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## Geology of the eastern part of the Tso Morari nappe, the Nidar Ophiolite and the surrounding tectonic units (NW Himalaya, India)

Nicolas Buchs and Jean-Luc Epard

Institut des sciences de la Terre (ISTE), Faculté des géosciences et de l'environnement, Université de Lausanne, Lausanne, Switzerland

### ABSTRACT

The Tso Morari nappe is well known for having suffered ultrahigh-pressure metamorphism in the northwest Himalaya. Its pressure-temperature evolution has been widely studied and debated since the end of the 1990s. However, the lithostratigraphy, structures and metamorphism of the tectonic units around the Tso Morari nappe are poorly known, especially in the eastern part of the nappe. Here, a detailed geologic map based on recent field work is presented. The survey area is the eastern part of the ultrahigh-pressure Tso Morari nappe, the surrounding tectonic units and the Nidar Ophiolite.

This map improves the knowledge of the geology and geometry of the North Indian continental plate and the ocean-derived units south of the Eurasian continent in eastern Ladakh. Knowledge of the present-day geometry will help to reconstruct the initial setting in the kinematic models of the formation and exhumation of the Tso Morari nappe in relation to its surrounding tectonic units.

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### KEYWORDS

Geology; Himalaya; Ladakh; Tso Morari; high-pressure metamorphism; ophiolites; Indus suture zone; mélange units; tectonic map

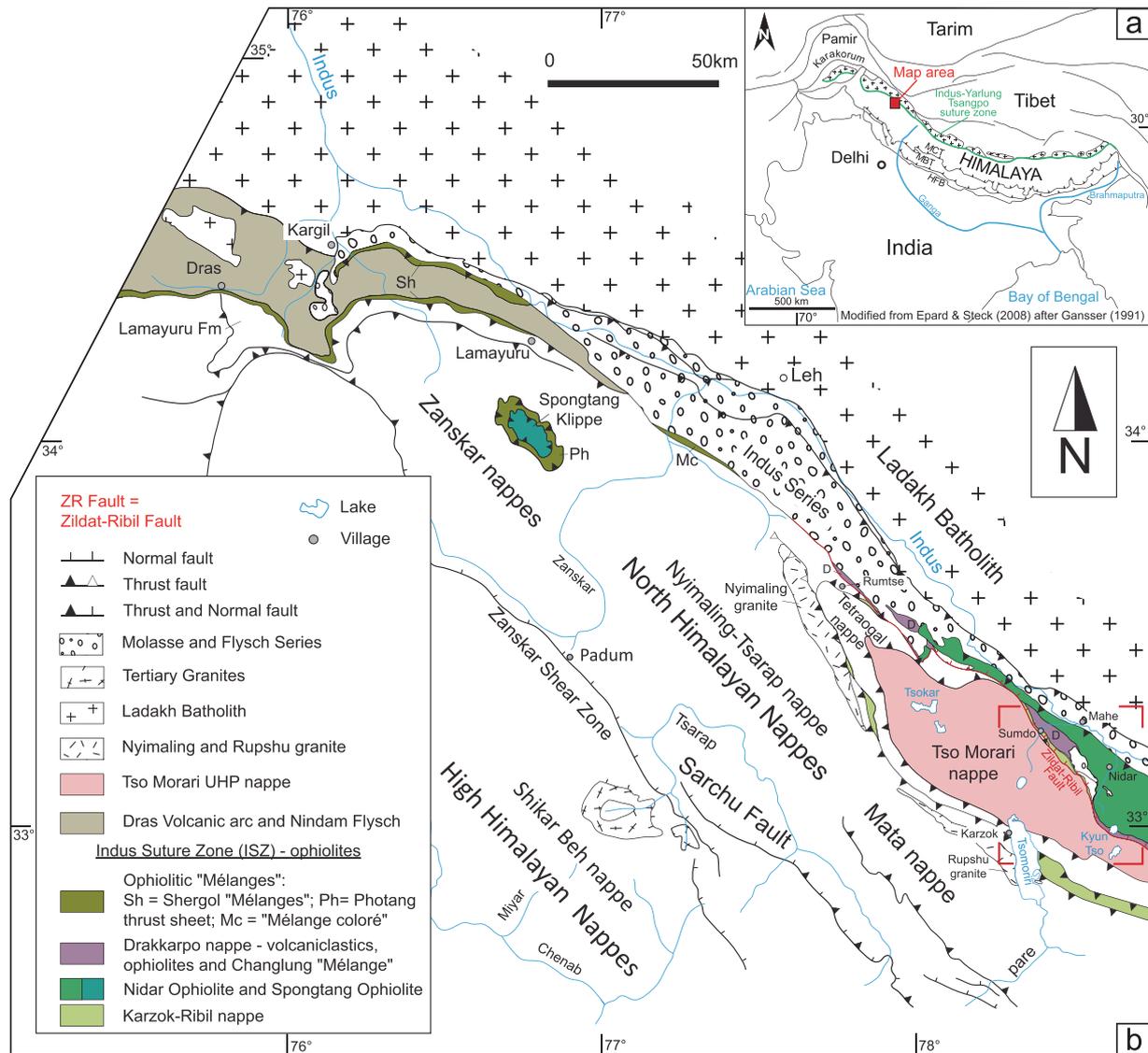
### 1. Introduction

The Himalaya is the largest mountain range in the world. The available geologic maps are rare, often imprecise or difficult to access. Since 1979, the University of Lausanne carried out different geological exploration and mapping studies (e.g. Baud et al., 1982; Epard, Steck, Vannay, & Hunziker, 1995; Steck, 2003; Steck, Spring et al., 1993; Steck, Epard et al., 1998; Steck, Epard, & Robyr, 1999; Epard & Steck, 2008) including PhD Theses (Dezes, 1999; Girard, 2001; Spring, 1993; Stutz, 1988; Vannay, 1993; Wyss, 1999; Robyr, 2002) in the northwest Indian Himalaya. However, the Eastern Ladakh, especially the Eastern part of the high-pressure Tso Morari nappe, remained incompletely mapped. Here, we present a geologic map of the Tso Morari nappe, the Nidar Ophiolite and the surrounding tectonic units.

