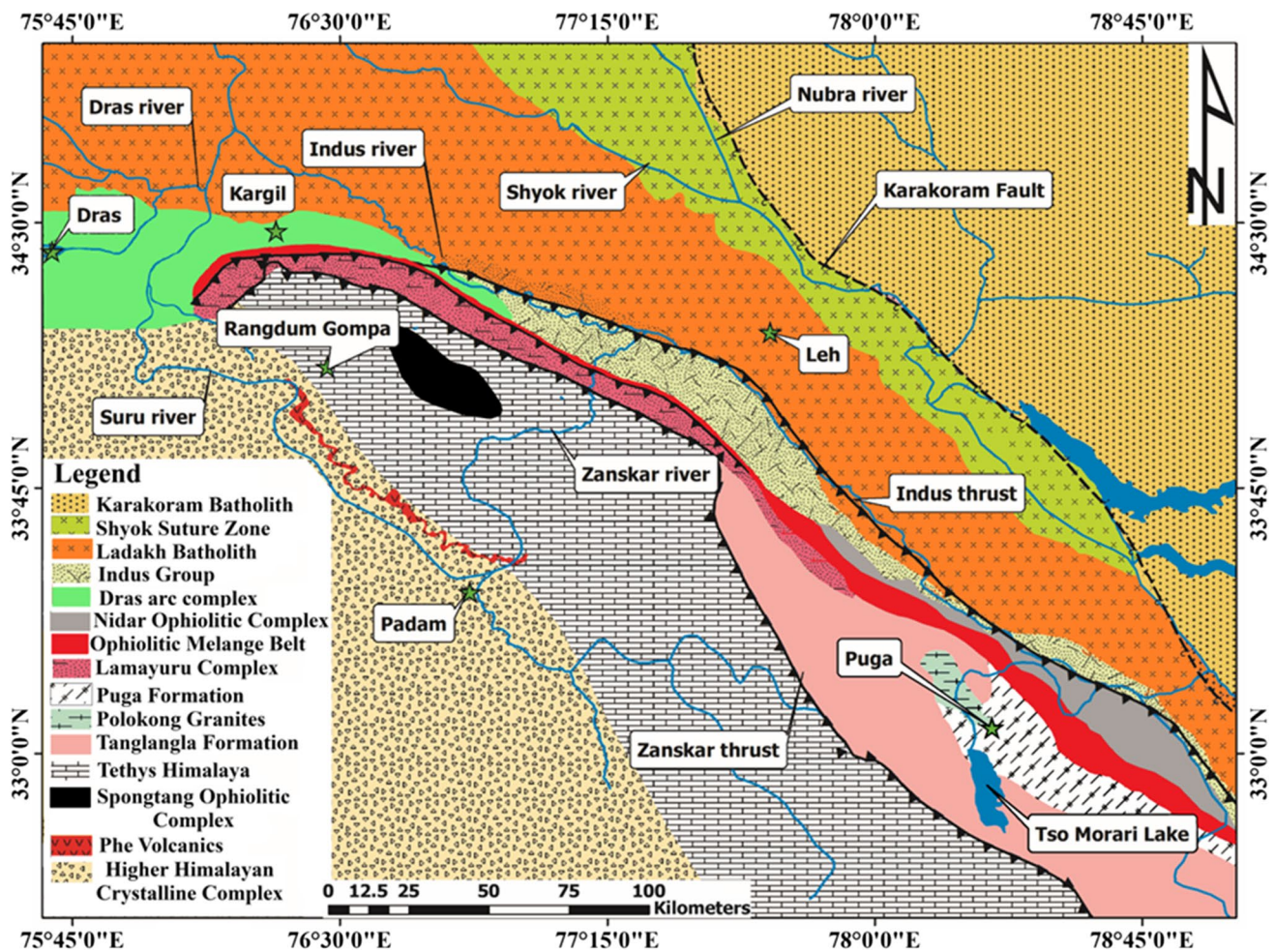


Fig. 2 Geological map of the Ladakh Himalaya showing various tectonostratigraphic units (modified after Maheo et al. 2004)

The metamorphic rocks include schists, quartzites, augen gneisses, and migmatites, while the igneous rocks include granites, granodiorites, and tonalities commonly known as Karakoram Batholith. The sedimentary rocks include limestones, dolomites, shales, sandstones, and minor conglomerate lenses.

### Indus Suture Zone (ISZ)

The ISZ is characterized by collage of different lithotectonic units from south to north, viz., the Lamayuru Complex—a continental slope deposit, ophiolitic melange belt, Dras arc complex—an intra-oceanic island arc, ophiolitic relics of the Neo-Tethys Ocean, Indus Group—a molassic deposit, and Ladakh Batholith—a plutonic complex. It ranges in age from Late Permian to Eocene (Fig. 2; Gansser 1980; Thakur 1992; Jagoutz et al. 2015).

### Lamayuru Complex

Lamayuru Complex is a NW–SE trending thrust belt of thickness 1000–1500 m, sandwiched between the ZZ towards the south and the ophiolitic melange belt towards the north. It consists of olive-green shales alternating with light grey impure sandstone beds and blue platy limestones, siltstones, slates, and phyllites deposited in a turbidite environment towards the northern part of the Indian continental slope adjoining to Neo-Tethys Ocean during Upper Permian to the Cretaceous (Thakur 1981).

### Ophiolitic Melange Belt

A chaotic assemblage of igneous, metamorphic, and sedimentary rocks is exposed as a linear belt, thrust bound between Lamayuru Complex towards the south and DAC towards the north (Fig. 2). This melange belt was formed due to tectonic processes and later emplaced during Late Cretaceous (around 80 million years ago) along the ISZ

(Brookfield and Reynolds 1981). It is best exposed to the northwestern side of ISZ and is known as the Shergol Ophiolitic Melange (SOM) consisting ophiolitic remnants within jasperoid shales, cherts, and pyroclastic lavas (Robertson 2000). This melange belt is further exposed towards the southeastern side of ISZ and is known as the Zildat Ophiolitic Melange (ZOM). According to Thakur and Mishra (1984), the ZOM is thrust over the TMC and, in turn, is thrust by the Nidar Ophiolitic Complex (Fig. 2). The ZOM occurs in a linear belt that can be traced from south of Chumathang Village (33°21'30"N and 78°20'26"E) through Sumdo Village (33°14'03"N and 78°21'60"E), extending further southeast into Hanle Village (32°47'24"N and 78°59'58"E). It comprises chaotic blocks of basic volcanics, amygdaloidal basalts, agglomerates, conglomerates, glaucophane schists, minor serpentinites, and marine microfossils dispersed in a turbidite matrix (de Sigoyer et al. 2004). It is characterized by marine platform affinity pelagic limestones, distributed as dissected exotic blocks (Sen et al. 2013). According to Ahmad et al. (1996), the ZOM mafic volcanic rocks predominantly classify as alkaline basalts with minor sub-alkaline basalts, respectively, analogous to OIB and NMORB. In addition, the high-pressure blueschist grade metamorphic rocks along the ophiolitic melange belt occur interbedded within the pyroclastic and serpentinite rock types near the Sapi Village towards the northwestern side and Sumdo Village towards the southeastern side of the ophiolitic melange belt.

