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PARADIGM SHIFT IN UNDERSTANDING THE YARLUNG-TSANGPO OPHIOLITES: INSIGHTS FROM COMPARISONS WITH ULTRASLOW-SPREADING OCEAN RIDGES

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ABSTRACT

The Yarlung-Tsangpo ophiolites (YTO) are crucial tectonic windows that preserve coherent remnants of the Neo-Tethyan oceanic lithosphere in the Tibetan Plateau. They are particularly characterized by geological features that are different from the Penrose model, but resemble oceanic lithospheres generated at slow- to ultraslow-spreading ridges (i.e., the Chapman model). However, geochemical studies on the YTO have widely accepted an origin of suprasubduction zones (SSZ). The seemingly paradoxes between geological and geochemical evidence exemplify the "ophiolite conundrum" that have also been commonly observed in global ophiolites, which thus should be reconciled by any model. The YTO, especially the Xigaze ophiolite in its central segment, exhibits laterally highly variable magmatic crustal sequences, indicating magma focusing during its formation. Notably, the lower crust is either absent or formed through episodic and intermittent magma supplies, probably representing the low end of the magma budget among ocean ridges over time. Decoupled with the thin crust, the mantle peridotites show significant compositional variations (e.g., bulk Al_2O_3 of 0.04-2.9 wt.% and spinel Cr/(Cr + Al) of 0.12-0.74) and reveal heterogeneous osmium isotope compositions ($^{187}Os/^{188}Os$ of 0.11295-0.14661). Such features indicate that they represent mantle residues of a heterogeneous asthenosphere containing recycled ancient mantle domains of variable origins. These findings, combined with the widespread occurrence of detachment faults, support an origin of ultraslow-spreading ridges for the YTO. In this scenario, the ophiolite conundrum of the YTO can be elucidated through alternative models: 1) re-melting of ancient mantle domains within the heterogeneous asthenosphere, and 2) subduction jump and re-initiation along detachment faults, a process superimposed arc-like magmatism on pre-existing mid-ocean-ridge-basalt-like oceanic crusts. Therefore, we suggest that ancient and modern oceanic lithospheres generated at ultraslow-spreading ridges provide resolutions to the "ophiolite conundrum" and also call upon a paradigm shift in our understanding of global ophiolites from the Penrose model to the Chapman model.

INTRODUCTION

Ophiolites are a suite of mafic-ultramafic rocks that are widely identified in global orogenic belts and suture zones (Anonymous, 1972). They are widely accepted as ancient oceanic lithosphere that formed in variable tectonic settings, such as mid-ocean ridge (MOR), suprasubduction zone (SSZ), and ocean-continent transition (OCT) (e.g., Dilek and Furnes, 2011). Ophiolites distributed along the Yarlung-Tsangpo suture (YTS) in the southern Tibetan Plateau are the Early Cretaceous remnants of the Neo-Tethys Ocean, an ancient ocean that existed between the Gondwana and Eurasian continents during the Mesozoic (Hébert et al., 2012; Liu et al., 2022b; Wu et al., 2014; Zhu et al., 2013). These ophiolites serve as crucial geological records for deciphering the seafloor structures and evolutionary histories of the Neo-Tethys Ocean, providing valuable insights into regional plate configurations. The Yarlung-Tsangpo ophiolites (YTO) have been the focus of multidisciplinary researches for more than sixty years since the pioneering work of Gansser (1964) and Chang and Zheng (1973). However, the origin of the YTO, in particular its tectonic setting of formation (i.e., MOR or SSZ) remains hotly debated, with diverse models proposed.

The tectonic setting of the YTO was first discussed during a joint China-France fieldwork in the early 1980s (Girardeau et al., 1985a, b; Nicolas et al., 1981; Wang et al., 1987). Systematic field observations revealed a series of "peculiar" geological features in the central part of the YTO, which can be summarized as: 1) a thick (up to > 10 km) mantle unit accompanied by a thin (< 2-3 km) crust, and 2) the absence of a sheeted dike complex replaced instead by isolated and sheeted diabase sills (Girardeau et al., 1985b; Nicolas et al., 1981). Together with the rare occurrence of lower crustal unit, these features, quite different from the classical "Penrose model", were considered as key evidence supporting a slow-spreading ridge origin for these ophiolites (Nicolas et al., 1981). In contrast, geochemical studies over the last two decades have identified arc-like signatures in both the basaltic rocks and mantle peridotites of the YTO, leading to an argument that the YTO formed in a SSZ setting, either in a forearc or back-arc context (e.g., Dai et al., 2011, 2013; Dubois-Côté et al., 2005; Hébert et al., 2012; Malpas et al., 2003). Similar hypotheses have further been proposed based on geochronological and geochemical studies of metamorphic soles underlying the YTO, demonstrating a rapid tectonic transition from mid-ocean ridges to back-arc basins (Bédard et al., 2009; Guilmette et al., 2009, 2012). As a result, the understanding of the tectonic setting of the YTO has transformed significantly from a slow-spreading ocean ridge to a subduction-related settings. The YTO is now regarded more as a geological record of subduction initiation within the Neo-Tethys Ocean, rather than a product of seafloor spreading at mid-ocean ridges.

Regardless of its tectonic setting, one of the major achievements in understanding the YTO is the identification of detachment faults and oceanic core complexes (Li et al., 2016; Liu et al., 2014; Maffione et al., 2015; Wu et al., 2014), which are diagnostic geological features of modern slow- and ultraslow-spreading ocean ridges, i.e., the Chapman model (Escartín and Canales, 2011; Maffione et al., 2013). The presence of detachment faults within the YTO suggests a relatively low magma supply during its formation (Tucholke et al., 2008). This geological observation argues against the high magma supply typically expected in a forearc setting owing to large-degree, multi-stage mantle melting (Ishizuka et al., 2011; Stern et al., 2012). Moreover, a classical forearc crust, which is typically composed from the bottom up of gabbros, forearc basalts, boninites, and subsequent island arc basalts, is notably absent in the YTO (Wu et al., 2014). Therefore, whether a MOR or a SSZ origin is considered, any proposed model must reconcile the evidence of a low magma supply, the development of detachment faults, and the observed arc-like geochemical features.

Here we present an updated review of our findings regarding the origin of the YTO over the past decade since the work by Liu et al. (2014) and Wu et al. (2014). Along with the compilation and re-evaluation of published geochemical data, the geological and geochemical characteristics of the YTO will be compared comprehensively with the new findings of modern slow- and ultraslow-spreading ridges. In this context, the arc-like geochemical signatures observed in the YTO can be explained by alternative models, such as the re-melting of ancient mantle domains in the heterogeneous asthenosphere and a subduction re-initiation superimposed on mid-ocean ridge processes. These models, inspired by modern slow- and ultraslow-spreading ridges, provide new insights into the long-standing controversy on the tectonic setting of the YTO. They also have a potential to resolve the "ophiolite conundrum", which describes the discrepancy between MOR-type structural and stratigraphic features and SSZ-type geochemical characteristics observed in global ophiolites (Moores et al., 2000, 2021), and call upon a paradigm shift in the understanding of global ophiolites from the Penrose model to the Chapman model.

GEOLOGICAL BACKGROUND

Tectonic framework of the Tibetan Plateau

The Tibetan Plateau has formed through the tectonic amalgamation of several continental and/or accretionary terranes, which, from north to south, include the Kunlun-Qilian, Songpan-Ganzi, North and South Qiangtang, and Lhasa (Fig. 1a; Yin and Harrison, 2000; Zhu et al., 2013). These terranes are separated by a series of east-west trending suture zones of the Tethys Ocean, namely the A'nyemaqen-Kunlun-Muztagh, Jinsha, and Longmuco-Shuanghu sutures of the Paleo-Tethys, the Bangong-Nujiang suture of the Meso-Tethys, and the YTS of the Neo-Tethys (Fig. 1a; Wu et al., 2020; Zhu et al., 2013). The YTS is the youngest and southernmost suture within the Tibetan Plateau, marking the surface boundary between the Lhasa terrane to the north and the Himalaya (Indian Plate) to the south.

Along the YTS, several tectonic units have been identified in relation to the Neo-Tethyan evolution (Fig. 1b). These units include, from north to south, the Triassic-Eocene Gangdese batholith and Linzizong volcanics (known as the Gangdese continental arc), the Early Cretaceous-Eocene Xigaze forearc basin, the YTO, the Triassic-Eocene accretionary and tectonic mélanges. Additionally, terranes with debated origins, such as the Zhongba terrane and Langjiexue Group, have been identified in southern Tibet.

