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Two-stage exhumation of Zildat Ophiolitic Melange rocks, NW Himalaya, India

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Abstract: Field geometry of Zildat Ophiolitic mélange (ZOM) is studied to understand the shallow-level exhumation history of this unit and the adjoining ones. The Indus Suture Zone (ISZ) characterizes continental collision between the Indian- and the Eurasian plate, consists of, on a NE-SW cross-section, the Tso Morari Crystalline (TMC) at SW and the Nidar Ophiolitic Complex (NOC) at NE. The ZOM separates the TMC from the NOC. The ZOM has a ~north dipping thrust, the Zildat Fault, between the ZOM and the TMC. The Zildat Fault initiated as a normal fault but reactivated as a reverse fault with SW vergence, an example of inversion tectonics ongoing collision. The NOC is un-metamorphosed and is devoid of penetrative tectonic fabrics. The ZOM is a bivergent wedge having components of accreted oceanic crust. We propose a two-stage exhumation of the ZOM assisted by TMC with NOC as a barrier. *(i)* The TMC exhumed with respect to the ZOM when the Zildat Fault activated as a normal fault. The ZOM accommodated the space for the TMC by acting as an extensional detachment. *(ii)* Subsequently, in response to achieve isostasy by the TMC dome. The Zildat Fault reactivated as thrust fault, the extensional detachments imbricated and thus the ZOM exhumed as a 'pop-up' block bound by opposite dipping thrusts.

Key words: Indus Suture Zone, Zildat Ophiolitic mélange, Nidar ophiolite, Tso Morari dome, Himalayan tectonics.

INTRODUCTION

The continued collision between India and Eurasia since ~ 55 Ma and northward under thrusting of the Indian plate beneath the Tibetan plateau produced the Himalayan mountain belt (Yin 2006). This collision zone is marked by suture zone(s) formed due to collision, accretion and subduction of continental and oceanic plates during the collisional history. The Indus Suture Zone (ISZ) is one such suture zone (Fig. 1a), formed ~ 55 Ma (Searle *et al*. 1987), where the Tethyan oceanic plate consumed as the Indian plate approached northward and finally collided with Eurasia. The ISZ is characterized by an ophiolitic mélange; the Zildat Ophiolitic Mélange (ZOM) sandwiched between a now retrogressed, UHP crystallines (Mukherjee *et al*. 2003) known as the Tso Morari Crystallines (TMC) and an ophiolite suite called the Nidar Ophiolitic Complex (NOC) (Thakur & Mishra 1984; Das *et al*. 2015). The exhumation history of TMC has been much studied and described by various workers (Guillot *et al*. 1997; Guillot *et al*. 2000; Steck et al. 1998; de Sigoyer *et al*. 2004; Epard & Steck 2008; Schlup *et al*. 2003). Steck *et al*. (1998) proposed that TMC thrust as nappe towards south. Guillot *et al*. (2000) suggested exhumation of TMC core complex through a low viscosity channel assisted by serpentinites as a lubricant. Epard & Steck (2008) proposed that combination of pure- and simple shears 'extruded' the TMC. According to them, TMC extruded by buoyancy and squeezed out between the Indian lithosphere and Eurasian mantle wedge. Despite these detailed studies, few issues in ISZ have remained poorly constrained: *(i)* the tectonic evolution and exhumation of the ZOM as a separate litho-unit; *(ii)* role of TMC for exhumation of ZOM in a convergent setting; *(iii)* whether the NOC played any part in the exhumation of this lithounit-ZOM. We unravel these issues through mesoscopic field observations across the ISZ.