### Dras Arc Complex

The Dras Arc Complex (DAC) forms a dominant litho-tectonic unit of the ISZ, faulted between Lamayuru Complex and ophiolitic melange belt towards the south and Indus Group and Ladakh Batholith towards the north (Fig. 4d). It is up to 15-km-wide and 400-km-long outcrop in the direction of the regional trend, best exposed along Srinagar-Leh National Highway. In Dras Village, this arc complex consists of over 3000 m mafic to intermediate volcanics known as Dras volcanics intercalated with shallow-deep marine volcano-sedimentary assemblage, viz., volcano-clastic sediments, Radiolarian Cherts, and Orbitolina Limestones of Middle to Late Cretaceous age (Dietrich et al. 1983; Reuber 1989). Near Hardus Village of Kargil, Dras volcanics are underlain by gabbro-norite mafic cumulates of the Upper Cretaceous to Tertiary Period (Honegger et al. 1982).

The DAC comprises three tectonostratigraphic units from west to east, viz., Suru unit, Naktul unit, and the Nindam Formation. The Suru unit represents the arc interior and is composed of arc extrusives, volcanoclastics, and tuffaceous sedimentary rocks. The Naktul unit is interpreted as a proximal fore-arc apron that comprises thickly bedded debris flow, volcanoclastic turbidites, and shallow-water carbonates.

In contrast, the Nindam Formation is interpreted as a distal deep-water fore-arc apron composed of deep-water volcanoclastic turbidites and pelagic carbonates (Robertson and Degnan 1994). According to Bhat et al. (2019a), the DAC reflects part of the intra-oceanic arc formed within the Neo-Tethys Ocean during the Cretaceous Period above an assumed northward-dipping subduction zone. Dismembered Late Jurassic to Early Cretaceous ophiolitic slices overlie the DAC. Such as mantle peridotites with minor gabbro blocks in the Suru Valley towards the south of Kargil (i.e., Suru Valley ophiolite of Bhat et al. 2019b) as well as mantle peridotites, pyroxenites, gabbros, and diabase dikes near Dras-Thasgam area towards the east of Kargil (i.e., Dras-Thasgam ophiolitic slice of; Bhat et al. 2021b).

### Indus Group

The Indus Group is about 4 km thick and 10–15 km wide, NW–SE trending belt of molasse sediments comprising conglomerates, dark-brown sandstones, grey-green siltstones, and shales mainly exposed around Hemis Gompa and along the Indus River. It is in tectonic contact with the DAC towards the south and is separated from the Ladakh Batholith towards the north by the south-dipping Kargil Thrust. The age of these sediments ranges from Middle Eocene to Early Miocene (Thakur 1981).

### Ladakh Batholith

The Ladakh Batholith is a NW–SE trending longitudinal belt traceable throughout the ISZ and comprises diorite-granodiorite-granite rock assemblages. Petrochemical studies reflect calc-alkaline affinity and an intrusive multiphase history (White et al. 2011). It shows a crosscutting relationship with the DAC and an unconformable relation with the overlying Indus Group sediments, reflecting its Late Cretaceous to Early Miocene emplacement age (White et al. 2011). The northern margin of the Ladakh Batholith consists of Khardung volcanics of andesite-dacite-rhyolite composition, occurring as a linear magmatic belt and conformably overlain by a thick lahar unit (Weinberg et al. 2000). U–Pb zircon ages of Khardung volcanics ranges from 69.7 to 62.5 million years (Saktura et al. 2021).

### Proposed Geoheritage Sites

In this study, the proposed geoheritage sites are the Ladakh Himalayan Ophiolites (LHO), broadly occur as dismembered ophiolitic slices and ophiolitic complexes. The dismembered ophiolitic slices include Dras, Thasgam, Suru Valley, Shergol, Khangral, and Chiktan ophiolitic slices towards western Ladakh, while as the ophiolitic complexes include Nidar

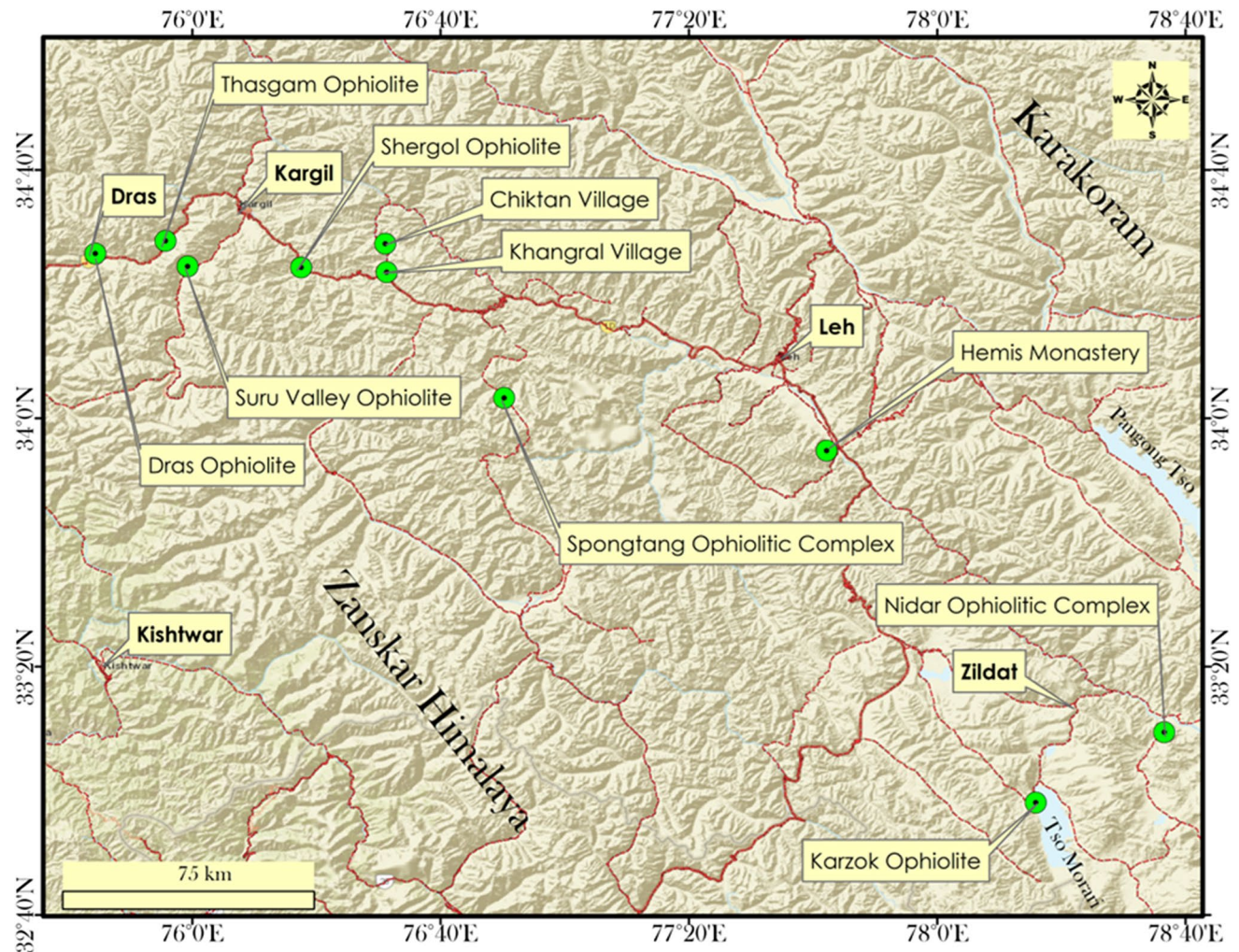
and Karzok towards eastern Ladakh and Spongtang towards southwestern Ladakh (Fig. 3). The ophiolites correspond to the remnants of the vast Neo-Tethys Ocean existed between the Indian and Eurasian Landmasses during Mesozoic Era (66 to 252 million years ago; Buckman et al. 2018). These sites are accessed by road and foot. The list of proposed geoheritage sites including their location, GPS coordinates, and geological aspects to be studied has been summarized in Table 1 and their geological observations are discussed in detail in later sections.