Geology of the Yarlung-Tsangpo ophiolites

Ophiolites crop out discontinuously along the YTS and extend for more than 1000 km (Fig. 1b; Dai et al., 2013; Hébert et al., 2012; Liu et al., 2022b; Wu et al., 2014; Xiong et al., 2016; Xu et al., 2020). These ophiolites are geographically divided into the western, central, and eastern segments (Fig. 1b). The western YTO is further grouped into northern (Dajiweng, Baer, Cuobuzha, and Zhalai) and southern (Dongbo, Purang, Zhagabu, Mayum, Danqiong, Xiugugabu, Zhongba, and Saga) sub-belts, which are separated by the Zhongba terrane. These ophiolites are mainly made up of variably serpentinized mantle peridotites that are surrounded by chert-matrix mélanges, whereas the magmatic crusts are extremely thin or even missing (Bédard et al., 2009; Bezard et al., 2011; Lian et al., 2016; Liu et al., 2014, 2018a; Zhang et al., 2023a, 2023d, 2025). Ophiolites in the central segment are distributed mainly south of Xigaze City, stretching from Ngamring in the west to Renbu in the east, thus are combined referred to as the Xigaze ophiolite. As the most studied ophiolite in China, the Xigaze ophiolite has been the focus of extensive research, regarding its field geology, structure, geochronology, petrology, geochemistry, and paleomagnetism. The Xigaze ophiolite has a complete and continuous sequence, from the uppermost mantle in the south, through the lower crust, to upper crustal basaltic rocks in the north (Girardeau et al., 1985a, b; Liu et al., 2021a, b; Nicolas et al., 1981; Wu et al., 2014). The detailed geological features and tectonic significance of the Xigaze ophiolite are provided in the Discussion section. Ophiolites in the eastern segment, mainly located in Zedong and Luobusa, exhibit geological features that differ significantly from those in the western and central segments. The eastern ophiolites typically consist of a mantle sequence of lherzolites and harzburgites, an ophiolitic mélange zone, and the Moho consisting of dunites and harzburgite xenoliths (Xiong et al., 2016, 2022; Zhang et al., 2016a, 2020b, 2024b). The magmatic crust in these ophiolites has a variable thickness and commonly outcrops as blocks within the mélange (Zhang et al., 2016a, 2024b).

The formation time of the YTO has been extensively studied using high-precision zircon U-Pb dating (Table S1). According to these age data, the YTO along the >1000-km-long suture formed in a relatively short time span of ~130-120 Ma (Fig. 1c; Table S1). Notably, there is strong consistency in the age results obtained across different lithologies, from the upper crust on the top, through the lower crustal gabbros, to

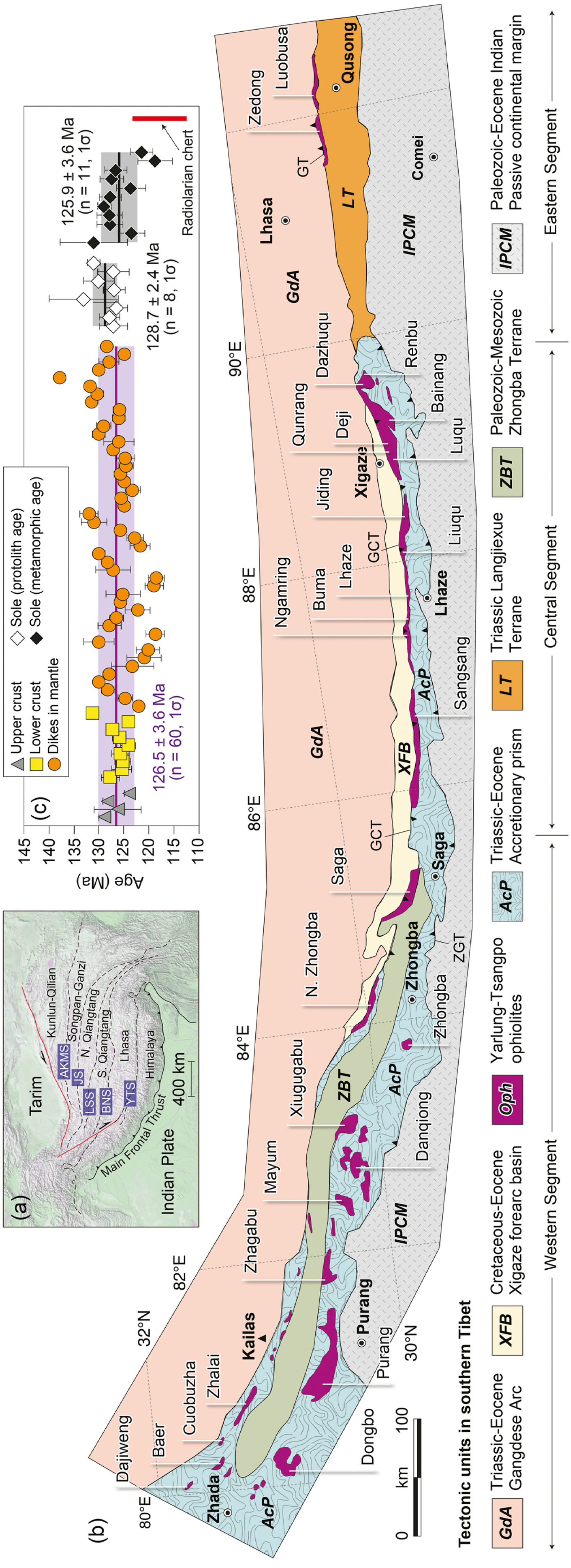

Fig. 1 - Geological framework of the Yarlung-Tsangpo ophiolites (YTO). (a) Tectonic framework of the Tibetan Plateau, showing the distribution and extension of major Tethyan sutures. AKMS: A'nyemaqen-Kunlun-Muztagh; JS: Jinsha suture; LSS: Longmuco-Shuanghu suture; BNS: Bangong-Nujiang suture; YTS: Yarlung-Tsangpo suture. (b) Tectonic units identified in southern Tibet and the distribution and segmentation of the YTO. (c) Zircon U-Pb dating results for different lithologies of the YTO and their comparisons with the ages of metamorphic soles and radiolarian cherts along the YTS. The age data is compiled in Table S1.

the mafic dikes that crosscut the mantle (Fig. 1c) (see Liu et al., 2016). The formation time of the ophiolite aligns closely, within error, with that of the underlying metamorphic sole (Duan et al., 2022; Guilmette et al., 2009, 2012; Zhang et al., 2016a, 2019, 2023b) and the overlying radiolarian cherts (Ziabrev et al., 2003) (Fig. 1c). The origin for such rapid accretion of the oceanic crust has been discussed previously. The proposed models are diverse, for example, subduction initiation and forearc spreading at the Asian continental margin (Dai et al., 2013, 2021), back-arc spreading in response to the intra-oceanic subduction of the Neo-Tethys (Guilmette et al., 2009, 2012; Hébert et al., 2012), detachment faulting at an ultraslow-spreading ridge (Liu et al., 2016), and southward trench migration and slab rollback (Xiong et al., 2016). Nonetheless, a consensus has emerged that the Early Cretaceous YTO represents only a snapshot of the vast Neo-Tethys Ocean, which has a spreading history of approximately 120 Myrs (Liu et al., 2023).

Geochemistry of the Yarlung-Tsangpo ophiolites

A series of studies have been undertaken to determine the geochemical characteristics of the YTO. Here we compiled available bulk-rock and mineral data for basalts and diabases (n = 379) and lower crustal gabbros (n = 121) from the well-studied Xigaze ophiolite in the central YTS, as well as for mantle peridotites (harzburgite and lherzolite, n = 550) along the entire suture. These data, along with Re-Os isotopes and highly siderophile elements (HSE) of the mantle peridotites, will be utilized to discuss the tectonic setting, crustal accretion, and mantle dynamics of the YTO.

Based on the dataset, we examined the fundamental characteristics of the crustal rocks and mantle peridotites of the YTO. Basalts and diabases typically exhibit rare earth element (REE) patterns characterized by a weak depletion in light REE (LREE) and relatively flat middle and heavy REE (MREE and HREE). These REE patterns are similar to that of normal mid-ocean ridge basalt (N-MORB); some diabases and minor basalts, however, display marked REE depletions relative to N-MORB (Fig. 2a). Compared to N-MORB, the basalts and diabases of the YTO exhibit noticeable depletions in Nb and Ta, along with a subtle depletion in Ti. Additionally, some of these rocks are enriched in large ion lithophile elements (LILE), such as Rb and Ba (Fig. 2a). In the Th/Yb vs. Nb/Yb diagram, the basalts and diabases have large variations (Fig. 2b), with some samples having elevated Th/Yb ratios that plot within the field of oceanic arcs.