The Tso Morari nappe extends south of the Indus Valley, from Kyun Tso to the southeast to Rumtse to the northwest (Figure 1). The N-S oriented Kalra and Nidar valleys cut most of the tectonic units of the Indus suture zone and of the North Himalayan nappes along two main geologic transects: the Mahe-Sumdo and the Nidar-Kyun Tso sections. Stoliczka (1865); Lydekker (1883); Oldham (1888); McMahan (1901); and Berthelsen (1953) were the first geologists to describe complex 'mélanges' and ophiolites along the Mahe-Sumdo section, but the first detailed maps were completed by Shanker et al. (1975) and by

Fuchs and Linner (1996). However, the Nidar-Kyun Tso section remained less studied and described than the Mahe-Sumdo section. Thakur and Viridi (1979) proposed a general map and several cross-sections associated with geochemical analyses that were mainly carried out on ophiolites (Thakur & Bhat, 1983). A more detailed map was published by the Geological Survey of India (Wangdus & Tikku, 1994) on the ultramafic unit of the Nidar Ophiolite north of the Kyun Tso. Due to the access difficulties (high elevation, border area) of the Nidar-Kyun Tso section, Philip, Ravindran, and Thakur (2000) and Philip, Ravindran, and Mathew (2003) published a general map of the Nidar Ophiolite based on remote sensing analyses. High-resolution IRS-1C/1D satellite sensor images were used.

The goals of the present study are as follows: (i) to map a relatively unknown area in Eastern Ladakh, especially the Nidar-Kyun Tso section, and to briefly describe the lithostratigraphy of the mapped tectonic units and (ii) to constrain the initial geometry of the Indian and Eurasian plates in Eastern Ladakh prior to collision. This new data will constrain the possible initial geometry and help to improve the future numerical modeling of ultrahigh-pressure metamorphic nappe exhumation (e.g. Beaumont, Jamieson, Butler, & Warren, 2009; Chemenda, Mattauer, Malavieille, & Bokun, 1995; Gerya & Stöckhert, 2006; Guillot, Hattori, de Sigoyer, Nægler, & Auzende, 2001).



**Figure 1.** (a) General map of the Himalaya. (b) Tectonic map of the NW Himalaya and location of the mapping area modified after Thakur and Viridi (1979); Thakur and Misra (1984); Robertson and Degnan (1994); Steck (2003) and Epard and Steck (2008).

The mapping leads to a better definition of several tectonic units and lithostratigraphic formations such as the Karzok-Ribil nappe, a new North Himalayan nappe composed of Indian continental rocks and ophiolites and the Changlung 'mélange' and the Gya Formation both found in the Drakkarpo nappe. We will follow the definition of 'mélange' by Raymond (1984), keeping it as a purely descriptive term without any genetic implication. Detailed mapping of the Nidar Ophiolite revealed a complex internal structure related to its formation and evolution in a suprasubduction context. Finally, the Tetraogal nappe and the newly defined Karzok-Ribil nappe can be followed along the northeastern and southeastern sides of the Tso Morari nappe.

## 2. Map construction

Geological mapping (Main Map) was performed in the field on 1:50,000 and 1:100,000 Landsat 7 and 8 images (WGS84 UTM 44N; September 2013 and October 2015)

from the USGS (<https://earthexplorer.usgs.gov/>) and using a 1:150'000 topographic map (Abram Pointet, Editions Olizane, 2013). The mapping was performed during the summer seasons of 2013, 2014, 2015 and 2016. ArcMap (ArcGIS 10.2 to 10.5 versions) was used to combine bands 4, 3 and 2 of the Landsat 7 and bands 5, 4 and 3 of the Landsat 8 satellite images. The panchromatic band (pixel size of approximately 15 m) was combined with the previously combined bands to improve the resolution. The combined infrared band (band 4 for Landsat 7 and band 5 for Landsat 8) improves the contrast between the different rocks. A GPS was used to obtain the position coordinate (WGS84-UTM) of the outcrops, samples and measured structures in the field. All collected data were georeferenced in ArcMap under the same coordinate system. Cross-sections were drawn perpendicular to the main foliation strike and major tectonic contact between the Himalayan units. Extrapolated stratigraphic and tectonic contacts between the rock formations or tectonic

units are represented by dashed lines. The Quaternary deposits in the main valleys are left in white to improve the readability of the map.