### Dismembered Ophiolitic Slices

Towards the northwestern Ladakh, dismembered blocks of ophiolitic rocks such as serpentinized lherzolites and harzburgites, cumulate dunites, pyroxenites, gabbros, and diabbases are exposed discontinuously at Dras, Thasgam, Suru Valley, Shergol, Khangral, and Chiktan locations (Fig. 4). Reuber et al. (1990) reported 176–157 Ma K–Ar amphibole

ages of non-deformed gabbros from the Thasgam Village, representing the older oceanic lithosphere formed at a MOR in the context of the Neo-Tethys Ocean.

Along the Dras–Kargil road parallel to the Dras River (Fig. 4), good exposures of serpentinized mantle peridotites are thrust over the DAC in the vicinity of Dras Village (Fig. 5a). Another outcrop of a dismembered ophiolitic slice composed of mafic–ultramafic cumulates with igneous layering, light grey diabbases, and ultramafic rocks—both mantle peridotites and coarse-grained dark-colored pyroxenites are exposed along the opposite banks of Dras River near Thasgam Village (Fig. 5b). The contact between these ophiolitic blocks and the underlying DAC is faulted as evident in the field (e.g., Radhakrishna et al. 1987; Robertson 2000; Bhat et al. 2021b). Similarly, at Trespone Village of Suru Valley, 17 km south of the Kargil town along the Kargil–Zanskar road, the DAC is unconformably underlain by dissected ophiolitic slice consisting of serpentinized mantle peridotites together with medium-grained dark-green



**Fig. 3** Map of the Ladakh Himalaya showing locations of the proposed geoheritage sites

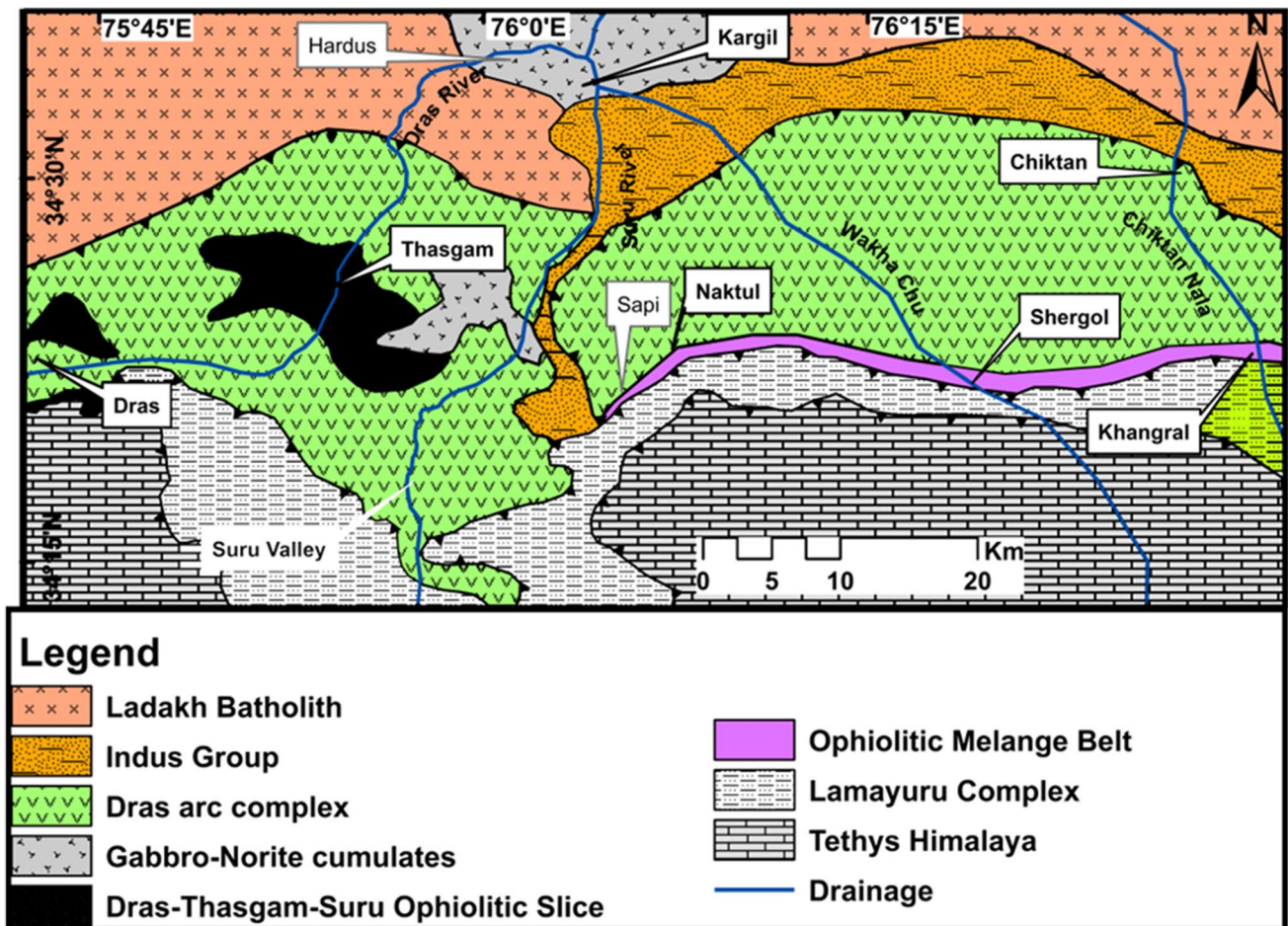
**Table 1** List of proposed geoheritage sites from Ladakh Himalaya including their location, GPS coordinates, and geological aspect to be studied

S. no	Geoheritage site	Location	GPS coordinates	Geological aspect can be studied
Dismembered ophiolitic slices				
1	Dras	Dras Village	34°25'50"N and 75°45'08"E	Mineralogy
2	Thasgam	Thasgam Village	34°28'17"N and 75°55'54"E	Stratigraphy
3	Suru Valley	Trespone Village	34°27'17"N and 76°04'10"E	Paleontology
4	Shergol	Shergol Village	34°24'18"N and 76°17'32"E	Geodynamics
5	Khangral	Khangral Village	34°22'34"N and 76°31'23"E	Geochemistry
6	Chiktan	Chiktan Village	34°27'24"N and 76°31'14"E	Sedimentology
Ophiolitic Complexes				
7	Nidar	Nidar Valley	33°09'29"N and 78°36'31"E	Geochronology
8	Karzok	Karzok Village	32°58'07"N and 78°15'51"E	Igneous petrology
9	Spongtang	Photoksar Village	34°04'22"N and 76°49'30"E	Structural geology
				Economic geology
				Metamorphic petrology
				Crust-mantle transition zone