The lower crustal cumulate rocks of the YTO comprise olivine-rich troctolite, troctolite, olivine gabbro, layered gabbro, isotropic gabbro, and minor gabbronorite and oxide gabbro (Girardeau et al., 1985a; Liu et al., 2018b, 2021a, b). These rocks overall display significant compositional variations, indicating variably evolved characteristics from relatively primitive olivine-bearing rocks to more evolved

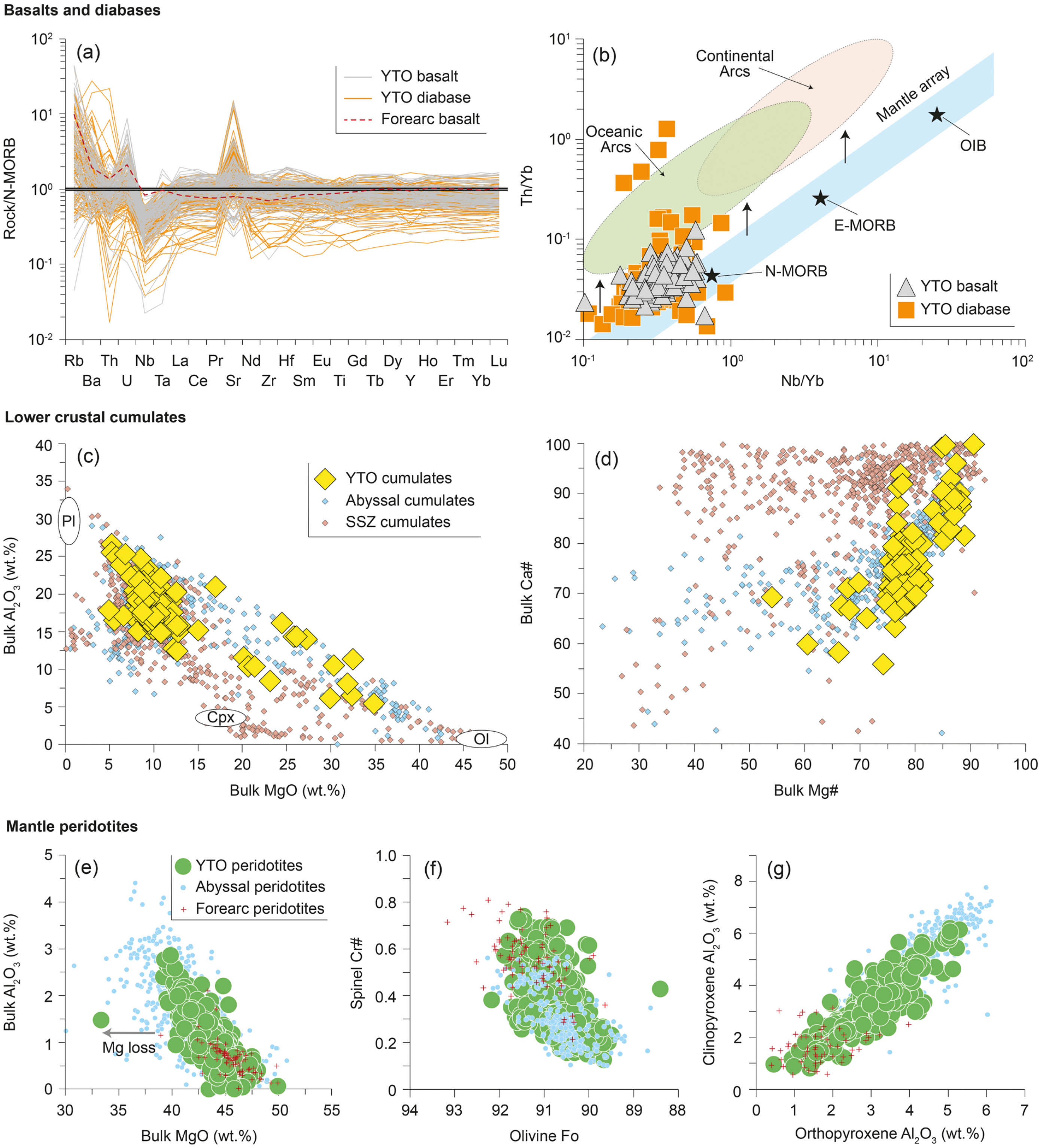

Fig. 2 - Basic geochemical characteristics of basaltic rocks (basalt and diabase; a-b), lower crustal cumulates (c-d), and mantle peridotites (e-g) of the YTO. Data for basalts, diabases, and lower crustal cumulates is for the well-studied Xigaze ophiolite in the central segment of the YTO. Data for the mantle peridotites is from the entire suture. Data for N-MORB is from Sun and McDonough (1989). Average compositions of forearc basalts are after Reagan et al. (2010). Fields of oceanic and continental arcs are after Pearce (2014). The compositions of abyssal and SSZ cumulates are after the compilation by Zhang et al. (2022). Data for abyssal and forearc peridotites are from the PetDB database (https://search.earthchem.org/). N-MORB: normal mid-ocean ridge basalt; E-MORB: enriched mid-ocean ridge basalt; OIB: ocean island basalt; Pl: plagioclase; Cpx: clinopyroxene; Ol: olivine; Cr#: Cr/ (Cr + Al); Fo: 100 × Mg/ (Mg + Fe2+).

olivine-free gabbros (Liu et al., 2018b). In the bulk Al_2O_3 vs. MgO correlation, the YTO cumulate rocks follow a fractionation trend that suggests an earlier precipitation of plagioclase compared to clinopyroxene (Fig. 2c). This trend is further exemplified by a rapid decrease in bulk Ca# [100 × Ca/ (Ca + Na)], followed by a decline in bulk Mg# [100 × Mg/ (Mg + Fe^{2+})] (Fig. 2d). This pattern is consistent with a significant removal of Ca during the fractionation of plagioclase. Overall, the composition of the YTO cumulate rocks is comparable to that of abyssal cumulates at modern mid-ocean ridges and can be distinguished from SSZ cumulates (Fig. 2c, d; compiled by Zhang et al., 2022).

Similar to the lower crustal cumulate rocks, the mantle peridotites along the entire suture exhibit significant variation in their geochemical compositions, ranging from refractory to relatively fertile characteristics (Fig. 2e-g). Most of these samples are compositionally comparable to abyssal peridotites (Fig. 2e-g; data from the PetDB database: https://search.earthchem.org/). A small subset, however, displays relatively lower bulk and pyroxene Al_2O_3, along with higher olivine forsterite [Fo; 100 × Mg/ (Mg + Fe^{2+})] and spinel Cr# [Cr/(Cr + Al)], resembling refractory forearc peridotites from the West Pacific subduction systems (Fig. 2e-g; PetDB database). The extensive compositional variations observed in the mantle peridotites of the YTO have been attributed to complex processes involving variable extents of mantle melting, melt-rock interaction, and prior melt depletions.

The geochemical characteristics of the YTO have been widely used to discriminate its tectonic setting. The enrichment in LILE and the depletion in some high field strength elements (such as Nb, Ta, Ti) in the basalts and diabases are regarded as diagnostic features supporting a SSZ origin for the YTO (Fig. 2a, b), either a forearc (Dai et al., 2013, 2021; Malpas et al., 2003; Xiong et al., 2016) or back-arc (Bédard et al., 2009; Hébert et al., 2012). Similarly, the refractory mantle peridotites, characterized by high spinel Cr# and elevated whole-rock LREE, have been interpreted as forearc or back-arc peridotites that interacted with slab-derived melts (Fig. 2e-g) (Bezard et al., 2011; Dubois-Côté et al., 2005; Dupuis et al., 2005; Xia et al., 2003; Xiong et al., 2016, 2017a, b; Xu et al., 2020). The arc-like geochemical features, however, are not present within the lower crustal cumulates. The gabbros in the YTO are characterized by an earlier crystallization of plagioclase relative to clinopyroxene, as evidenced by their geochemical compositions (Fig. 2c, d) and petrographic observations (Liu et al., 2018b, 2021b). This is consistent with the low-pressure crystallization of dry basaltic magmas (Grove et al., 1992). The presence of troctolite within the lower crustal cumulates of the YTO further support an anhydrous line of descent (Liu et al., 2018b). Moreover, intra-oceanic arcs associated with the subduction of the Neo-Tethyan slab are also absent along the suture (Wu et al., 2014; Zhang et al., 2014). To resolve the ongoing debate regarding the tectonic setting of the YTO, a clear distinction must be made. In the following discussions, we will illustrate how the understanding of the origin and tectonic setting of the YTO has undergone a paradigm shift and how ophiolite conundrum can be reconciled through a comprehensive comparison with the structures and geochemical characteristics of oceanic lithospheres at modern ultraslow-spreading ridges.

DISCUSSION

Thin and highly variable oceanic crusts

One of the most conspicuous geological features of the YTO is its extremely thin oceanic crusts along the entire suture. The entire belt of the YTO extends roughly in an E-W direction, the thickness of its magmatic crusts thus was measured in the field perpendicularly to this direction (Girardeau et al., 1985b; Liu et al., 2021a, b; Nicolas et al., 1981). In localities where the magmatic crust is well developed, the thickness of the crust also refers to the orientation of crust-mantle boundary and foliation of gabbros and mantle peridotites (Girardeau et al., 1985b; Liu et al., 2021a, b; Nicolas et al., 1981).