### 3. Geologic outline

The Tso Morari nappe and its overlying Tetraogal, Karzok-Ribil and Mata nappes belong to the North Himalayan nappes. This nappe succession forms a dome structure that extends from Rumtse to the northwest until the Kyun Tso area to the southeast. These units belong to the North Indian continental plate and its transition to the oceanic domain. The Drakkarpo nappe and the Nidar supra-subduction Ophiolite form a NW-SE trending discontinuous suture zone of approximately 150 km long. These two ophiolitic units were not involved in the North Himalayan nappe stack and outcrop parallel to the Indus suture zone. North of that, the Indus valley is dominated by outcrops of Indus Flysch and Molasse series locally transgressing or thrust on top of the Ladakh Batholith.

This chapter gives a geological overview of the different tectonic units mapped in the studied area. The following tectonic units are described from north to south, namely, from the Ladakh Batholith to the North Himalayan nappes.

#### 3.1. Ladakh Batholith

The Ladakh Batholith belongs to the active Asian margin north of the Indus Suture Zone and is principally made up of granites, granodiorites, diorites and tonalites. The calc-alkaline magmatic activity of the Ladakh Batholith is related to the subduction of the Indian plate below the Asian plate. The magmatic ages range from approximately 100 to 29 Ma (Bouilhol, Jagoutz, Hanchar, & Dudas, 2013; Honegger et al., 1982; Schärer, Xu, & Allègre, 1984; Singh, Kumar, Barley, & Jain, 2007; St-Onge, Rayner, & Searle, 2010; Upadhyay, Frisch, & Siebel, 2008; Weinberg & Dunlap, 2000) between Kargil and Chumathang. The age of the Ladakh batholith in the northern part of the map is not yet established.

#### 3.2. Indus suture zone

##### 3.2.1. Indus group

The Indus group (Garzanti & Van Haver, 1988) is made up of continental shale, conglomerates and sandstones. These molasse sediments were deposited in the intramontane Indus Basin (Brookfield & Andrews-Speed, 1984; Searle, Pickering, & Cooper, 1990; Sinclair & Jaffey, 2001; Steck, 2003; Van Haver 1984) from the Upper Eocene to Miocene. Pebbles in the conglomerates consist mainly of ophiolites and magmatic rocks from the underlying Ladakh Batholith. The Indus Molasse is locally transgressing stratigraphically on

the Ladakh Batholith (Upshi Molasse; Frank, Gansser, & Trommsdorff, 1977) and is overthrust by other molasse units (Gongmarula-Hemis-Nurla Molasse) of the Indus Group (Steck, 2003; Steck et al., 1993). On our map, the Indus Group is overthrust by the Nidar Ophiolite along the south dipping Nidar Thrust (Thakur & Virdi, 1979).

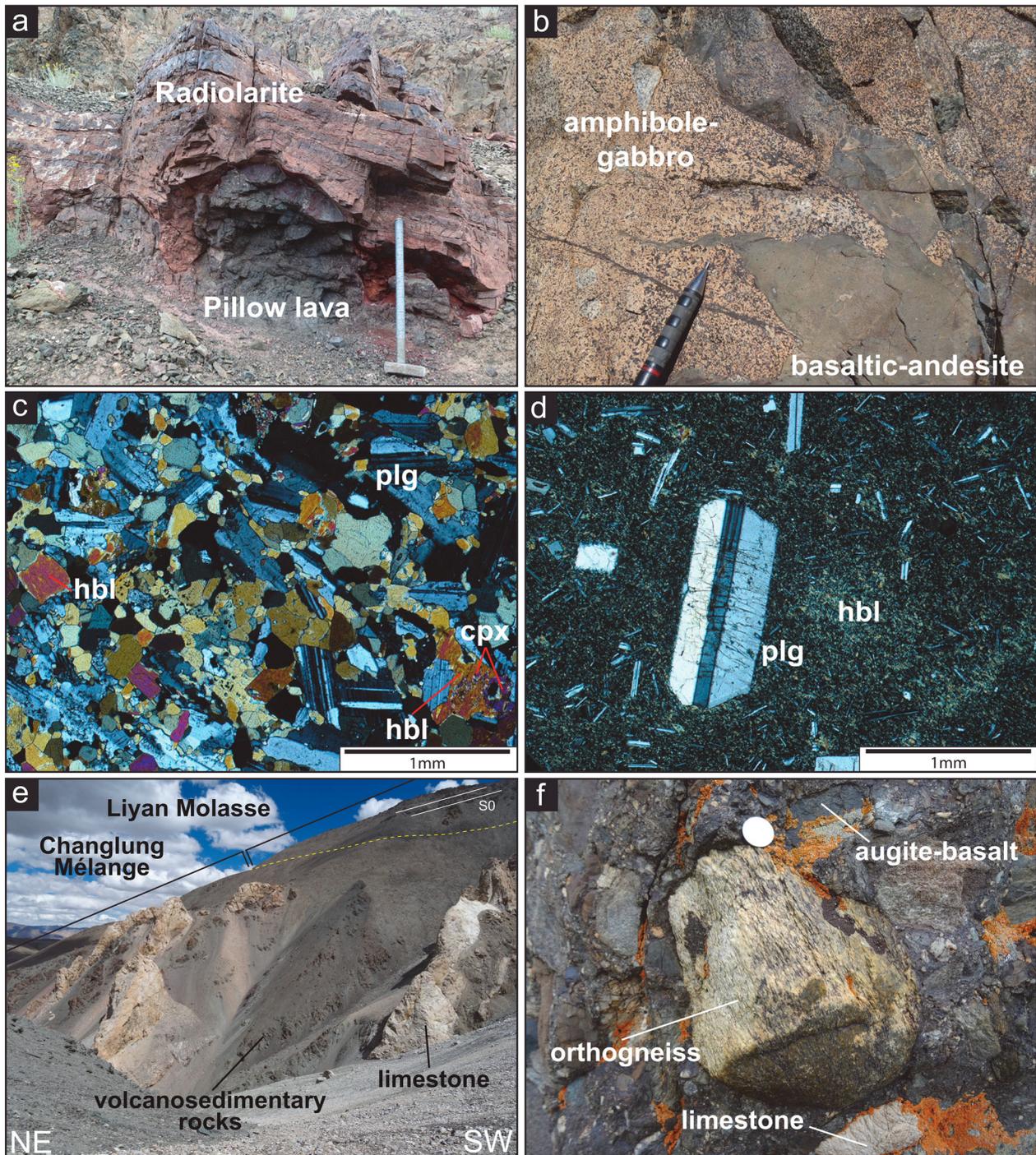
The Indus Molasse underwent a metamorphism related to the Upper Eocene, NE-directed back-thrusting of the North Himalayan nappes (Steck et al., 1993; Van Haver, Bonhomme, Mascle, & Aprahamian, 1986). It grades from the anchizone (illite crystallinity, Van Haver et al., 1986) up to prehnite-pumpellyite facies metamorphism (Steck et al., 1993).