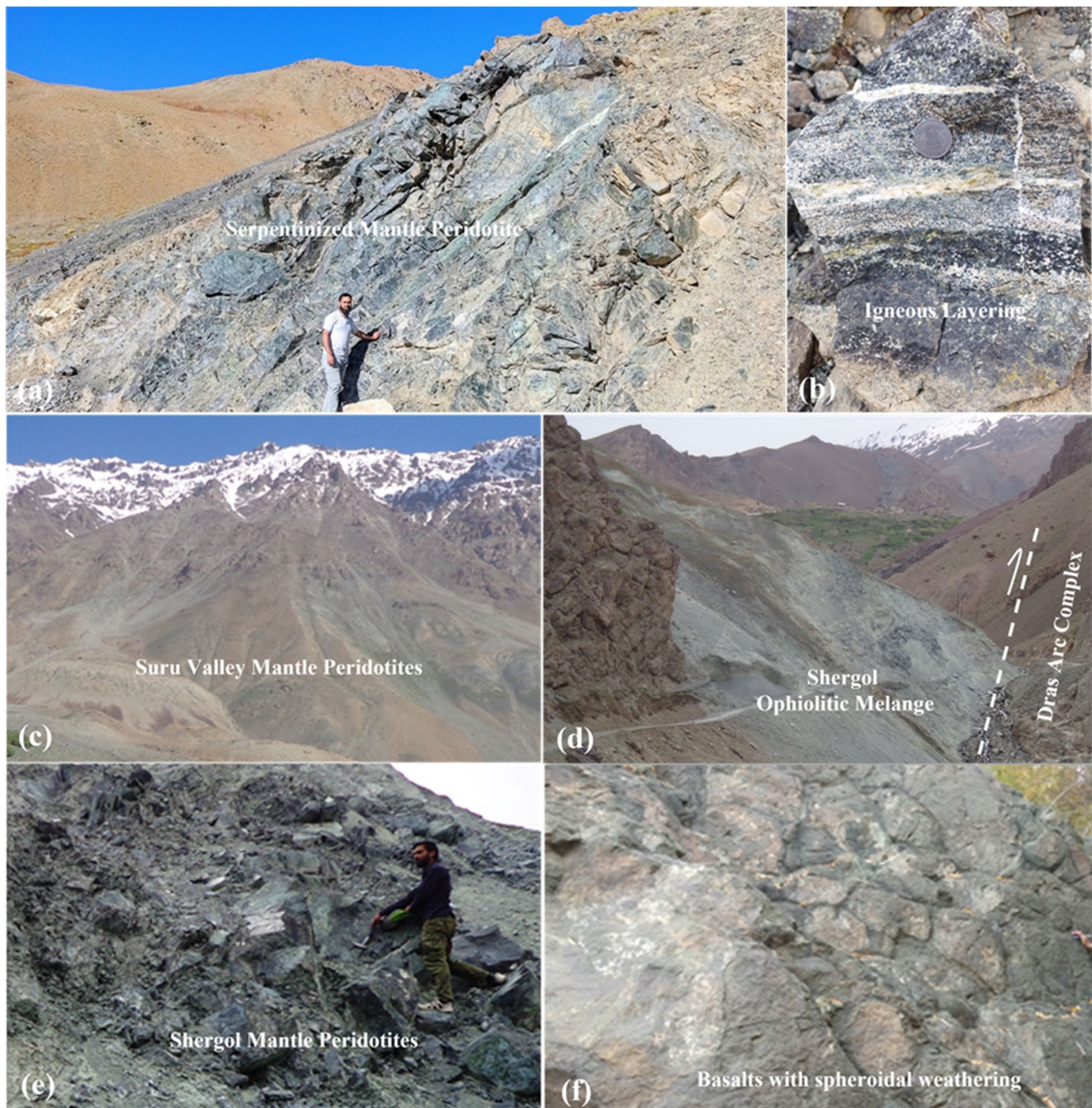
coloured massive gabbros (Fig. 5c). The southeastern outcrop of this ophiolitic slice is exposed along the left bank of downstream Suru River near Trespone Village. Based on the mineral and whole-rock geochemistry, these ophiolite

peridotites represent the tectonically disrupted oceanic substratum of the DAC (Robertson 2000; Bhat et al. 2021b).

Further, at Shergol Village, towards 30 km east of Kargil town along the Kargil-Leh National Highway, a well-defined



**Fig. 4** Geological map of northwestern Ladakh Himalaya (modified after Reuber 1989)



**Fig. 5** Field photographs showing; **a** serpentinized mantle peridotite near Dras village, **b** igneous layering in mafic–ultramafic cumulates at Thasgam Village, **c** Suru Valley mantle peridotite at Trespone Village, **d** Shergol ophiolitic melange near Shergol Village, **e** sheared

serpentinized Shergol mantle peridotites at Shergol Village, and **f** porphyritic basalt along Khangral-Chiktan road section showing spheroidal weathering

SOM sequence is exposed (Fig. 5d). It consists of mafic volcanics, minor gabbros, and serpentinized mantle peridotite blocks intercalated with pelagic sediments (Fig. 5e; Bhat et al. 2019c, and references therein). Based on the mineral and bulk-rock geochemistry, gabbros and serpentinized peridotites reflect subduction zone affinity (Bhat et al. 2017, 2019c), while mafic volcanics reflect island arc and ocean island basalt

(OIB) geochemical characteristics (Sinha and Mishra 1994). At Khangral Village, towards 62 km east of Kargil town along the Kargil-Leh National Highway, this ophiolitic melange is exposed along the Khangral-Chiktan road section parallel to Chiktan Nala (Fig. 4). Here, it forms a nearly 8-km-thick east–west trending thrust bound zone, consisting of greenschist-grade mafic volcanics, pillow basalts, and serpentinized



peridotite blocks accompanied by flysch sequence of thinly bedded greenish-grey shales with occasional massive greyish limestones of Nindam Formation (Rai 1987). These metabasalts are considered equivalent to Dras volcanics by earlier workers (e.g., Honegger et al. 1982). The isolated dark green-colored serpentinitized peridotite blocks are exposed at Chiktan Village towards the left bank of the downstream Chiktan Nala and are associated with the sedimentary rocks of the ophiolitic mélangé belt. A minor unit of porphyritic basalt showing prominent spheroidal weathering is exposed along the Chiktan Nalla in the surroundings of Chiktan Village (Fig. 5f).

## Ophiolitic Complexes

### Nidar Ophiolitic Complex

Towards eastern Ladakh, a large fragment of oceanic lithosphere known as Nidar Ophiolitic Complex (NOC) delineates the southern margin of the ISZ (Kojima et al. 2001; Sachan 2001). It is a thrust-bound unit sandwiched between the Indus Group to the north along with a south-dipping thrust and an ophiolitic melange belt, i.e., ZOM to the south along with a north dipping thrust (Fig. 6; Thakur and Mishra 1984). To the south of the TMC near Karzok Village, a small ophiolitic slice exists called Karzok ophiolite within

the Permian Tethys sediments of Tanglangla Formation. It consists of highly deformed chromitites, serpentinites, and minor metamorphic gabbros of a crust-mantle transition zone (Maheo et al. 2004). However, de Sigoyer et al. (2000) thought that it might represent a detached klippe of NOC.