GEOLOGY OF THE STUDY AREA

The Tso Morari Crystalline (TMC) represents Paleozoic Indian continental margin, which subducted and ultra-high pressure metamorphosed during subduction (Mukherjee & Sachan 2001; Mukherjee *et al*. 2003). TMC is a domal structure and consists of both ortho- and para-gneisses along with metabasic (amphibolites to eclogite) boudins. Few of these boudin-like structures also contain signature of UHP metamorphism (Mukherjee & Sachan 2001; Mukherjee *et al*. 2003). Eclogitization of TMC took place at 2 ± 0.2 GPa at ~ 45 km depth (Guillot *et al*. 1997). Metamorphic ages obtained by de Sigoyer *et al*. (2000) suggest ~55 Ma age for eclogitization of TMC, followed by amphibolite facies metamorphism at ~ 47 Ma. According to these workers, TMC exhumed to the upper crustal level at ~ 30 Ma. On the other hand, Donaldson *et al*. (2013) suggested that TMC experienced peak metamorphism ~ 47-43 Ma. The Zildat Ophiolitic Mélange (ZOM) is presumably a relic of ocean seamounts that accreted with the Indian continental margin during collision (de Sigoyer *et al*. 2004). Overall, the ZOM bears signature of greenschist facies metamorphism and contains fragments of basic rocks, blueschists and marine microfossils (de Sigoyer *et al*. 2004). The metabasic fragments are alkaline "ocean island basalt" in origin (Fuchs & Linner 1997). The ZOM is also characterized by marine carbonates distributed as dismembered exotic blocks. Stable isotope signature of these carbonates suggests marine platform affinity (Sen *et al*. 2013). However, towards the contact between TMC and ZOM, these carbonates show depleted isotopic trend suggesting influence of external fluid that derived from the adjacent TMC unit (Sen *et al*. 2013). The Nidar Ophiolitic Complex (NOC) started forming at a spreading center (Das *et al*. 2015), prior to continental collision ~ 110-140 Ma (Mahéo *et al*. 2004; Ahmed *et al*. 2008).

OBSERVATIONS

The ZOM and the NOC are well exposed in ~ 8 km stretch from Sumdo to Mahe village along a stream that ends up in the river Indus near Mahe (Fig. 1b). The NOC is followed by foreland sediments in the north, called the Indus Molasse and an Andean type magmatic arc, which consists of dominantly calc-alkaline granitoids and is called the Ladakh Batholith. TMC and ZOM have a tectonic contact called as the Zildat Fault. ZOM shows systematic lithological variation from the Zildat Fault to its contact with the NOC (Fig. 1c). Its contact with the TMC at Zildat Fault zone is characterized by calcite and quartz vein bearing metabasics. This mylonitizd foliated unit dips northeast (Fig. 1b). The quartz veins form