##### 3.2.2. Nidar Ophiolite

The Nidar Ophiolite is a well preserved supra-subduction ophiolitic sequence (Ahmad et al., 2008; Mahéo et al., 2004) that underwent a prehnite-pumpellyite to a low greenschist facies metamorphism. The Nidar Ophiolitic sequence is close to a Penrose type succession (Anonymous, 1972) (mantle rocks, gabbros, basalts and sediments) and the following rocks type have been distinguished

Various detrital sedimentary rocks immediately overlying the volcanic rocks and the Lower Cretaceous radiolarites (Figure 2(a)) (Kojima et al., 2001; Zyabrev, Kojima, & Ahmad, 2008). The detrital rocks are composed of conglomerates with quartz and K-feldspar rich pebbles and conglomerates with clasts of basalts and radiolarites. This compositional heterogeneity reflects the evolution in contribution from different sources, e.g. from the felsic part of the batholith and from the upper part of the Nidar Ophiolite. The felsic contribution in the conglomerates and sandstones increases from the bottom to the top of the sequence. b) Pillow lavas are the most abundant volcanic rocks and are located at the top of the layered gabbros. The pillow lava zone is locally intruded by dacitic dykes. c) The underlying gabbros are the main plutonic rocks of the Nidar Ophiolite and are intruded by several kilometer-sized intrusive complexes type I and II. These complexes contained porphyritic-basalts, amphibole-gabbros (Figure 2(b-d)), pegmatite-gabbros, dunite, wehrlites, pyroxenites and plagiogranites. These intrusions are related to the arc emplacement in a preexisting layered gabbro in a suprasubduction zone at around 131 Ma (Buchs, Epard, & Müntener, 2018). d) The underlying partially serpentinized mantle rocks are dunites forming channels in the surrounding harzburgites. The northern and upper part of the mantle rocks is intruded by the intrusive complex type III. These complexes contain mainly clinopyroxenites, olpyroxenites and cumulate leucogabbros

Along the Mahe-Sumdo section, the ophiolitic sequence is highly reduced in comparison with the Nidar-Kyun Tso section. The ultramafic and



**Figure 2.** Examples of rock types from the Nidar Ophiolite, Drakkarpo nappe and Liyan Molasse in the mapping area. (a) Irregular stratigraphic contact between banded radiolarites and pillow lavas of the Nidar Ophiolite in the Nidar valley (0274360/3669764 UTM44N). (b) Intrusive complex of the Nidar Ophiolite: amphibole-gabbro intruded by a fine-grained basaltic-andesite (0271936/3667561 UTM44N). (c) Microgabbro consisting mainly of anhedral hornblende and subhedral plagioclase. Magmatic clinopyroxenes are present and rimmed by hornblende. (d) Porphyritic basalt consisting of euhedral plagioclase phenocrysts in an amphibole recrystallized matrix. (e) Limestone and volcanosedimentary rocks of the Changlung 'Mélange' (Drakkarpo nappe) in Changlung Valley. The Changlung 'Mélange' is stratigraphically overlaid by the conglomerate of the Liyan Molasse, S0 = stratification (0262870/3676497 UTM44N). (f) Polygenic and heterometric conglomerate of the Liyan Molasse. The conglomerate contains pebbles of a Tso Morari nappe orthogneiss, an augite-basalt of the Karzok-Ribil or Drakkarpo nappes and a recrystallized limestone of undetermined origin (0266466/3672461 UTM44N). All the photomicrographs were made under cross-polarized light, and the mineral abbreviations are according to [Siivola and Schmid \(2007\)](#).

volcanosedimentary parts of the ophiolite are lacking. The Nidar Ophiolite was first thrust to the south over the Drakkarpo nappe and then backthrust toward the north over the Indus Series.

### 3.2.3. Drakkarpo nappe

The Drakkarpo nappe (Zildat Ophiolitic mélangé, [Thakur & Viridi, 1979](#); Sumdo Complex, [Steck et al., 1998](#)) was named by [De Sigoyer \(1998\)](#) after a summit east of

the Sumdo Yongma village (Figure 1). This nappe is discontinuously outcropping along a 150 km long area from the Kyun Tso region to the Rumtse village (Figure 1).