In the western segment, the magmatic crust is nearly absent; in the eastern segment, it is only minor; in the central segment, it does not exceed 2-3 km in thickness (Fig. 3). This is markedly distinct from the Penrose-type oceanic lithosphere, which typically has a crustal thickness of 6-7 km, such as the East Pacific Rise and the Oman and Troodos ophiolites (Fig. 3). A thin crust may have resulted from extensive tectonic dismemberment during ophiolite obduction and the subsequent Indo-Asian collision. However, field observations

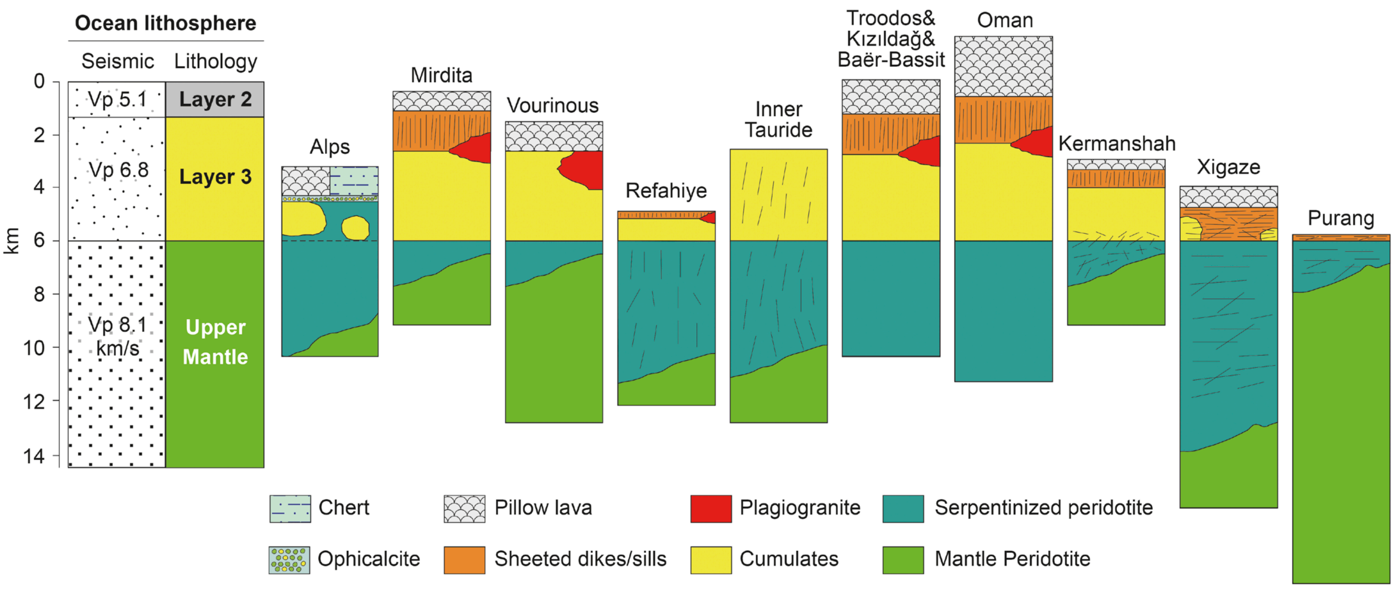

Fig. 3 - Pseudostratigraphy of representative ophiolites along the Neo-Tethyan belt from the Alps to Tibet. References: Alps (Manatschal et al., 2011; Sanfilippo and Tribuzio, 2011, 2013), Mirdita (Dilek and Furnes, 2009; Nicolas et al., 1999), Vourinous (Bortolotti et al., 2004), Refahiye (Liu et al., 2024; Parlak et al., 2012; Sarifakioğlu et al., 2009), Inner Tauride (Parlak et al., 2013; Xin et al., 2021), Troodos & Kızıldağ & Baër-Bassit (Dilek and Thy, 2009), Oman (Dilek and Furnes, 2009), Kermanshah (Ao et al., 2016), Xigaze (Liu et al., 2021a, b; Nicolas et al., 1981), Purang (Liu et al., 2014).

from previous studies (Girardeau et al., 1985b; Nicolas et al., 1981; Wang et al., 1987) indicate that tectonic dismemberment is negligible, a finding that has also been confirmed by our field work (Liu et al., 2021a, b). Notably, an intrusive contact has been identified between the lower crustal gabbros and underlying mantle peridotites (Fig. 4a; Liu et al., 2016). In this intrusive contact, the peridotites are moderately serpentinized, while the gabbros are leucogabbros with abundant plagioclases (Fig. 4a). These features indicate a cold lithospheric mantle intruded by relatively evolved gabbros at shallow level. Additionally, pillow lavas on top of the crust are directly overlain by radiolarian cherts (Fig. 4b; Wang et al., 2017). The preservation of these primary contacts indicates that the internal structures of the YTO are relatively intact, suggesting that thin crust is an inherent feature rather than a product of significant tectonic dismemberment. The magmatic crust of the YTO is also highly variable in both thickness and structure. Notably, the lower crust, defined as seismic layer 3, is discontinuous. For example, lower crustal gabbros are developed only in three localities (i.e., Jiding, Baigang, and Dazhuqu) within the Xigaze ophiolite of the central YTO (Girardeau et al., 1985a, b; Liu et al., 2016; Nicolas et al., 1981; Wang et al., 1987; Wu et al., 2014). In Baigang, the thickness of these gabbros does not exceed ~800 m, while in Jiding, it is only about ~350 m (Liu et al., 2016). The lower crustal gabbros, along with the mantle peridotites, are ubiquitously intruded by a second generation of mafic rocks. These later intrusions crosscutting the mantle unit consist of diabase, gabbro, rodingite, and foliated amphibolite, while those intruding the lower crustal unit are predominantly diabases (Fig. 5). In both cases, the proportion of these isolated mafic rocks increase upwards, passing gradually into a sheeted diabase unit composed entirely of diabases. Overall, the isolated mafic rocks throughout the ophiolite sequence have variable orientations (Liu et al., 2021a). They typically strike sub-parallel to the high-temperature ductile foliation in mantle peridotites and the layering of lower crustal gabbros, and are thus referred to as diabase sills (Fig. 5; Girardeau et al., 1985a, b; Liu et al., 2021a, 2022b; Nicolas et al., 1981; Wu et al., 2014). Diabases with orientations oblique or subperpendicular to the mantle fabric and gabbroic layering are also observed (Fig. 5d). The sheeted diabase unit is dominated by diabase sills and has been defined as "sheeted sill complex" (Fig. 5f; Girardeau et al., 1985a, b; Liu et al., 2021a, 2022b; Nicolas et al., 1981; Wu et al., 2014).

The along-axis crustal thickness in a W-E direction has been measured for the well-studied Xigaze ophiolite, from Jiding in the west to Dazhuqu in the east (Fig. 6). The result underscores a highly variable magmatic crust within the Xigaze ophiolite (Fig. 6b). In the west (Jiding) and east (Baigang-Dazhuqu), the crustal unit is relatively thick, comprising 350-800 m of lower-crustal gabbros overlain by an upper crust no more than 2 km thick. These areas correspond to volcanic segments ~25 km long in the west and ~38 km long in the east along the paleo-ridge. In contrast, the central part of the Xigaze ophiolite, spanning about ~53 km, exhibits an extremely thin magmatic crust, which is even absent in some areas, resembling an amagmatic zone. Notably, lower crustal gabbros are also lacking in this zone. This highly variable and unevenly distributed oceanic crust suggests strong magma focusing during the formation of the Xigaze ophiolite (Liu et al., 2021b). The observation of thin or missing crust in the central amagmatic zone imply extensive exposure of the mantle on the ancient seafloor, bordered by smaller-scale volcanic segments (Fig. 6b). These features mimic the crustal architecture of modern ultraslow-spreading ocean ridges, which are characterized by highly focused magmatic accretion and mantle exposures (Cannat et al., 2003; Dick, 1989; Dick et al., 2003; Li et al., 2015; Mendel et al., 1997; Rommevaux-Jestin et al., 1997; Whitehead et al., 1984; Zhang et al., 2024a). This crustal architecture is distinctly different from the uniform and continuous oceanic crust typical of fast-spreading ridges (Babcock et al., 1998; Sinton and Detrick, 1992) and can also be distinguished from the relatively weak magma focusing and more closely spaced smaller volcanic centers characteristic of slow-spreading ridges (Lin and Morgan, 1992; Lin et al., 1990; Mendel et al., 1997; Rommevaux-Jestin et al., 1997; Tolstoy et al., 1993).