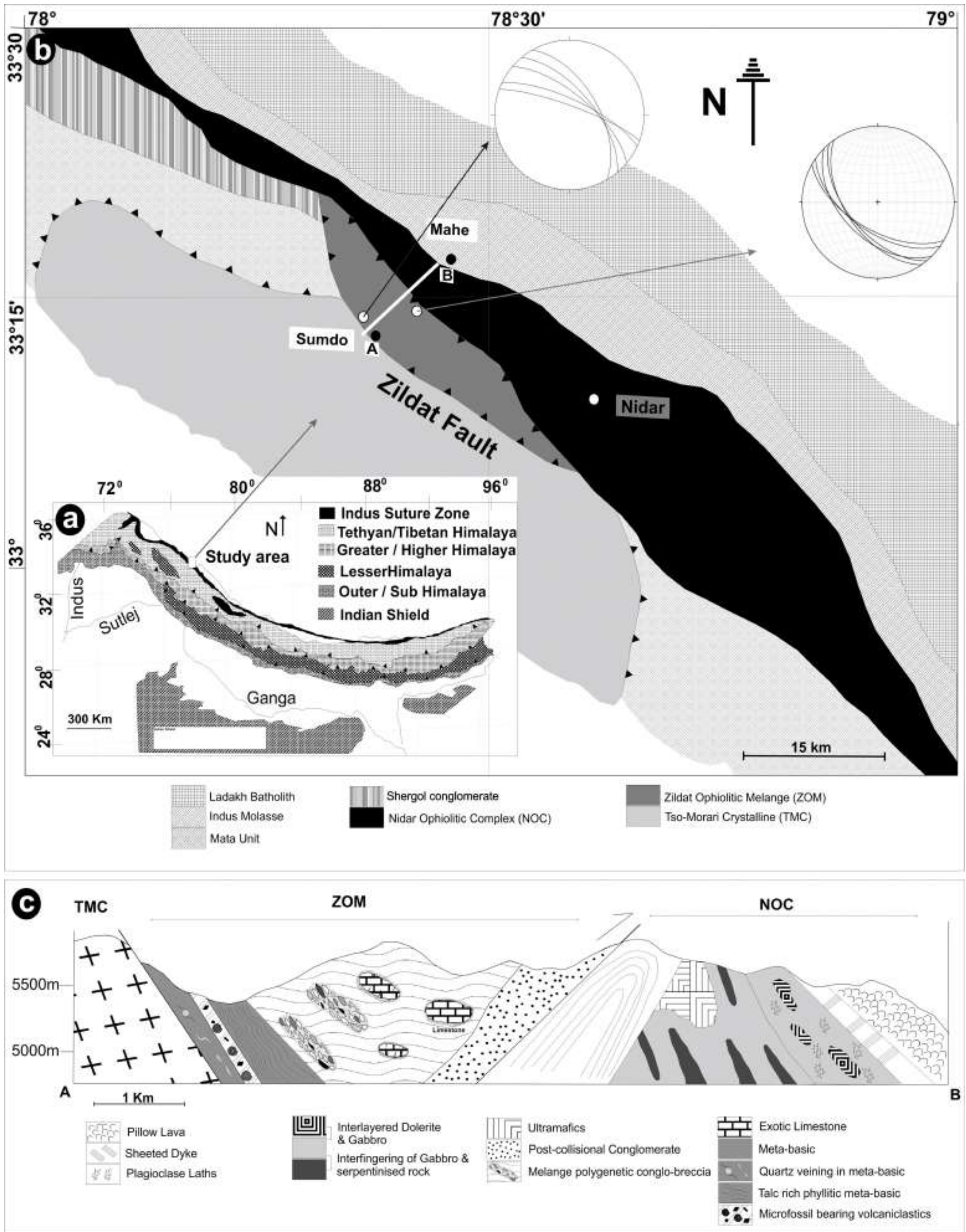

Fig. 1. (a) Study area marked in the generalized geological map of Himalaya (after Gansser 1964). (b) Simplified geological map of study area in the Indus Suture Zone, NW Himalaya (modified after Thakur & Misra 1984; Steck *et al*. 1998; Mahéo *et al*. 2006). Inserted stereonets show measurement of latest foliation fabric near to the boundary of ZOM bounded by two oppositely dipping thrusts. (c) Cross section along AB in Fig. 1b, across the Indus Suture Zone showing litho-units of the Zildat Ophiolitic Mélange and the Nidar Ophiolitic Complex.

asymmetric boudins shows down-to-north shear indicating normal sense of movement along the Zildat Fault (Fig. 2a). However, these same veins also show late imbrications (Fig. 2b), which suggest subsequent thrusting of the Zildat Fault.

Further north, volcanic-clasts contain clasts of pyroxene, marine microfossils, quartz veins and vesicles filled by secondary quartz and calcite. Adjacent to this unit, a phyllitic talc-rich metabasic unit crops out. The foliation of this unit is