The Gya formation underlines the base of the Drakkarpo nappe. It consists of black argillites, sandstones and microconglomerates with few marly beds. The proportion of the vesicular volcanic elements in the detrital rocks of the Gya formation increases toward the top of the formation and the sediments progressively change to thick polygenic conglomerates and volcanosedimentary rocks. They contain mainly tuffs and augite-basalts (OIB). The volcanic and volcanosedimentary rocks are more abundant along the Mahe-Sumdo section than the Nidar-Kyun Tso section. Pebbles of serpentinites, radiolarites and pillow lavas (OIB) are present in minor quantities. Meter-thick conglomeratic limestones with volcanic clasts form channels in the volcanosedimentary formation. In the Kalra valley (Mahe-Sumdo section), some of these limestones were interpreted as the equivalent of the Aptian-Albian Khalsi limestones by Fuchs and Linner (1997) of the Tibetan margin or as Permian limestone olistoliths from the Indian margin (Colchen et al., 1987). Fuchs and Linner (1996) propose an Upper Cretaceous age for the Drakkarpo unit based on poorly preserved planktonic and benthic foraminifera found in breccia, red marls and limestones. The Drakkarpo nappe underwent a low-grade metamorphism attested by the formation of pumpellyite and chalcedony in OIB pillow lavas.

A new ‘Changlung mélange’ is defined in the northern part of the Drakkarpo nappe. This mélange is observed from Rumtse to the east of the Kyun Tso. It is made up of blocks and small clasts of volcanosedimentary rocks, pillow lavas, radiolarites, serpentinites, breccias, red marls and limestones eroded from the underlying part of Drakkarpo nappe (Figure 2(e)). The matrix of the ‘Mélange’ is commonly formed by sandstones contained in Upper Ypresian nummulite-bearing limestones. Pebbles of volcanic rocks from the overlying Nidar Ophiolite and Ladakh Batholith are present in conglomerates of the ‘Changlung Mélange’.

The Drakkarpo nappe is derived from the accretionary wedge with slices of oceanic island arc and its related sediments. The oceanic island arc was developed during the Upper Cretaceous on the Indian plate. The Changlung ‘Mélange’ is interpreted as formed in a shallow sedimentary basin dominated by detrital material in a forearc context during the Upper Ypresian. These Tertiary sediments were deposited on the already structured Cretaceous formation of the Drakkarpo nappe. The Drakkarpo nappe underlines the Indus suture zone.

#### 3.2.4. Liyan formation

The Liyan Formation (Shanker, Padhi, Prakash, Thussu, & Das, 1982) is a molasse deposit that consists

of an alternation of sandstones, conglomerates and shales. The pebbles of the first conglomeratic beds (Figure 2(f)) frequently reflect the nature of the underlying North Himalayan nappes (Tso Morari, Tetraogal or Karzok-Ribil nappes) and the Indus suture zone units (Drakkarpo nappes and Nidar Ophiolite). A continental depositional environment is attested by the presence of well-preserved fossils of palm leaves. Tiwari (2003) proposed an Upper Eocene age based on the discovery of a *Juxia* (Perissodactyla, Hyraco-dontidae) (Chow & Chiu, 1964) northwest of Liyan. The Liyan Molasse was deposited in an intramontane basin bounded by normal faults on the Drakkarpo and Nidar tectonic units.

### 3.3. The North Himalayan nappes

The North Himalayan nappes are derived from the northern part of the Indian margin and are stacked from base to top as follows: Tso Morari, Tetraogal, Karzok-Ribil and Mata nappes. The Tso Morari nappe was subducted below the Eurasian plate during the Paleocene and underwent an eclogite facies metamorphism, while the other North Himalayan nappes were incorporated in the accretionary wedge below the Drakkarpo unit during the Upper Cretaceous and Paleocene (de Sigoyer, Guillot, & Dick, 2004 and Epard & Steck, 2008).

#### 3.3.1. Karzok-Ribil nappe

The Karzok-Ribil nappe is composed of the Karzok Ophiolites (Berthelsen, 1953) and the Ribil Unit (De Sigoyer, 1998). The Karzok-Ribil nappe can be followed at the top of the Tetraogal nappe around the Tso Morari dome. The Karzok-Ribil nappe is composed of slices of an ophiolitic sequence (serpentinized peridotites, gabbros, and pillow lavas), chromite, radiolarites, marbles and dolomitic marbles, polygenic conglomerates, breccia and agglomeratic slates from the Indian margin. The Karzok-Ribil nappe also contained augite-basalts (OIB) (Figure 3(a and b)) and volcanosedimentary rocks similar to those of the Drakkarpo nappe. The ophiolitic sequence associated with minor volcanosedimentary rocks is well exposed in the Umlung area at the southern edge of the Tso Morari nappe, whereas the volcanosedimentary rocks and augite-basalts are more abundant along the northern limit in the Mahe-Sumdo section.

De Sigoyer (1998) correlates the brown-orange marbles in the Ribil valley to the Permian ‘fil d’Ariane’ described by Stutz and Steck (1986) in the Langtang nappe in Zanskar. The discovery of a poorly preserved ammonite in the volcanosedimentary sequence does not provide any useful age constraints. The same for the rare coral debris, crinoids and shells found in this tectonic unit.