Episodic lower crustal accretion

A ~350-m-thick lower crust has been measured in the Jiding section of the Xigaze ophiolite to examine its compositional variation (Fig. 6a, 7a; Liu et al., 2021a, b). The Jiding lower crust is composed of gabbroic rocks and diabase dikes/sills. The gabbroic rocks are predominately olivine-free, with only negligible occurrence of olivine gabbros and gabbronorite. They are mainly layered gabbros with evident magmatic foliations, which are defined by shape preferred orientations of clinopyroxene and plagioclase. The upper

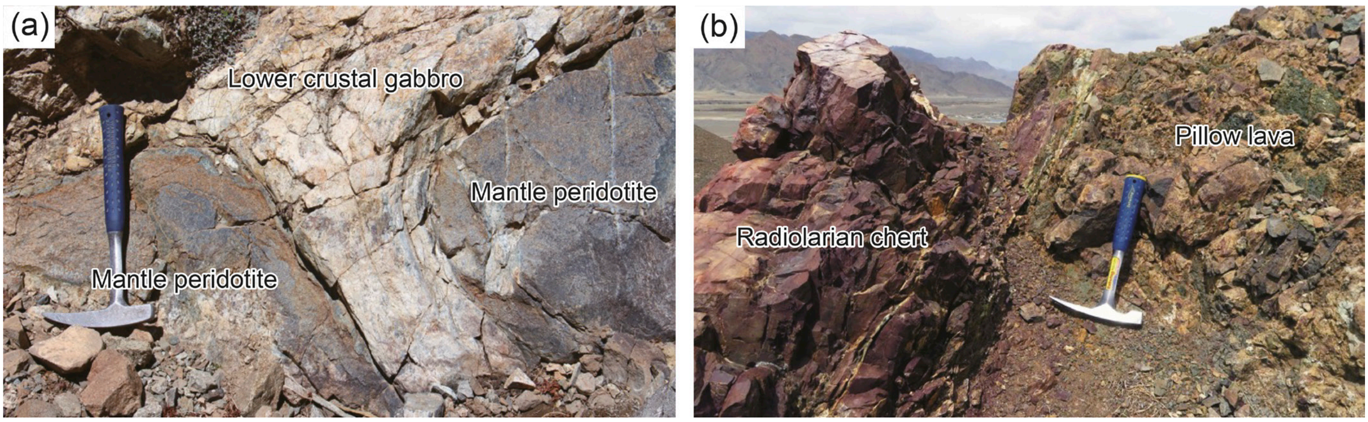

Fig. 4 - Field photos of the primary contacts at the bottom and on the top of the magmatic crust of the Xigaze ophiolite, central YTO. (a) Intrusive contact between lower crustal gabbros and serpentinized mantle peridotites (Dazhuqu). (b) Pillow lavas are directly overlain by radiolarian cherts (Naxia).

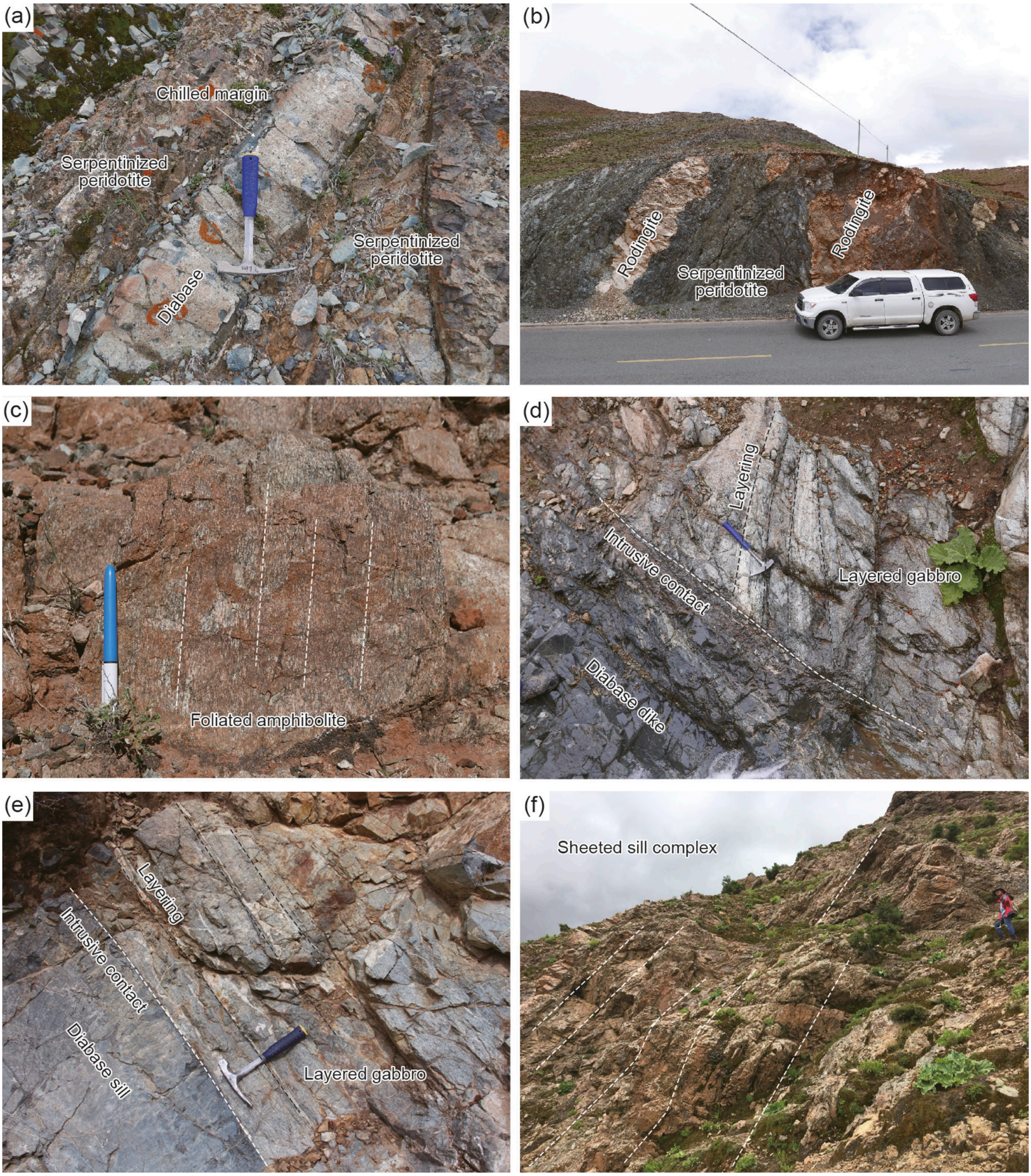

Fig. 5 - Field relationships for the isolated mafic dikes/sills and sheeted sill complex in the Xigaze ophiolite, central YTO. (a) Serpentinized mantle peridotites are intruded by a fresh diabase dike, which displays clear two-way chilled margins (Pengcang). (b) Serpentinized mantle peridotites crosscut by several rodingite dikes (Ngamring). (c) Foliated amphibolites identified in the serpentinized mantle peridotites (Luqu). (d-e) Diabase dikes and sills intruding the lower crustal layered gabbros (Jiding). (f) Sheeted sill complex composed entirely of diabase sills (Jiding).

20-30 m of the section is made up of oxide gabbros. It is evident that the Jiding lower crust is extremely thin with respect to the ~2.5-km-thick Atlantis Bank gabbro massif at the Southwest Indian Ridge (Dick et al., 2019; Zhang et al., 2020c) and the ~5-km-thick lower crust in the Oman ophiolite (Koepke et al., 2022; Müller et al., 2022) (Fig. 7b). This likely reflects a lower magma flux in Jiding compared to Atlantis Bank and Oman (Liu et al., 2021b). Alternatively, it may indicate that the magmas responsible for lower-crustal accretion at Jiding were transported from elsewhere,