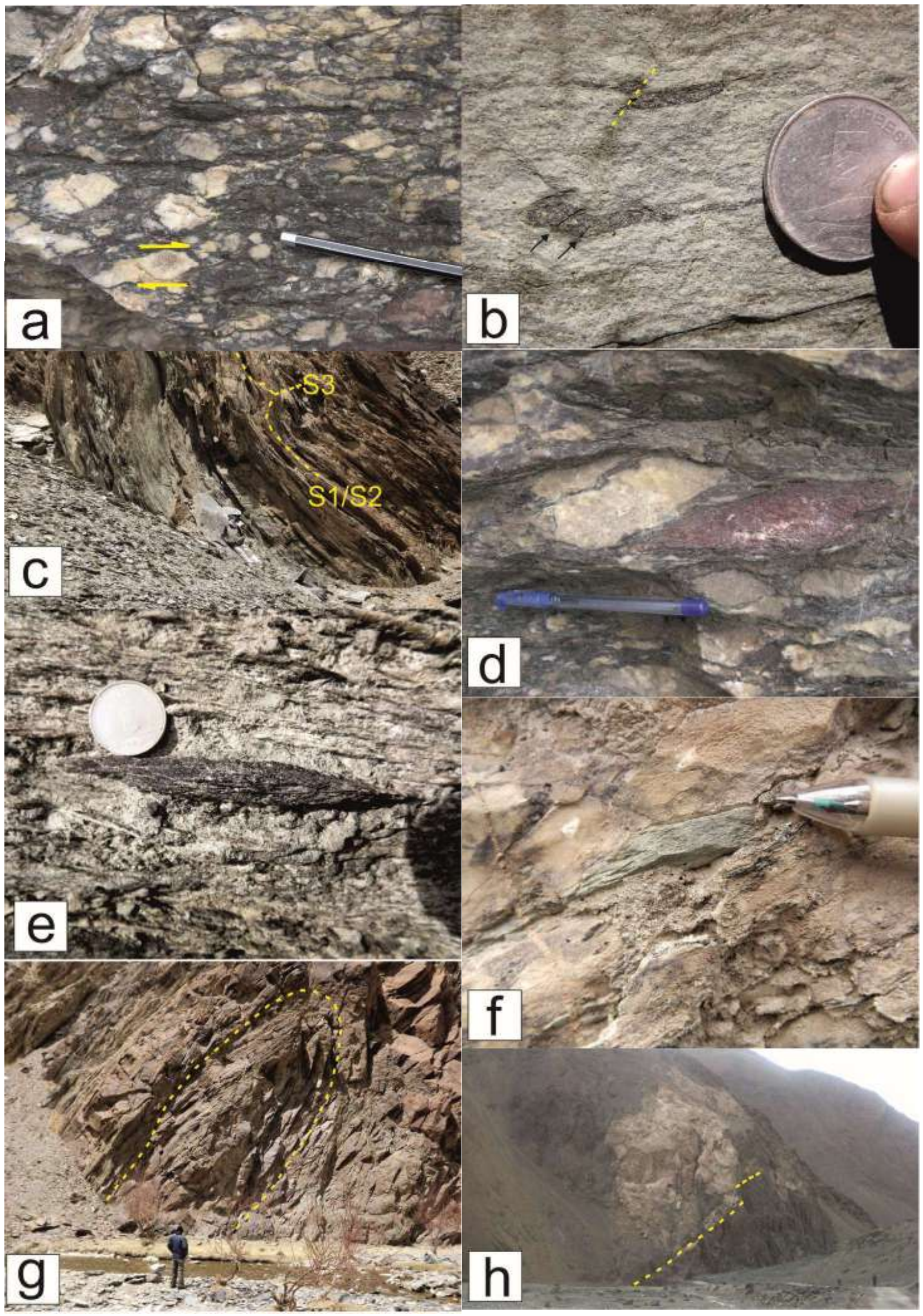

Fig. 2. Mesoscopic features within the Zildat Ophiolitic Mélange (a) Top-to-north sheared quartz vein within metabasics. (b) Compressed quartz veins within the same metabasics fractured and imbricated (black arrows). (c) Later warped foliation concordant with the contact between the TMC and the ZOM. (d) Chert and calcite clasts/tectonic inclusions within the ZOM are imbricated and top-to-S sheared (see Mukherjee 2014 for details of inclusion deformation). (e) Clast of gabbro present within metagreywacke of ZOM. (f) Clast of serpentine within the ZOM. (g) N verging fault-propagation fold near the contact between ZOM and NOC. (h) Exotic carbonate block of ZOM thrusts over NOC. Thrust plane dipping S.

axial planar to isoclinally folds, concordant to the attitude of the Zildat Fault, i.e., dips north. These folds are further gently warped (Fig. 2c). Further north of these metabasics, polygenic metagreywackes/ polymictic conglomerate exist. The matrix of this unit is basic and metamorphosed to greenschist facies. These metagreywackes contain clasts of carbonates and chert showing imbrications 'top-to-south' thrust (Fig. 2d), typical of Himalayan in-sequence deformation (Mukherjee *et al*. 2015). Clasts of gabbro (Fig. 2e) and serpentine (Fig. 2f) are also seen within this unit. This is followed by a horizon of large exotic carbonate blocks of several meters dimension enclosed in a low-grade matrix. The Shergol conglomerate lies north of the carbonate exotics. It consists of clasts from TMC, NOC and ZOM. It is classified as a post-collisional conglomerate (de Sigoyer *et al*. 2004) and is the only unit within the ISZ consisting clasts from TMC. The contact between ZOM and NOC is marked possibly by a large fault-propagation fold that dips towards south (Fig. 2g). At this contact the carbonate blocks of ZOM are thrust over the ophiolitic suite of NOC (Fig. 2h).

The crustal part of the NOC is well exposed in the Mahe-Sumdo valley, while its mantle part expose in the adjacent Nidar valley (Fig. 1b, c) (Das *et al*. 2015). The NOC at the Mahe-Sumdo section consists of pillow lavas, sheeted dikes, gabbros and radiolarian cherts (Fig. 1b). This crustal part of the ophiolite is undeformed, indicated by circular vesicles in pillow lavas (Fig. 3a) and haphazard plagioclase laths in cumulate gabbros (Fig. 3b). It does not show any penetrative tectonic fabrics. Here, the gabbroic crustal-part of the