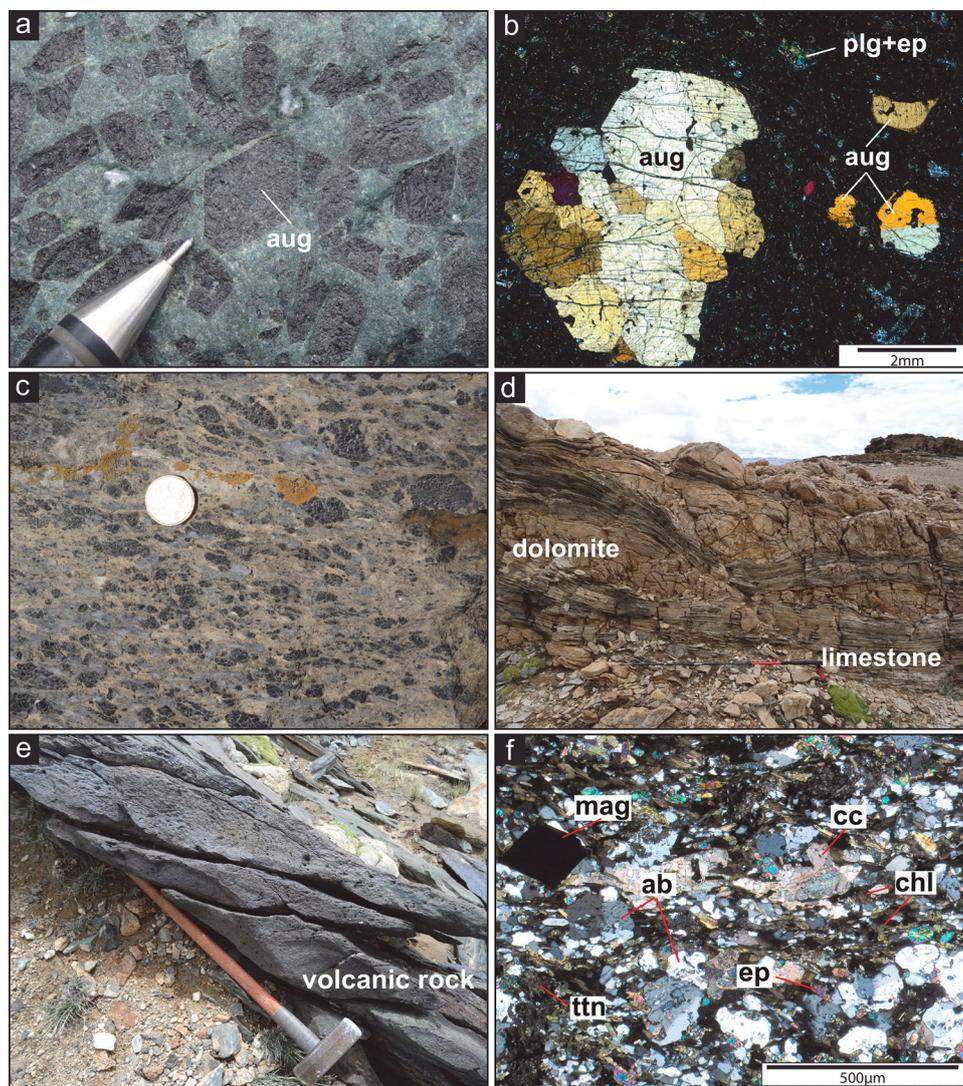
The Karzok-Ribil nappe underwent a greenschist facies metamorphism (actinote + zoisites + clinozoisite + albite + titanite) recorded by the magmatic rocks of

Karzok, Umlung and Sumdo La. [Virdi, Thakur, and Kumar \(1977\)](#) reported the presence of glaucophane along the Zildat valley (NW of Puga Sumdo). This sample was attributed to the Zildat Ophiolitic Mélange, now included in the Karzok-Ribil nappe. Nevertheless, the presence of glaucophane in this nappe has never been confirmed since that finding. The possibility that this glaucophane-bearing sample could come from the underlying Tso Morari nappe has to be envisaged.

Karzok-Ribil nappe is interpreted as being originally derived from an oceanic island arc, located close to the Indian passive margin in an ocean-continent transition zone. This unit is accreted below the Drakkarpo nappe in the accretionary wedge and then involved in the North Himalayan nappe stack.

### 3.3.2. Tetraogal nappe

The Tetraogal nappe ([Steck et al., 1998](#)) underwent a greenschist facies metamorphism and consists of Paleozoic to Mesozoic conglomeratic limestones ([Figure 3\(c\)](#)), limestones, dolomites ([Figure 3\(d\)](#)), calc-schists, sandstones, graywackes, slates, quartzites, volcanosedimentary rocks and volcanic rocks. The volcanic rocks derive from basalts to basaltic-andesites ([Figure 3\(e\)](#)) composed of albite, chlorite, epidotes, titanite, magnetites and minor actinolite ([Figure 3\(f\)](#)) diagnostic of a greenschist facies metamorphism. Neither eclogite nor pseudomorphosis of minerals after high-pressure assemblages have been found in the metavolcanics of the Tetraogal nappe. Locally, the magmatic vesicular texture ([Figure 3\(e\)](#)) and flow structure are preserved