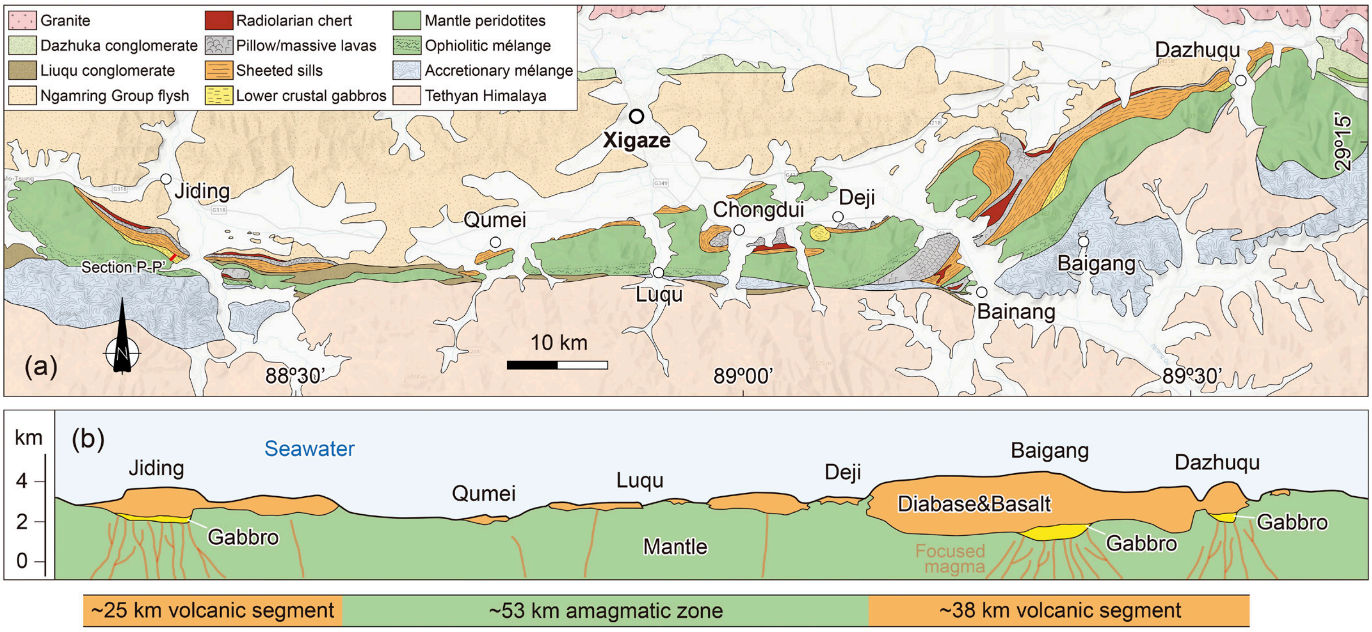

Fig. 6 - (a) Geological map of the Xigaze ophiolite (modified after Wang et al., 1987). (b) Reconstructed oceanic crustal thicknesses along the paleo-ridge axis at the time of the ophiolite formation (~126 Ma; after Liu et al., 2021b).

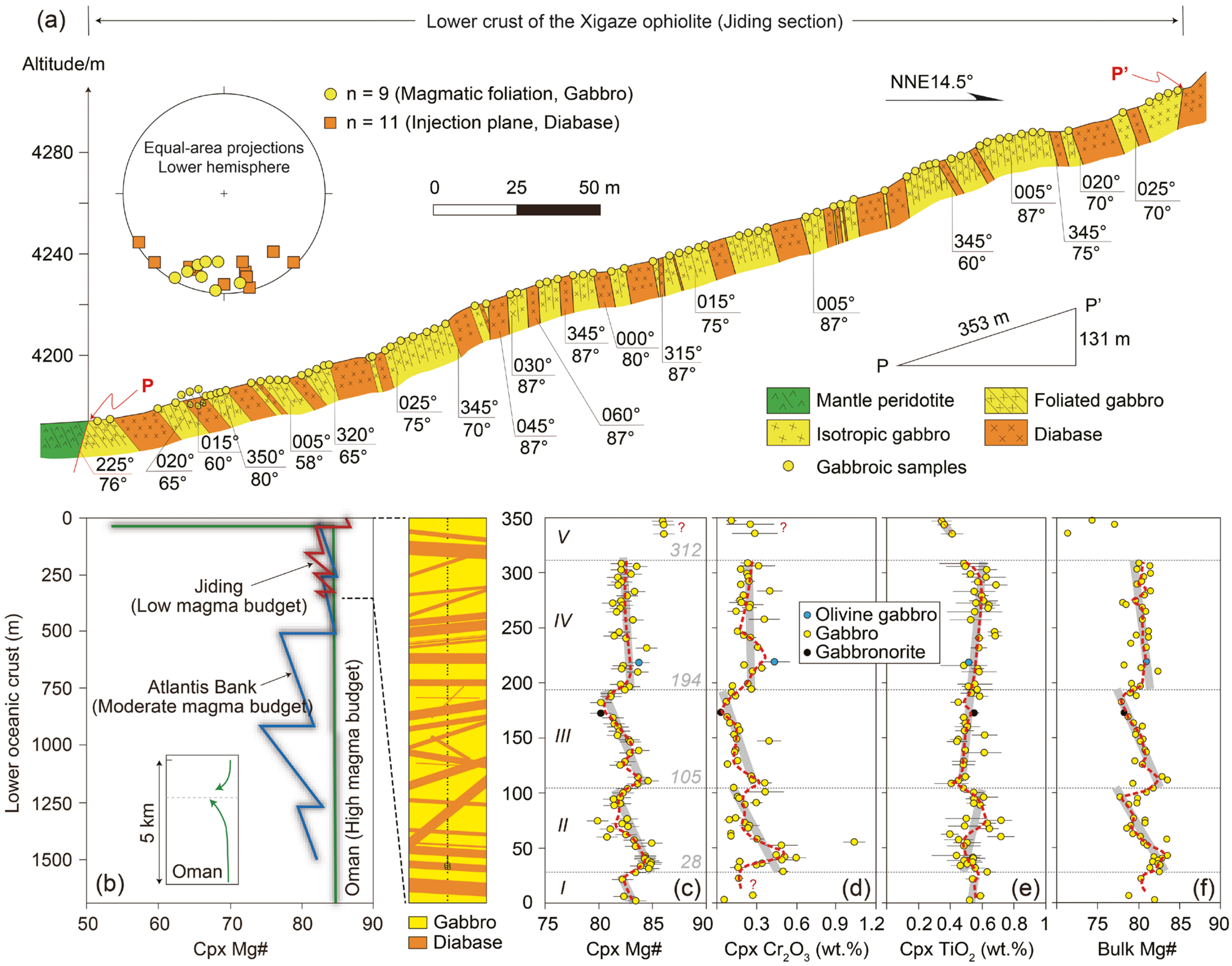

Fig. 7 - (a) The measured ~350-m-thick lower crust in the Jiding ophiolite section, Xigaze ophiolite. (b) Schematic cryptic chemical variations of the Jiding lower crust (representing a low magma budget) and its comparison with the Atlantis Bank gabbro massif of the Southwest Indian Ridge (after Dick et al., 2002) and the Oman ophiolite (after Koepke et al. (2022) and MacLeod and Yaouancq (2000)). (c-f) Cryptic chemical variations of the Jiding gabbroic rocks.

as documented at transform faults and slow-spreading mid-ocean ridges (Basch et al., 2024; Brunelli et al., 2020). It should be noted that primitive gabbroic rocks (troctolites and olivine gabbros) have been widely identified in other localities of the Xigaze ophiolite, i.e., Dazhuqu and Baigang (Liu et al., 2018b), which resemble the primitive gabbroic rocks of modern slow- and ultraslow-spreading ridges (Lissenberg and Dick, 2008; Sanfilippo et al., 2018). This suggests that the Jiding lower crust was more evolved than those in Dazhuqu and Baigang (Liu et al., 2018b). However, even considering the entire Xigaze ophiolite as a whole, its lower crust is still thin and does not exceed 800 m in thickness (Liu et al., 2018b). Therefore, it is more likely that the Xigaze ophiolite has a lower magma flux than Atlantis Bank and Oman.

The cryptic chemical variation of the Jiding lower crust is also distinct from those observed at Atlantis Bank and Oman. Based on our previous geochemical data, the Jiding gabbros display episodic chemical variations in both bulk-rock and mineral compositions (Fig. 7c-f), which can be categorized into five units. Within individual units, clinopyroxene Mg#, Cr_2O_3, and bulk Mg# gradually decrease upwards, while clinopyroxene TiO_2 content increases. There are clear breaks at unit boundaries. Such features have been interpreted to indicate that the lower oceanic crust was constructed through multiple magma intrusions (Dick et al., 2000, 2002). In each intrusion, interstitial evolved melts in the crystal mush can be transferred towards the top of the sequence by compaction, as evidenced by the pervasive occurrence of reactive porous flow throughout the lower crust (e.g., Boulanger et al., 2021; Lissenberg and MacLeod, 2016; Sanfilippo et al., 2020). Such episodic lower crustal accretion is not exclusive to the Jiding section, but has also been identified at Atlantic Bank, as evidenced by the downhole variations recorded in ODP/IODP Hole 735B and U1473A (Dick et al., 2000, 2002; Zhang et al., 2020c). A clear distinction, however, exists between Atlantis Bank and Jiding, particularly in the size of individual intrusive cycles. The intrusive cycles at Atlantis Bank are nearly an order of magnitude larger than those at Jiding (~500 m in Atlantis Bank compared to ~100 m in Jiding; Fig. 7b). This difference can be attributed to variations in their magma fluxes, with Atlantis Bank representing an anomalous, moderate magma budget compared to the rest of the ultraslow-spreading Southwest Indian Ridge (Dick et al., 2019; Zhou and Dick, 2013).

Episodic lower oceanic crustal accretion is not typical of the supposed oceanic crust of the Oman ophiolite (Coogan, 2014; Koepke et al., 2022; MacLeod and Yaouancq, 2000; Müller et al., 2022) nor of modern fast-spreading oceanic crust, such as those at the East Pacific Rise (Coogan, 2014; Lissenberg et al., 2013). The geochemical compositions of the Oman lower crust are relatively homogeneous throughout the majority of the section, with the exception of the uppermost horizon, which contains numerous varitextured gabbros representing the fossil axial melt lens (Fig. 7b; MacLeod and Yaouancq, 2000). Recent studies from the Oman drilling project have identified noticeable compositional variations between the upper and lower foliated gabbro units (see Fig. 7b), which were interpreted by hybrid accretion with the contributions from the axial melt lens on the top and the gabbro sills underneath (Koepke et al., 2022; Müller et al., 2022). Nonetheless, the Oman ophiolite is characterized by a much higher magma supply supporting ~5-km-thick lower oceanic crust. The Oman ophiolite thus represents a higher class of magma budget compared to Jiding (low) and Atlantis Bank (moderate) (Fig. 7b; Liu et al., 2021b).