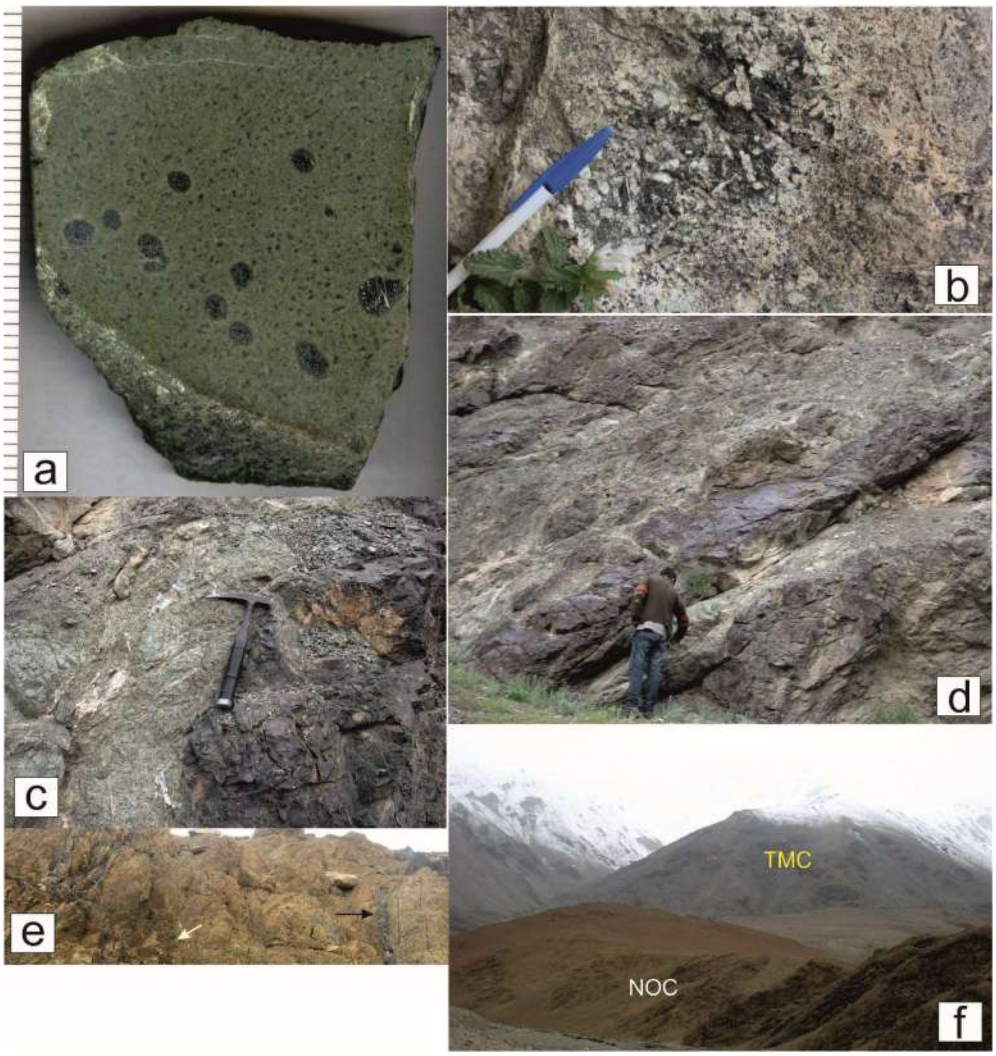

Fig. 3. Mesoscopic features within the Nidar Ophiolitic Complex. (a) Circular undeformed vesicles within the pillow lava. Vesicles bear secondary fills. (b) Random orientated plagioclase laths within ophiolitic gabbro. (c) Contact between serpentinized ultramafic and gabbro in the Mahe valley. (d) Intercalation of gabbro and serpentinized peridotites marks the petrological Moho within the NOC. (e) Spinel-bearing dunite from the mantle section of the NOC. This unit contains layered chromite and serpentinite veins, in contact with the TMC. (f) Contact between the TMC and the NOC at Nidar

ophiolites has a contact with serpentinized peridotites, which is the uppermost part of mantle ultramafics of the ophiolite (Fig. 3c). The contact is identified as a relict petrologic Moho within the NOC. It occurs as ~500 m thick zone with gabbros repeatedly intercalated with serpentinites (Fig. 3d).