Although, the type section of NOC is present in Nidar Valley, while its best section is exposed in the Mahe-Sumdo section along the Leh-Tso Morari road. After crossing the Mahe Bridge (33°16'06"N and 78°28'08"E) over the Indus River (around 158 km from Leh), this ophiolitic complex consists of three litho-units from the top, i.e., towards north to bottom, i.e., towards the south. On top lies a 500-m-thick crustal section made of basalt and andesites with poorly preserved pillow structures near its base (Fig. 7a and b), and gradually passes into volcanogenic sediments, viz., chert, jasper, shale, and siltstone associated with Radiolarian fossils of Cretaceous age (Kojima et al. 2001). Towards the south, these rocks are underlain by 500-m-thick massive gabbros (Fig. 7c) with crosscutting dolerite dikes resting on 100-m cumulate gabbros (Maheo et al. 2004). Both micro gabbros with ophitic texture and cumulate gabbros are present (Ahmad et al. 2008). Further towards the south, the ultramafic unit (Fig. 7d) comprises spinel-harzburgite at lower levels and spinel-dunite with chromite veins at higher levels (Sachan 2001). Although the NOC exhibits an almost complete

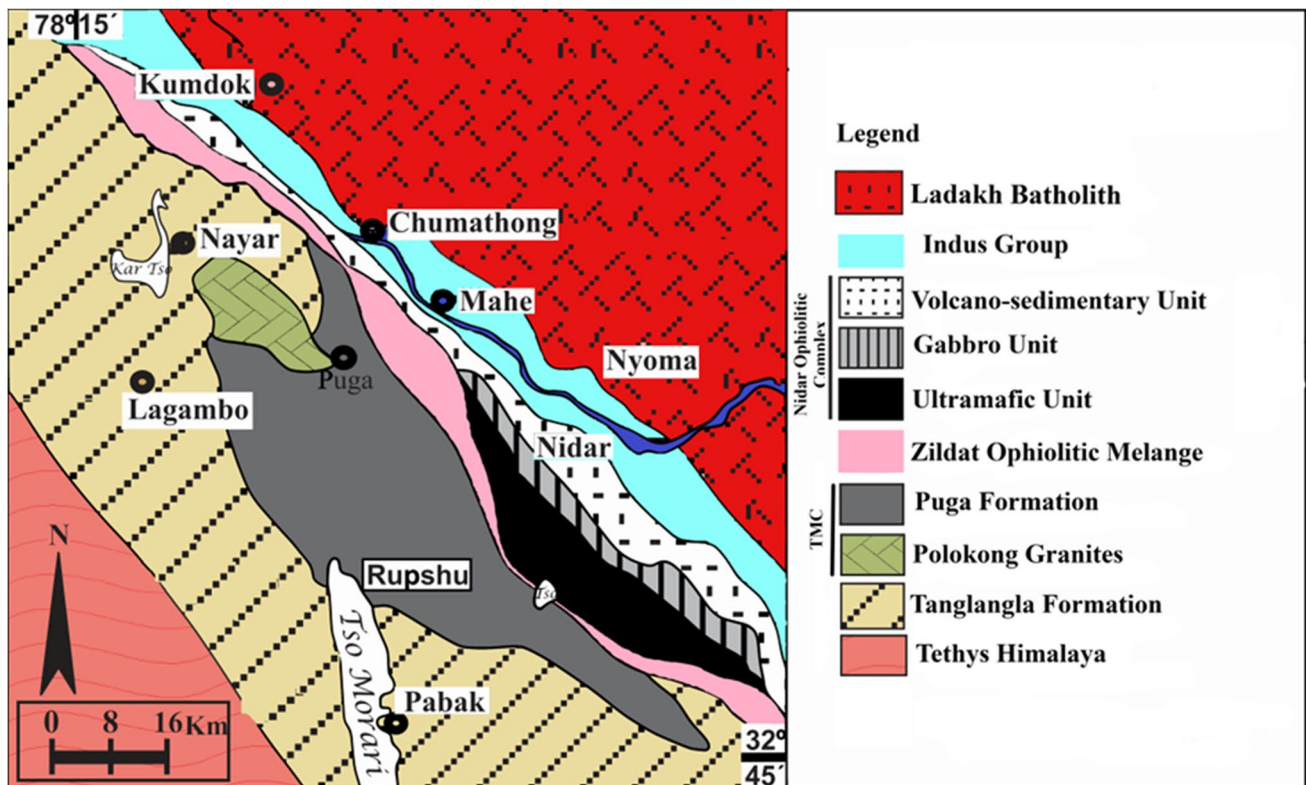
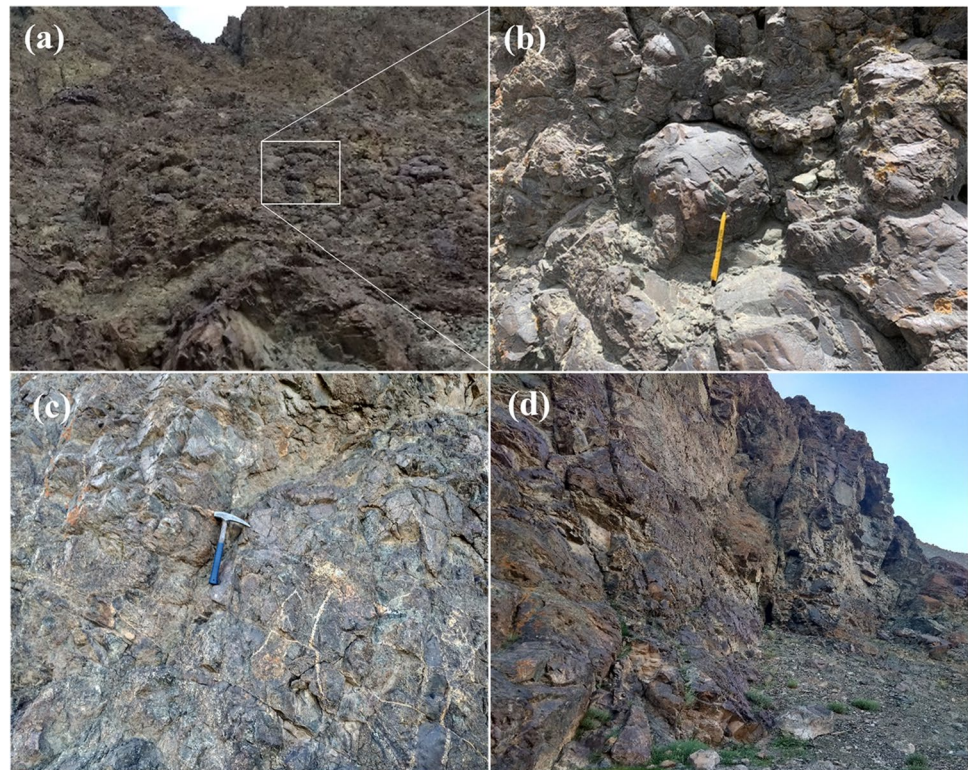


Fig. 6 Geological map of eastern Ladakh Himalaya (modified after Thakur and Mishra 1984)

**Fig. 7** Field photographs showing; **a, b** pillow volcanics near Mahe bridge, **c** medium- to coarse-grained deformed gabbros, and **d** ultramafic rocks of NOC, eastern Ladakh