**Figure 3.** Examples of rock types from the Karzok-Ribil and Tetraogal nappes observed in the mapping area. (a) Augite-basalt (OIB) of the Karzok-Ribil nappe in the Ribil valley (0255989/3678360 UTM44N). (b) Basalt of the Karzok-Ribil Unit in the Ribil Valley consisting of centimeter-size subhedral augite phenocrysts in a dark recrystallized matrix. The plagioclase phenocrysts are partially replaced by a metamorphic mineral association of epidote and plagioclase. (c) 'Dalmatian' conglomeratic limestone of the Tetraogal nappe south of Kyun Tso. The black elements and the light gray matrix are limestones (0270248/3642628 UTM44N). (d) Permian crinoid-rich dolomites in the deformed limestone of the Tetraogal nappe, south of Kyanse La (0367701/36420659 UTM44N). (e) Vesicular metabasic rock of the Tetraogal nappe located below the Permian dolomites. (f) Metabasite (prasinite) consisting of porphyroblasts of albite + chlorite + epidote + titanite + magnetite + calcite; this metabasite is attributed to the Permian Panjal Trap volcanism. All the photomicrographs were made under cross-polarized light, and the mineral abbreviations are according to [Siivola and Schmid \(2007\)](#).

in the metabasites intercalated in brown-orange crinoid-rich dolomites and calcschists.

The geochemistry of these volcanic rocks shows strong similarities with the Permian continental flood basalt, Panjal Traps, in Kashmir (Shellnutt et al., 2014; Shellnutt, Bhat, Brookfield, & Jahn, 2011) and in Spiti valley in Zaskar (Chauvet et al., 2008; Vannay & Spring, 1993). The stratigraphy of the Tetraogal nappe is not well established due to the lack of a fossil record. Nevertheless, the strong detrital component in the Tetraogal sediments could represent deposition on the northern slope of the Indian shelf and its transition toward the basin (Epard & Steck, 2008; Stutz, 1988). The Tetraogal nappe is imbricated below the Karzok-Ribil tectonic unit in the orogenic accretionary wedge.

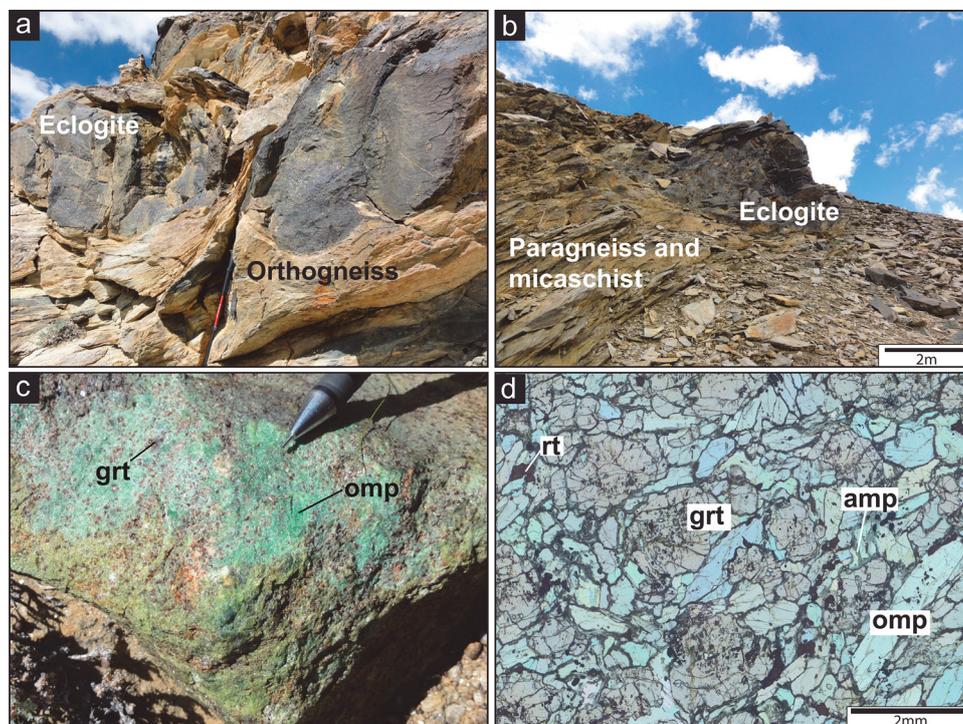
### 3.3.3. Tso Morari

The Tso Morari nappe is composed of  $479 \pm 2$  Ma (Girard & Bussy, 1999) metagranite and orthogneiss (Figure 4(a)) intruded in the Phe (Late Precambrian to Early Middle Cambrian) and Karsha (Middle Cambrian) Formations. The granites show a wide range of deformation texture from an almost unstrained granite body to a highly foliated mylonitic orthogneiss. The Phe Formation consists of an alternation of paragneiss and micaschists (Figure 4(b)), and the Karsha Formation is defined by the first occurrence of a brown-orange dolomite intercalated in metagraywackes.