In the adjacent Nidar valley (Fig. 1b), the TMC has a direct contact with the ophiolite ultramafics which is the lowermost part of the ~ 7 km thick NOC. The ultramafic part is un-metamorphosed. It comprises of partially serpentinized peridotites, pyroxenites, podiform chromites, elongated dunite layers and serpentinites. About 3 km thick spinel bearing dunite layer defines the bottom of this mantle ophiolitic section (Das *et al.* 2015). This body is essentially composed of olivine along with disseminated Cr-spinel and layered chromites (Fig. 3e). Serpentinization is heterogeneous, often fracture-controlled and varies from 20-60%. The serpentines may indicate hydration of the mantle wedge above the subducting slab. Generally spinel peridotites originate at < 60 km depth (< 2 GPa; Coleman 1977). So the contact between the TMC and dunite may extend up to ~ 50 km depth. In Nidar, the mélange is completely absent. TMC has a North dipping contact with the mantle section of the ophiolite suite (Fig. 3f).

DISCUSSION

Nature of the Mélange

The ZOM contains various components of oceanic lithospheric units includes clasts of gabbros, serpentines and radiolarian cherts derived from the adjacent ophiolites. It also shows the presence of blueschists within it. Sm-Nd whole rock dating of gabbro from NOC gives an age of ~ 140 Ma (Ahmed *et al*. 2008). Kojima *et al*. (2001) inferred an age of about 113-134 Ma for the radiolarian cherts of the NOC. Honegger *et al*. (1989) carried out K-Ar dating on the blueschist clasts present within the Indus Suture Zone and obtained ~ 98 Ma age for the blueschist metamorphism. Based on these, the formation of this ophiolitic mélange presumably cannot be older than ~140 Ma and probably started later than ~98 Ma. Surprisingly, the ZOM is devoid of any clasts from the TMC or the Indian continental part, apart from siliceous veins along the Zildat Fault. Considering the timing of India-Eurasia continental collision to be ~ 50 Ma (Searle *et al*. 1987; Najman *et al*. 2010), the formation of ZOM completed before ~ 50 Ma. Presently the ZOM shows low-grade greenschist facies metamorphism. Although it contains clasts of high-grade metamorphic rocks, it cannot be equated with the metamorphic history of the mélange. Only at the contact between the TMC and the ZOM, along the Zildat Fault, the presences of quartz veins are related with amphibolite grade metamorphism. Based on variation in calcite microstructures in the ZOM, Sen *et al.* (2013) inferred a strain gradient across ZOM: deformation weakens from the Zildat Fault towards north. As the ZOM shows maximum deformation and metamorphism along its contact with the TMC, we envisage that the metamorphism of ZOM related with the continental collision.

TMC Assisted Exhumation of ZOM

The exhumation of TMC was facilitated by serpentine present in the mantle wedge that acted as a lubricator (Guillot *et al*. 2000). The presence of serpentinized spinel dunite adjacent to the TMC in Nidar valley (Fig. 3e) supports this. Guillot *et al*. (2000) also suggested that, in absence of any sediment to assist exhumation at shallower depth, the near-surface exhumation of the TMC was facilitated by serpentines. However, in present day field configuration we have observed that serpentine present at the contact of TMC & ZOM only in few blocks and narrow patches. This inferred, serpentine might have played important role, to initiate exhumation process of both the units.

Past studies indicated that the ophiolite present adjacent to TMC is remnant of an obducted slab, which was placed over the passive Indian continental margin prior to collision (Makovsky *et al*. 1999; Arora *et al*. 2007). It is also suggested that the ophiolite underwent considerable syn-collisional deformation, folding and stacking (Searle *et al*. 1997). However, our observations suggest that the whole NOC preserves a continuous section from pillow lava to ultramafics (Fig. 1c). The Nidar ophiolite does not show any evidence of metamorphism and has not been deformed coeval to its adjacent units. The ophiolite is locally deformed but the tectonic fabric mismatch with that of the adjacent litho-units. The head (pillow) of the ophiolite suite is towards the overriding slab and the tail towards the downgoing plate (Fig. 1c). The trend of the lowermost dunite cumulates along with ultramafics is ~ orthogonal to the TMC-NOC contact (Fig. 3f). Neither the sheeted dikes in the crustal part nor the dunite dikes of the mantle part of the ophiolite are deformed. There are no nappes like structure is observed within the ophiolite. The mantle section of the ophiolites exposed in Nidar valley is ~ 7 km thick and recent geophysical images shows that its contact with TMC may have gone crustal level (Hazarika *et al*. 2014). These indicate that the ophiolitic rocks are not scrapped off blocks placed on the surface.