Recognition of detachment fault and its evolution

The thin and highly variable magmatic crust along the entire suture, coupled with episodic lower crustal accretion in the central segment, suggests that the YTO formed under a condition of low magma supply, likely at an ancient ultra-slow-spreading ridge (Liu et al., 2021b). This argument is further substantiated by the occurrence of detachment faults and oceanic core complexes identified within the YTO. Such interpretations are supported by multidisciplinary evidence encompassing structural geology, petrology, geochronology, geochemistry, and paleomagnetism.

It has been suggested that the mantle unit of the Xigaze ophiolite has undergone large-scale internal rotations, revealed by paleomagnetic studies of crosscutting diabase dikes (Maffione et al., 2015). This behavior is analogous to the block rotations observed in active detachment faults of modern mid-ocean ridges (MacLeod et al., 2011; Morris et al., 2009). Structural studies have provided further evidence for the existence of detachment faults. (1) Retrograde serpentinite fault zones were identified in both the Xigaze ophiolite in the central segment (Li et al., 2016, 2021) and the Zedong ophiolite in the eastern segment (Li et al., 2025b), where talc-rich schists replaced the primary ductile deformation of mantle peridotites. (2) Tectono-sedimentary breccias are developed on the top of serpentinite fault zones, consisting of serpentinite breccias in the sheared serpentinite matrix (Li et al., 2025b). These structural features resemble those within the interface of detachment faults at both modern slow- and ultraslow-spreading ridges (Escartín et al., 2003; Hansen et al., 2013; MacLeod et al., 2002) and the Apline-Apennine ophiolites (e.g., Manatschal et al., 2011).

Numerous mafic dikes/sills crosscut the serpentinized mantle peridotites of the YTO. They are composed mainly of diabase and gabbro, some of which are subject to extensive hydrothermal alteration and ductile deformation, resulting in the formation of rodingite and foliated amphibolite, respectively (Fig. 5a-c; Li et al., 2016; Liu et al., 2021a; Zhang et al., 2016b, 2023c; Zhou et al., 2023). This is a notable feature, as diabases in oceanic lithosphere are typically generated at shallow depths and are not expected to exist in the mantle. The geological and structural characteristics of the YTO suggest that mantle exhumation may have occurred prior to the intrusion of fresh diabase dikes (Liu et al., 2016). Rodingites are typically regarded as alteration products of mafic dikes, formed through hydrothermal alteration by Si- and Ca-rich fluids during serpentinization (Bach and Klein, 2009; Li et al., 2007). The widespread presence of rodingites within the serpentinized mantle peridotites thus indicates that some amounts of magmas have intruded into the mantle before it was exhumed and serpentinized (Liu et al., 2016, 2022b; Wu et al., 2014). Additionally, petrological studies reveal that the foliated amphibolites within the YTO mantle peridotites underwent relatively high-temperature metamorphism under amphibolite-facies condition and ductile deformation of their protoliths (Liu et al., 2021a; Zhang et al., 2023c; Zhou et al., 2023). As noticed above, all the mafic rocks within the YTO share consistent formation ages of 130-120 Ma. In individual ophiolite sections, the duration of mafic magmatism was likely even shorter (i.e., <5 Myr; Liu et al., 2016). Notably, diabase and gabbro dikes intruding the mantle, together with rodingites and foliated amphibolites, are geochronologically indistinguishable from the overlying magmatic crust, indicating that their formation was broadly contemporaneous with crustal accretion (Fig. 1c). This indicates a dynamic linkage between melt crystallization and mantle exhumation, accompanied by hydrothermal alteration (serpentinization and rodingitization), ductile deformation, and high-temperature metamorphism (foliated amphibolites). These findings align well with previous paleomagnetic and structural studies that support the occurrence of mantle exhumation, rotation, and serpentinite ductile shear zones in the YTO (Li et al., 2016, 2025b; Maffione et al., 2015).

All lines of evidence from petrology, geochronology, geochemistry, paleomagnetism, and structural geology confirm the occurrence of detachment faults in the YTO (Li et al., 2016, 2025b; Liu et al., 2014, 2016, 2021a, 2022b; Maffione et al., 2015). This conclusion is further supported by a recent microstructural study revealing a multi-stage deformation history for the YTO mantle peridotites, which encompasses high-temperature ductile shearing followed by the development of detachment-fault-hosted mylonitization (Zhang et al., 2025). The formation and evolution of these detachment faults, in particular the associated footwall rotations, are the primary mechanisms to account for the pervasive occurrence of variably oriented mafic dikes in both the mantle and lower crust (Liu et al., 2021a). Similar mafic dikes are also not uncommon in other slow-spreading-type ophiolites and in boreholes from ocean drillings at modern slow- and ultraslow-spreading ridges (Liu et al., 2024 and references therein). The geometries of these mafic dikes, as well as their relationships with the host mantle and lower crustal rocks, exhibit considerable diversity (e.g., Blackman et al., 2006; Godard et al., 2009). This diversity can be attributed to multiple stages of dike intrusion into variably exhumed and rotated mantle peridotites and gabbros within the detachment footwall (Liu et al., 2021a). Consequently, the resulting architecture records a complex interplay among magma emplacement, mantle exhumation, and tectonic rotation.

In summary, the thin and highly variable crust, episodic lower crustal accretion, and occurrence of detachment faults combined lead us to conclude that the YTO formed under a low magma budget at an ancient ultraslow-spreading ridge. This ridge exhibited along-axis magma focusing (Fig. 8a) and cross-axis detachment faulting (Fig. 8b). The YTO differs markedly from the classical Penrose model, which envisages a layered oceanic crust approximately 6-7 km thick. In contrast, it more closely resembles the Chapman-type oceanic lithosphere, which is characterized by a thin or locally absent oceanic crust, as well as the development of detachment faults and oceanic core complexes (Escartín and Canales, 2011; Maffione et al., 2013). In fact, Chapman-type ophiolites, which share crustal architectures similar to that of the YTO, are far more common than Penrose-type ophiolites, accounting for approximately 90% and 10% of known ophiolites, particularly along the extensive Neo-Tethyan ophiolite belt stretching from the Alps to Southeast Asia (Fig. 3; Liu et al., 2024). This suggests that either Chapman-type oceanic lithospheres have a greater likelihood of preservation compared to Penrose-type (e.g., Ganade et al., 2024) or that slow- and ultraslow-spreading ridges were more abundant than fast-spreading ridges throughout the evolutionary history of the Neo-Tethys Ocean.

The highly heterogeneous mantle underneath

The thin crust of the YTO demonstrates an overall low magma supply along the paleo-ridge. It implies a relatively fertile residual mantle along the entire suture, which however is not the case for the mantle peridotites underneath. In Fig. 9, we reconstructed the compositional variations of mantle peridotites along the >1300-km-long Neo-Tethyan ocean ridge represented by the YTO. The results indicate a significant variation in mantle composition, such as bulk Al_2O_3, spinel Cr#, and clinopyroxene Yb (Fig. 9b-d). This is further exemplified by considerable variations in olivine Fo and pyroxene Al_2O_3 (not shown here). Such large variations are evident not only along the entire suture, but also within individual segments (i.e., western, central, and eastern) and

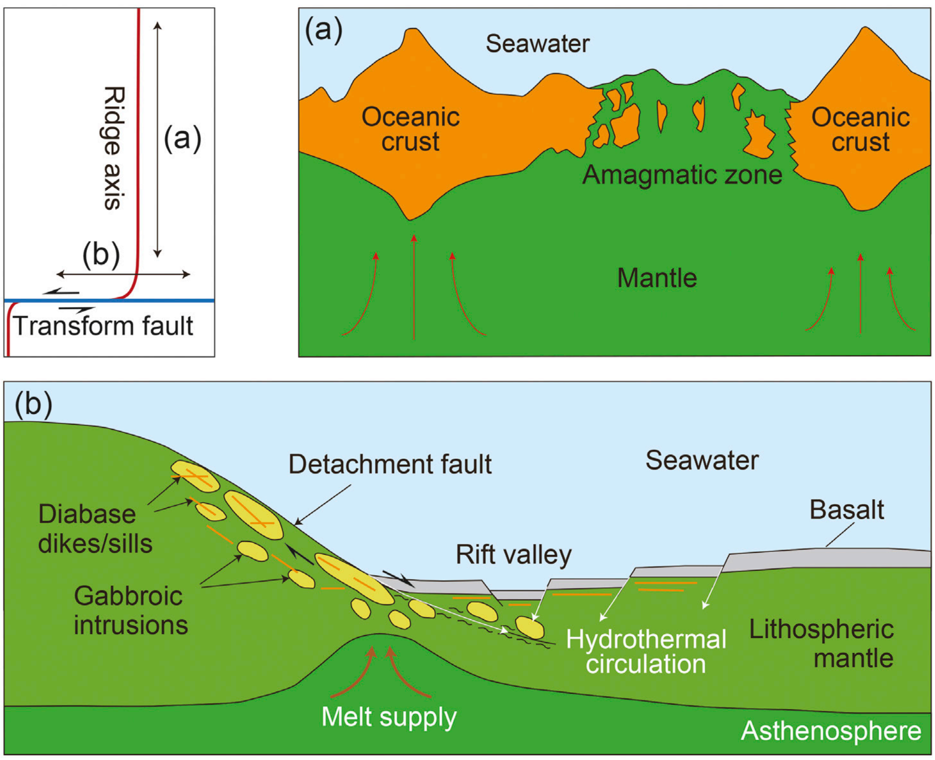

Fig. 8 - Along axis magma focusing (a) and cross-axis detachment faulting (b) identified for the paleo-ridge of the YTO, after Liu et al. (2016, 2021b).