Eclogites (Figure 4(c and d)) can be found as mafic dykes and larger intrusions several meters in diameter. These eclogite bodies are present in both the granitic intrusion and in its metasedimentary country rock (Figure 4(a and b)). The ultrahigh pressure metamorphism is shown by the presence of coesite inclusions in garnet and omphacite (Mukherjee & Sachan, 2001; Wilke, O'Brien, Schmidt, & Ziemann, 2015). The Tso Morari nappe belongs to the north Indian continental margin and was subducted under the Eurasian plate. It underwent an ultrahigh pressure metamorphism at  $53.3 \pm 0.7$  Ma (Leech, Singh, & Jain, 2007). This metamorphic event is followed by a Barrovian regional metamorphism under amphibolite facies conditions at  $45.2 \pm 0.7$  Ma (Leech et al., 2007) during the stacking of the North Himalayan nappes (Epard & Steck, 2008). The pressure-temperature conditions at the eclogite peak metamorphism is widely debated, ranging from 20 to 48 kbar and from 400 to 750°C (Chatterjee & Jagoutz, 2015; De Sigoyer, Guillot, Lardeaux, & Mascle, 1997; Guillot, De Sigoyer, Lardeaux, & Mascle, 1997; Mukherjee, Sachan, Ogasawara, Muko, & Yoshioka, 2003; Palin, Reuber, White, Kaus, & Weller, 2017; St-Onge, Rayner, Palin, Searle, & Waters, 2013; Wilke et al., 2015).

### 3.3.4. Mata-Nyimaling-Tsarap nappe

The Mata nappe is composed of Cambrian to Upper Cretaceous Indian passive margin sediments



**Figure 4.** Example of rock types of the Tso Morari nappe. (a) Eclogite boudins in an orthogneiss of the Tso Morari nappe south of Kyagar Tso (0247028/3664710 UTM44N). (b) Eclogite lens in paragneiss and micaschists of the Phe Formation of the Tso Morari nappe in the Nidar Valley (0267153/3660999 UTM44N). (c) Fresh eclogite (omphacite + garnet) in the Phe Formation of the Tso Morari nappe in the Lunglung valley (0252692/3660582 UTM44N). (d) Fresh eclogite thin section consisting of garnet + omphacite + rutile; the omphacite is locally rimmed by blue-green amphibole.

(Girard, 2001; Steck et al., 1998). The Mata nappe is a NW verging recumbent fold in the Karzok area with Late Paleozoic to Triassic sediments in the overturned and normal limbs (Steck et al., 1998). The core of the nappe is composed of the Phe and Karsha Formations intruded by the  $482.5 \pm 1$  Ma Rupshu granite (Girard & Bussy, 1999). The Nyimaling-Tsarap nappe (Stutz & Steck, 1986) and the  $460 \pm 8$  Ma Nyimaling granite (Stutz & Thöni, 1987) is the northwest equivalent of the Mata nappe and Rupshu granite (Steck et al., 1998).

#### 4. Area of future mapping

The presented map revealed some areas that would benefit from future geologic mapping. Detailed geologic mapping of the extension of the Nidar Ophiolite to the east is lacking. The Landsat images show a thinning of the Nidar Ophiolite toward the east up to Hanley (outside of the map area – 0302355/3648557 UTM44N), especially for the ultramafic and gabbroic sequences. This interpretation is in agreement with the general map of Thakur and Misra (1984). The stratigraphy of the Indus series north of Nidar in the Nyoma area is missing. The precise nature (tectonic vs stratigraphic) of the contact between the molasse sediments and the batholith-related rocks is unclear. The mapping of the eastern and southern part of the Kyun Di is missing and deserves special attention despite the presence of recent faults and the lack of good outcrops.

#### 5. Conclusions

The mapping of the eastern part of the Tso Morari nappe and its surrounding tectonic units revealed the lithostratigraphic of well-defined tectonic units assigned to the Indus suture zone or to the North Himalayan nappes. The gabbro unit of the Nidar Ophiolite revealed a complex internal structure related to emplacement at approximately 131 Ma in a suprasubduction setting of two distinct intrusive complexes in preexisting layered gabbros. Ophiolite, OIB and related sediments of the Drakkarpo nappe define the Indus suture zone. Its upper part contains a Lower Eocene mélange (Changlung mélange) that is thrust by the Nidar Ophiolite.

Lithostratigraphic data improves the definition of the Karzok-Ribil nappe, a new North Himalayan nappe grouping the previously defined Ribil Unit and the Karzok Ophiolites. The Karzok-Ribil nappe can be mapped above the Tetraogal nappe all around the Tso Morari dome. The Tetraogal nappe consists of thick Paleozoic to Mesozoic sedimentary sequences, with minor volcanic rock deposits attributed to the Permian Panjal traps. The volcanic rocks of the

Tetraogal nappe recorded a greenschist facies metamorphism and never underwent an eclogite facies metamorphism.

The use of satellite Landsat images makes the mapping in the field easier. It also helps the interpretation of geologic features in remote areas. The presented map improves the knowledge of the geology of Eastern Ladakh, particularly concerning the detailed composition of the Nidar ophiolite, the extension of the Tso Morari UHP nappe and the geometry and lithostratigraphy of its surrounding tectonic units. This new map can be the base for future detailed geologic research and exploration in the area.

#### Software

ArcMap from ArcGIS suite version 10.4 was used to draw the geological map and the topographic base map. The topographic base map was obtained from the DEM (digital elevation model) SRTM 90 m produced by NASA. Topographic profiles related to cross-sections were created from the DEM and then exported in an Excel table and scaled using GRAPHIER 6. Final drafting was performed with Illustrator CS5 to add the legend, scale, north arrow, localities, summits, pass, lakes, rivers and locations of the longitude-latitude grid.

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#### ORCID

Nicolas Buchs  <http://orcid.org/0000-0002-0078-2597>

Jean-Luc Epard  <http://orcid.org/0000-0003-2319-9967>

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