de Sigoyer *et al*. (2004) suggested three stages deformation exhumed the TMC. They also assessed the evolution of the ZOM and the NOC during these deformation events. The study suggests, exhumation of TMC began from ~ 120 km depth along with early upright folds (D1 folds), at this time both ZOM and obducted NOC formed southwest verging folds. This was followed by doming of TMC (Mukherjee & Mulchrone 2012) during D2 deformation, when TMC exhumed up to base of the crust by folding and ductile shear. At this time, the part of the ZOM adjacent to the TMC ('Ribil unit' of de Sigoyer *et al*. 2004) developed extensional structures and the interior of the ZOM ('Drakkarpo unit' of de Sigoyer *et al*. 2004) formed double

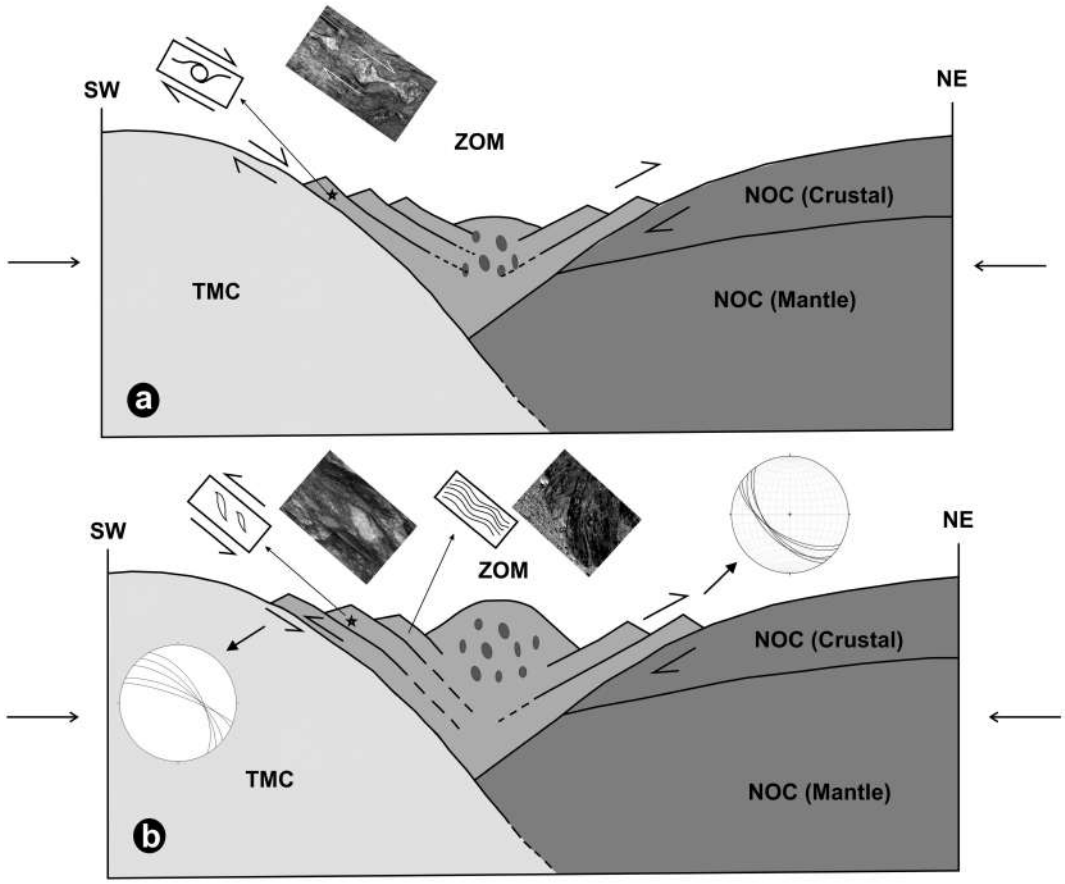

Fig. 4. Cartoon showing two-stage exhumation of ZOM and the development of present day configuration of ZOM (not to scale). (a) Continued northward propagation of the Indian plate and compression against the rigid NOC causes late stage crustal-scale exhumation of the TMC with respect to the ZOM. The Zildat Fault activates as a normal fault: down-to-N sheared indicated by quartz veins (inset and Fig. 2a). TMC moves upward relative to the ZOM and the later extends as an asymmetric detachment. Due to space problem and having the rigid NOC at one side, ZOM thrusts over the NOC. (b) With continued convergence, TMC show isostatic response after exhumation. Due to this, the Zildat fault reactivates as thrust (not the top-to-S shear indicated by imbrications of chert and carbonate clasts (inset and Fig. 2d). The ZOM underwent mild superposed deformation (inset and Fig. 2c) and got bound by two oppositely dipping thrusts and assumed the present day bivergant wedge shape. Inserted stereonets show measurement of latest foliation fabric near to the boundary of ZOM bounded by two oppositely dipping thrusts.