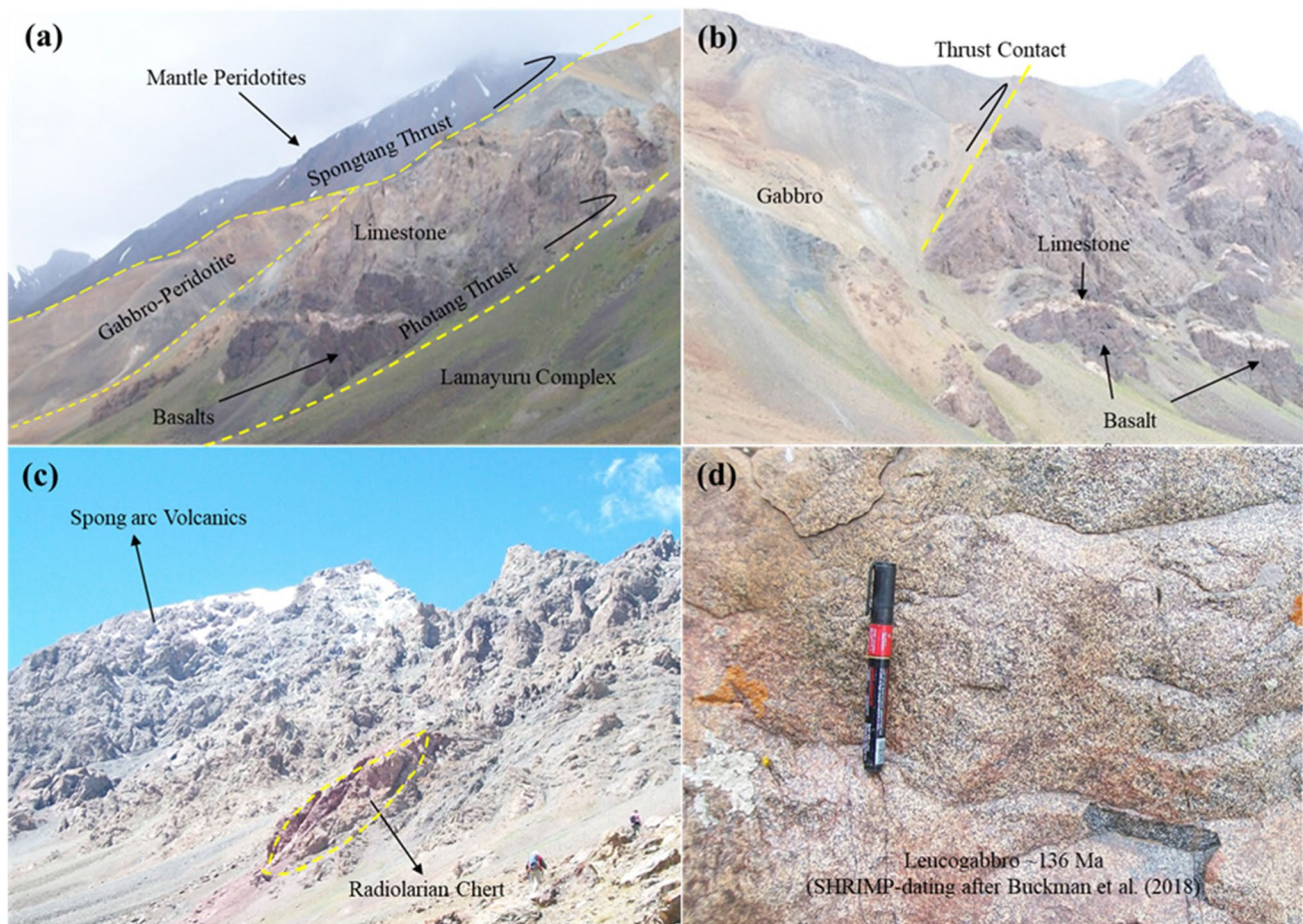
ophiolite succession from the upper mantle and crustal rocks to marine pelagic sediments, a typical sheeted dike complex is absent (Sachan 2001). The volcanic and volcanoclastic rocks of this ophiolite complex correlate with the DAC rocks towards the northwest and likely record the onset of arc volcanism towards eastern Ladakh (Zyabrev et al. 2008). Towards the south, both the ophiolitic complex and the blueschist-bearing ZOM are thrust over the TMC (Thakur and Mishra 1984).

### Spongtang Ophiolitic Complex

The Spongtang Ophiolitic Complex (SOC) lies about 30 km south of the ISZ at an elevation of above 5000 m and crops out as an isolated klippe near the Photoksar Village of Zaskar Himalaya (Fig. 2; Corfield et al. 2001). This ophiolitic complex overlies the Lamayuru Complex and, from bottom to top, consists of mantle peridotites (viz., harzburgite and spinel-lherzolite with dunitic pods), layered mafic–ultramafic rocks, isotropic gabbros with minor plagiogranites, highly tectonized sheeted dike complex, mafic lavas, and Radiolarian Cherts associated with other deep-sea pelagic sediments (Fig. 8a and b). The whole ophiolite sequence is overlain by a volcano-sedimentary arc sequence known as the Spong

arc of SSZ affinity, characterized by basalt-andesitic flows alternating with Radiolarian Chert bands of Cretaceous age (Fig. 8c; Pedersen et al. 2001) and is underlain by a serpentine mélangé called Photang thrust sheet (Corfield and Searle 2000; Pedersen et al. 2001). Earlier, Corfield et al. (2001) inferred that the Spong arc complex and the DAC represent two separate arc complexes within the Neo-Tethys Ocean; however, Buckman et al. (2018) suggested that these arc complexes are part of the same island arc complex. Recently, Buckman et al. (2018) reported the U–Pb zircon ages of 136–133 Ma for leucogabbros (Fig. 8d) intrusive in mantle peridotites reflecting intra-oceanic subduction initiation within the Neo-Tethys Ocean during Early Cretaceous, thus corroborating the earlier radiometric interpretations of Reuber et al. (1990), Pedersen et al. (2001), and Maheo et al. (2004).

Recent studies concluded that the DAC is dominated by tholeiitic to calc-alkaline Dras volcanics as well as subordinate sedimentary rock associations and reflects a part of the intra-oceanic island arc complex, emplaced during the Late Jurassic to Middle Cretaceous above an assumed north-dipping subduction zone in the context of Neo-Tethys Ocean (e.g., Bhat et al. 2019a, and references therein). Towards eastern Ladakh, the Nidar ophiolitic mafic volcanics share



**Fig. 8** Field photographs showing; **a** Spongtang Ophiolitic Complex (SOC) near Photoksar Village, Zaskar, **b** basalts and gabbros with limestone lenses, **c** Spong arc volcanics with associated radiolarian chert bands, and **d** leucogabbro ~ 136 Ma age

similar geochemical characteristics to that of the Dras volcanics (Dietrich et al. 1983) and the Chalt volcanics of Kohistan, northern Pakistan (Khan et al. 1997). In addition, both OIB and NMORB affinity volcanics are associated with the ophiolitic mélangé belt along the Khangral-Chiktan road section, therefore corroborating the earlier observations towards the western and eastern extensions of the ophiolitic melange belt (e.g., Sinha and Mishra 1992, 1994; Ahmad et al. 1996). Based on the mineral, whole rock, and isotope geochemistry, Bhat et al. (2021a, 2021b) concluded that the Dras-Thasgam-Suru dissected ophiolitic slices as well as NOC and SOC were evolved in an intra-oceanic subduction system corresponding to Dras-Nidar-Spong arc complex.