thrusting structure. Finally, flanks of the TMC dome developed normal shear structures, as an isotopic response of unroofing (D3) of TMC dome exhumed to near-surface depth at ~ 30 Ma. According to the study, during D3, NOC too developed north-east verging back thrusts. However, field observations from the present study suggest three key features, regarding tectonic evolution of the ZOM and the NOC. Firstly, NOC has not deformed being devoid of any folds or back thrusts (Fig. 3a-d); secondly the Zildat fault activated as a normal fault (Fig. 2a) but later switched as a thrust (Fig. 2b, d). Thirdly ZOM, as a whole, is bound by two opposite dipping thrust sheets (Fig. 1c) and it also has suffered mild superposed deformation (Fig. 2c). Based on our observations, we propose a two-stage model in the following section that explains the shallow surface structural evolution of the zone and explains the exhumation the ZOM at crustal level.

Two- stage Exhumation of the ZOM

Sen *et al*. (2013) suggested that intrusion of volatile-rich siliceous fluids from the TMC into the ZOM indicate a synchronous deformation of both these units at amphibolite facies. We suggest that, with ongoing northward convergence of the Indian continent and presence of NOC as a 'fixed barrier', both TMC and ZOM squeezed up being lighter than the NOC. The last-stage exhumation of these two units at crustal-scale occurred in two stages. The quartz veins present in ZOM, along the Zildat Fault indicate normal shear sense (Fig. 2a). This indicates that initially TMC slipped upwards with respect to the ZOM. ZOM accommodated TMC within this fixed boundary region by forming extensional detachments (Fig. 4a) and by thrusting over the NOC (Fig. 2h). This can be correlated with the 'D2' deformation during amphibolite facies metamorphism (de Sigoyer *et al*. 2004) at

~ 47 Ma. The amphibolite facies condition for this event can also be corroborated by the presence of mylonitized quartz veins (Fig. 2a).

In the next stage, TMC dome responses isostatically. Due to this, materials are transported away from the elevated, thickened TMC crust by gravity sliding and the adjacent ZOM accommodated this by re-activation of extensional detachments as thrust slices (Fig. 4b). The veins showing normal sense of shear got imbricated due to this compressional event (Fig. 2b) and the pre-existing foliation within ZOM enjoyed mild superposed deformation (Fig. 2c). The chert and the carbonate clasts present within the metagreywacke of ZOM underwent greenschist facies metamorphism, indicate thrusting (Fig. 2d). As the asymmetric extensional detachments formed within ZOM during earlier amphibolite facies condition imbricated over the TMC, ZOM attained the present day bivergent wedge shape (Fig. 4b). This event might have relates to the 'D3' deformation of de Sigoyer *et al*. (2004) ~ 30 Ma at greenschist conditions. However, we conclude, NOC did not take part in this deformation and rather it acted almost as a rigid barrier. Therefore the crustal-scale exhumation of TMC and ZOM occurred synchronously with a relative movement. NOC played a crucial role that facilitated this compression assisted upward movement.

In present day field configuration, the Zildat fault appears to be a steep (~ 60°) northeast dipping shear zone demarcating the boundary between continental TMC gneissic dome and oceanic ZOM group of rocks. The fault has been linked with obduction (Thakur & Virdi 1979) and the melange rocks juxtaposed over TMC along this fault zone (Ravikant 2003). The exhumation of TMC dome is also believed to have taken place along the Zildat detachment fault (Steck *et al*. 1998; Epard & Steck 2008), which explains the overprinting of late-stage brittle deformation on the fault zone rocks (de Sigoyer *et al*. 2004). However the steepness of Zildat fault misfits the classical definition of detachment faults in continental extensional setting (Davis 1988; Davis & Lister 1988; Fossen 1992). We emphasize that the Zildat fault initiated as detachment and reactivated as thrust. The steepening of Zildat fault may be explained by a back-shear (Agarwal *et al*. 2016; Joshi *et al*. 2017; Bose & Mukherjee, 2019) deformation. Rotation of such fault by bulk shear regime has been reported geologically (Exner *et al*. 2004). Rapid exhumation of the TMC might provide the back deformation required for steepening of Zildat Fault (Schlup *et al*. 2003).

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