The associated Callovian-Tithonian Radiolarian Cherts constrain the age of the DAC i.e., < 144.2 Ma (Honegger et al. 1982), as well as by the Albian to Cenomanian Orbitolina Limestones (Reuber 1989). These ages corroborate well with the radiometric ages, i.e., ~ 156 Ma (U–Pb zircon

ages of DAC felsic tuff near Kargil after Walsh et al. 2021) and ~ 101 ± 2 Ma (U–Pb zircon ages of granodiorite intrusives into DAC near Kargil after Schärer et al. 1984). Similarly, the NOC gabbros and basalts yield a Sm–Nd whole-rock and mineral isochron age of 140 ± 32 Ma, reflecting the time of formation of the ophiolitic crust (Ahmad et al. 2008). Earlier, amphiboles from the NOC gabbros gave argon ages ( $^{39}\text{Ar}/^{40}\text{Ar}$  step-heating technique) between 124 and 110 Ma, corresponding to hydrothermal metamorphism related to the initiation of subduction within the Neo-Tethys Ocean (Maheo et al. 2004). Consistent ages of Upper Barremian to Aptian have been revealed from the Radiolarian Cherts associated with the NOC volcano-sedimentary section (Kojima et al. 2001; Zybrev et al. 2008). Pedersen et al. (2001) reported a U–Pb zircon age of 177 ± 1 Ma from SOC diorite and 88 ± 5 Ma from the overlying Spong arc andesite. They interpreted the older ages to represent the Neo-Tethys Ocean

crust on top of which the Spong arc developed during the Late Cretaceous (~ 88 Ma). Recently, Buckman et al. (2018) reported 136–133 Ma gabbros, with arc-like geochemical signatures, intrusive into the mantle peridotites from the SOC and possibly signified intra-oceanic subduction initiation and fore-arc spreading in ~ 177 Ma Neo-Tethys oceanic crust. Therefore, based on the radiometric age data, the intra-oceanic island arc complex was active from Late Jurassic to Middle Cretaceous within the eastern side of the Neo-Tethys Ocean (Walsh et al. 2021, and references therein). Part of this intra-oceanic arc complex is presently reflected in the form of the Dras-Nidar-Spong Island arc/ophiolite complex along the ISZ. Recently, Bhat et al. (2021a) proposed that the LHO exhibit characteristics similar to the subduction initiation rule analogous to the existing Izu-Bonin-Mariana arc system within the western margin of the Pacific Ocean (Reagan et al. 2017).

### Sociocultural Heritage of Ladakh

The union territory of Ladakh, erstwhile part of Jammu and Kashmir State, is rich in historical and cultural heritage owing to its unique geographical location and a mixture of varying civilizations. This region is home to diverse communities like Buddhists, Muslims, Hindus, and others. The ancient inhabitants of Ladakh were the immigrants of Tibet, Skardo, and nearby parts like Purang, also known as Dards, an Indo-Aryan race. Buddhism traveled from central India to Tibet through Ladakh leaving its imprint in Ladakh. Also, islamic missionaries made a peaceful penetration of Islam in the early sixteenth century. In Ladakh, from costumes to cuisine, although everything is heavily influenced by the Tibetan Culture, its own culture is rich and fascinating, and that includes gompas or monasteries, costume and cuisine, folk music and dance, arts and crafts, and sports. Traditional houses of Ladakh are made of clay, stone, and wood (Supplementary Fig. S1a). The income source of the local communities comes from the handicrafts by making stone jewellery, woolen clothes, and mural paintings on the walls of the monasteries, which also symbolizes the various aspects of Buddhism. Also, milk production is one of the largest professions in the region; therefore, animals such as cow, goat, and sheep are widely domesticated.

Much of the everyday life of the Ladakhi people revolves around the monasteries, which forms a major part of their culture. These monasteries are the center points around which the spiritual and religious life of the Buddhist population revolves. Besides complementing the beauty of its rugged landscape, these monasteries are famous for their

location and architecture. Some rest precariously on rock cliffs, while others are on the unimaginably rugged and barren mountain peaks. Most famous monasteries of Ladakh are Hemis Monastery, Thiksey Monastery, Karsha Monastery, and Alchi Monastery. Hemis Monastery is one of the most popular monasteries in Ladakh situated around 45 km away from the Leh City (Supplementary Fig. S1b). It is a seventeenth-century Buddhist shrine of Drukpa Lineage which was re-established in 1672. Its entrance is through a giant gate that opens to a large courtyard. It consists a white-walled main building with a library on its premises, and two assembly halls with architecture of Tibetan style. It is known for its 2-day religious event known as Hemis Festival, held annually in the month of June or July. The major attraction during the festival is the cham dance and unfurling of the giant age-old Thangkas (religious paintings).

The lifestyle of the Ladakhi people is very simple and is heavily influenced by Buddhism and Tibetan Culture. People cultivate each other's agricultural fields during the harvest season, which promotes community feeling and brotherhood. The Ladakhi Men wear a long woolen robe known as Goucha in local language, and Ladakhi Women wear a similar kind of robe known as Kuntop in local language (Supplementary Fig. S1c). Whereas, Perak, a long hat, is worn by both men and women. Most dishes are prepared from local products consisting of pumpkins, beans, potatoes, beetroot, barley, rice, mutton, chicken, yak meat, etc. Besides, skyu, momos, thukpa, gur gur chai (nun chai), and chhang (local alcohol) are also widely enjoyed by the people. Also, the rich cultural heritage of Ladakh includes folk music and dance. One of the most famous dances is chham or the mask dance, signifying victory of good over evil, mostly performed by monks in monasteries (Supplementary Fig. S1d). The folk music is heavily influenced by Tibetan music and involves religious chanting, i.e., holy recitations of sacred texts (an example is Yang Chanting) accompanied by resonant drums and low sustained syllables. Daman, Surna, and Piwang are the instruments used in the performance of folk music and dances. Throughout the year, several festivals accompanied by masked dances, folk performances, and other traditional programs are celebrated by the people of Ladakh. Some of the famous ones are Losar, Hemis Tsechu, Diskit Gustor, Saka Dawa, and Ladakh Polo Festival.

Most of the daily use items for domestic and religious purposes are handcrafted such as cooking pots, agricultural tools, embroidery, pattu (woolen clothing material), willow twig baskets, carved wooden tables and lintels, chang pots, tea cup stands, ladles, and bowls, which are manufactured locally and add to the aesthetic value (Supplementary Fig. S1e). The traditional sports are archery and polo (Supplementary Fig. S1f).

Archery and polo competitions are being held providing an occasion for the villagers to get together and enjoy themselves by traditional dancing, drinking, and gambling.

### Strength Weakness Opportunity Threats (SWOT) Analysis

Strength Weakness Opportunity Threat (SWOT) analysis is a management tool commonly used to set out the business marketing plans. However, due to its usefulness in evaluating the qualitative potential of geoheritage sites, it is nowadays extensively used as a tool in the geotourism sector (Antic and Tomic 2017; Bhosale et al. 2021). The SWOT analysis assists the feasibility of a particular geoheritage site as a potential tourist attraction by converting the possible avenues and ongoing threats into opportunities. It also produces a comprehensive illustration by taking into account internal factors, viz., strength and weakness, and external factors, viz., opportunities and threat. Therefore, policies, viz., boost the strengths, reduce the weaknesses, maximize the opportunities, and minimize the threats can be executed in enhancing the geotourism sector (Kalantari et al. 2011).

For geoheritage sites, the SWOT analysis integrates available field data as well as cultural and historical features of a geoheritage site and separates them into internal and external factors. Such type of analysis will either assist in accomplishing the objectives or will demarcate obstacles that need to be minimized to get the proposed outcome. In this analysis, an evaluation matrix is performed on both the internal and external factors, respectively, classified

as internal factor evaluation matrix (IFEM) and external factor evaluation matrix (EFEM). Both IFEM and EFEM will result in the total weighted score (TWS). For IREM and EFEM, appropriate components of internal and external factors are identified and their respective priorities are computed (Schmoldt et al. 2001). Each factor component is having a separate score, ranging from 1 to 4 (i.e., 1 for poor, 2 for average, 3 for good, and 4 for excellent). Also, for each factor component, the shareholder weight is applied ranging from 0 (not significant) to 1 (most significant). Then, weighted score for each factor component is computed by multiplying its score with weight, and sum of the weighted scores gives the TWS.

In the present study, SWOT analysis of the proposed geoheritage sites was carried out. The IFEM and EFEM are shown in Tables 2 and 3, respectively. The TWS for IFEM and EFEM is 3.22 and 3.25, respectively (Fig. 9), and is greater than 2.5 reflecting that the strength overshadows weakness and the opportunities overshadows threats. Therefore, these results prove that the proposed sites are potential to be designated as a geoheritage site.

### Summary and Conclusion

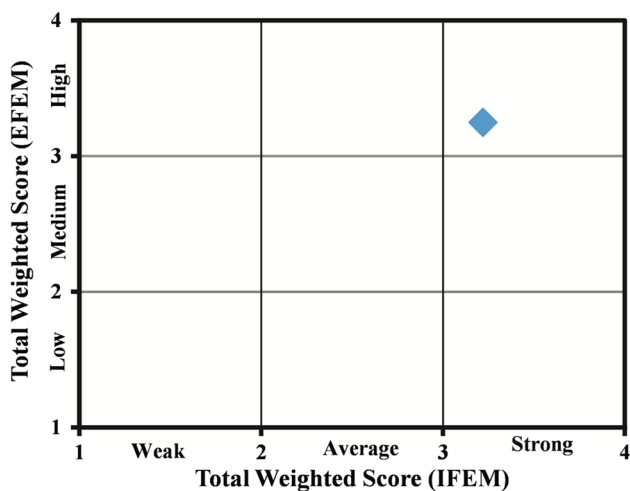
Ladakh has a rich and fascinating sociocultural heritage owing to its unique geographical location and a mixture of varying civilizations. Also, its culture is heavily influenced by the Tibetan Culture including gompas or monasteries, costume and cuisines, folk music and dance, arts and crafts,

**Table 2** Strengths and weaknesses of internal factor evaluation matrix (IFEM)

Particulars	Weight	Score	Weighted score
<b>Strengths</b>			
Hemis Monastery with its seventeenth-century Buddhist Shrine architecture consisting sculpture, cupolas, and engraved buildings of historic and artistic value	0.12	3	0.36
Understanding various aspects of geology such as igneous and metamorphic petrology, paleontology, mineralogy, geochemistry, geochronology, geodynamics, structural geology, crust-mantle transition zone, economic geology, and geomorphology, with room for additional scientific research and educational values	0.18	4	0.72
Avenues to learn about the geocultural values that surround the geoheritage sites	0.15	3	0.45
Communication availability and motorable road accessibility to the proposed geoheritage sites	0.20	2	0.40
<b>Weaknesses</b>			
Lack of awareness in inhabitants about the geological and economic importance of the Ladakh Ophiolites	0.10	4	0.40
Lack of concrete government policies and legislation for conservation of geoheritage sites	0.08	4	0.32
Lack of media coverage, advertisements, signboards, and hoardings about the geoheritage sites	0.05	3	0.15
Lack of involvement of local people in protection of geoheritage sites	0.06	4	0.24
Tourist season are limited to summers only due to cold and harsh winters	0.06	3	0.18
Total weighted score (TWS)	1		3.22

**Table 3** Opportunities and threats of external factor evaluation matrix (EFEM)

Particulars	Weight	Score	Weighted score
<b>Opportunities</b>			
Opportunity for the government and other organizations to promote these geoheritage sites as a tourist destination	0.19	4	0.76
Introducing local culture to tourists during several cultural events (e.g., Hemis, Losar, and Polo Festivals)	0.16	3	0.48
Establishing a market for the sales of indigenous handicrafts, cuisines, and various geoproducts (e.g., fossils, maps, badges) for the benefit of local community	0.11	3	0.33
Constructing environment and budget-friendly homestay facilities for tourists and showcasing indigenous culture	0.10	3	0.30
<b>Threats</b>			
Loss of various geological features as a result of natural processes such as weathering and erosion	0.17	4	0.64
Illegal mining and careless rock and fossil collection by amateur and local collectors	0.12	3	0.36
Pollution to these geoheritage sites by tourists and locals due to lack of proper garbage disposal facilities	0.08	3	0.24
Inadequate banking services, telecommunication, and medical services	0.07	2	0.14
Total weighted score (TWS)	1		3.25

**Fig. 9** Graph of total weighted score of internal and external factor evaluation matrix showing the potential of proposed Ladakh Himalayan Ophiolites as geoheritage sites

and sports. The source of income mostly comes from the milk production and handicrafts, e.g., making stone jewelry, woolen clothes, and mural paintings. In addition, the Ladakh Himalaya, recognized as a geological monument, possesses prodigious geological diversity from Paleozoic to Pleistocene with good rock exposures. The existence of LHO along the ISZ bears witness to the presence of the Neo-Tethys Ocean. Studying these ophiolitic complexes helps understand the various aspects of petrology, such as mantle melting and differentiation, mantle wedge metasomatism, fluid/melt rock interaction, mantle-crust geochemical evolution, and collision events. Although, geological studies in Ladakh go back to mid-nineteenth century, a smaller number of native as well as foreign researchers have shown interest

in studying LHO. Because of the fact that LHO provide the world's best well-exposed on-land records of Neo-Tethys Oceanic remnants in the northwestern India coupled with the presence of good and fresh rock exposures, these ophiolites provide picturesque and aesthetic value to the landscape. Besides, high-altitude exposures (mostly > 4000 m.a.s.l.) of these ophiolitic slices provide the world's best camping spots after tracking few kilometers from the base. As the Ladakh is the pivot of local as well as foreign tourists, travelling lengthy distances to various popular but crowded far-flung destinations such as Tso Morari, Pangong Tso, Tso Kar lakes, high altitude passes, and hot sulfur springs might lead them to miss these (LHO) imperturbable, tranquil, astonishing, and memorable sites of Ladakh.

Concerned about the internationally acclaimed geodiversity of Ladakh that is being unknowingly destroyed under the garb of urbanization development coupled with the actions of the natural processes, these ophiolitic outcrops needs to be protected, conserved, and maintained owing to their geoscientific significance and geotourism potential. Therefore, it is the need of the hour for collaborative cooperation of the earth scientists, environmentalists, geographers as well as Ladakh Science Foundation to come together to promote as well as to protect and preserve the geoheritage sites of Ladakh. Although it seems almost impossible to stop the unchecked urbanization activities in Ladakh, public awareness through various media platforms and education can help in preserving these critical sections for future research activities and promoting geotourism in Ladakh. Proposed geoheritage sites of Ladakh have already gained international recognition; therefore, they can attract global researchers and increase the revenue of local people and the government. They can also help enhance education and learning opportunities through stronger bilateral relationships between

the partner countries. Therefore, the integrated protection and preservation measures of important geoheritage sites can prevent any possible future socioeconomic ill-use and leave a good legacy for future generations. In addition, in SWOT analysis, the resulting TWS for the IFEM is 3.22 indicating that strength exceeds weaknesses, while the TWS for the EFEM is 3.25 suggesting that the opportunity to develop and conserve the proposed geoheritage site exceeds the threat. Hence, these suggested strategies, viz., enhancing the strengths and reducing the weaknesses while maximizing the opportunities and minimizing the external threats, can be implemented to the proposed LHO for geotourism potential.

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## Declarations

**Conflict of Interest** The authors declare no competing interests.

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