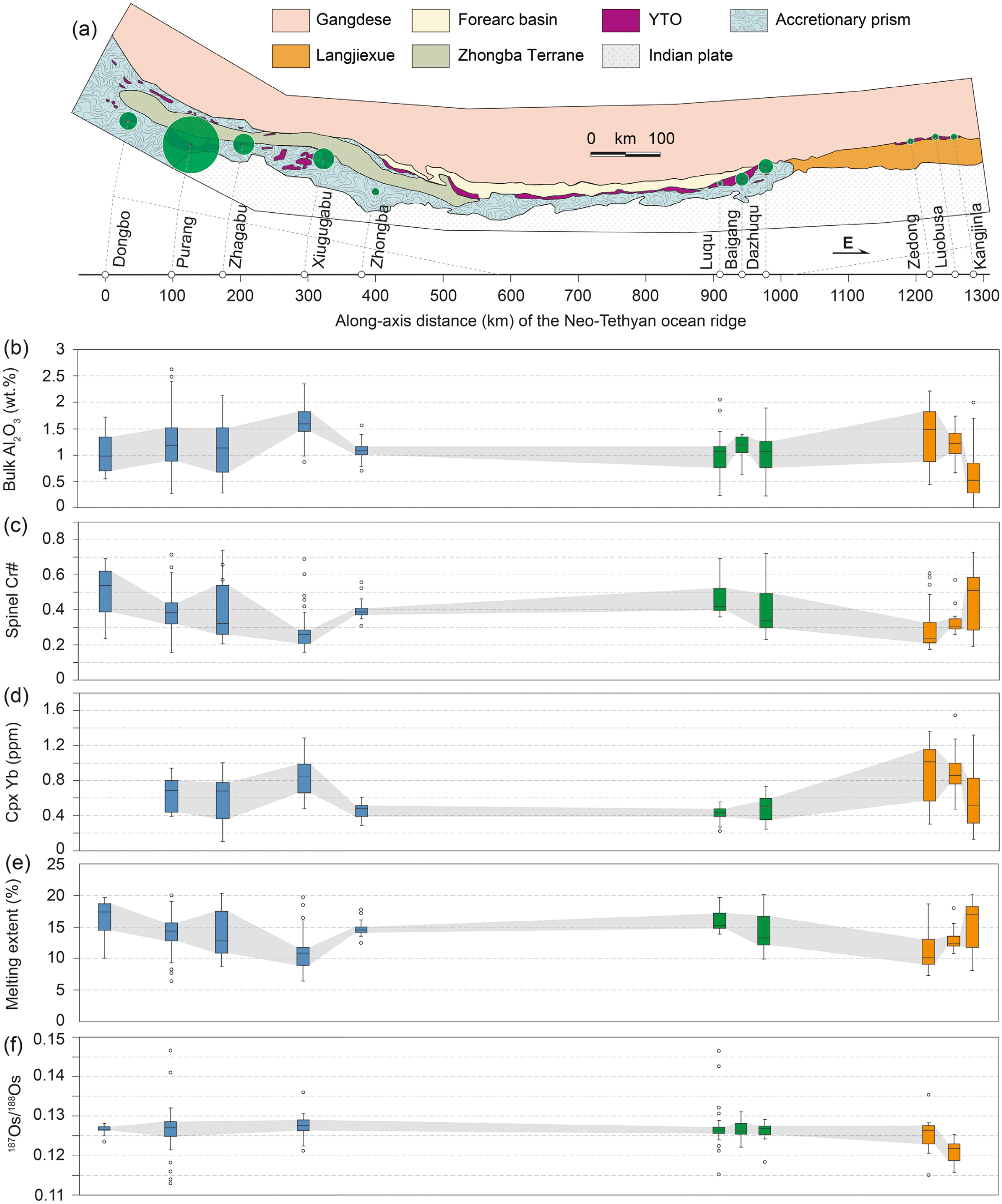

Fig. 9 - Reconstructed geochemical variations of the mantle peridotites along the ancient, >1300-km-long Neo-Tethyan mid-ocean ridge represented by the YTO. Melting extent is calculated by the empirical formula established based on spinel Cr# values of mantle peridotites (Warren, 2016).

even in single ophiolite sections. Based on spinel Cr#, we calculated the along-axis variation in the extent of mantle melting using the empirical formula: F = 9 × ln (Cr#) + 23 (F = melting extent; Warren, 2016), which also demonstrates dramatic changes (Fig. 9e). Assuming that the highest values of F (17.8%-20.1%) for the mantle peridotites in each ophiolite section represent the maximum extent of melting in the 60-km deep melting regime, a simple mass balance calculation yields an estimated oceanic crustal thickness that is as high as 6.0-6.8 km. This estimation, however, does not align with the observed crustal thickness for the YTO, where the magmatic crust is absent in its western and eastern segments and does not exceed 2-3 km in its central segment. Considering that the influence of tectonic dismemberment for the crustal thickness of the YTO is minor, mantle melting beneath the ancient Neo-Tethyan mid-ocean ridge was likely limited.

An explanation for the discrepancy between a refractory mantle and a thin crust is that the mantle has undergone a complex melting history rather than a single-stage sub-ridge melting (Liu et al., 2019; Xu et al., 2020; Zhang et al., 2017, 2023a; Zhu et al., 2025), a scenario that is consistent with the ubiquitous ultra-depleted mantle domains beneath the Mid-Atlantic and Gakkel Ridges revealed by Hf-Nd isotopes (e.g., Sanfilippo et al., 2024; Sani et al., 2023; Stracke et al., 2011, 2019). This argument is supported by the extremely depleted compositions in Os isotopes along the YTO mantle (Fig. 9f), which confirm that these mantle peridotites have experienced ancient melting (up to ~2.2 Ga) prior to their entry into the sub-ridge melting regime (Gong et al., 2016; Lian et al., 2024; Liu et al., 2012, 2019; Niu et al., 2015; Xu et al., 2020, 2025; Zhang et al., 2020a, b, 2023a; Zhu et al., 2025). The evidence for multi-stage mantle melting is further illustrated by the correlations between the $^{187}Os/^{188}Os$ ratios vs. the $^{187}Re/^{188}Os$ ratios and bulk Al_2O_3 contents (Fig. 10a, b). On the one hand, the Re-Os isotope system is relatively resistant to post-melting metasomatism and therefore preserves signatures of long-term mantle depletion (Liu et al., 2008; Rudnick and Walker, 2009). On the other hand, because the Re-Os system evolves over geological timescales, osmium isotopic compositions remain largely unaffected by recent melting events, whereas lithophile-element fertility indices, such as Al_2O_3, can be significantly modified by subsequent episodes of melt extraction. Consequently, the combined use of Os isotopes and fertility indicators provides a powerful means of distinguishing ancient melting events from more recent mantle depletion processes (Lassiter et al., 2014). In the correlation between $^{187}Os/^{188}Os$ and bulk Al_2O_3, the mantle peridotites in the YTO exhibit roughly three linear trends, with slopes becoming steeper from high to low Al_2O_3 contents (Fig. 10b). This feature indicates a shift in the Al-Os isochron, which is not uncommon for abyssal peridotites (Lassiter et al., 2014) and other ophiolitic mantle peridotites (Li et al., 2025a; Wang et al., 2023). The Al-Os isochron shift can be attributed to the multi-stage melting experienced by mantle peridotites, significantly affecting Al without similarly impacting Os. For abyssal peridotites, this shift is thought to be caused by recent melting beneath the mid-ocean ridge that overprints prior melt depletion events (Lassiter et al., 2014). A similar conclusion of multi-stage mantle melting has also been achieved by studies on Hf-Nd isotopes of MORB and abyssal peridotites (e.g., Sanfilippo et al., 2024; Sani et al., 2023; Stracke et al., 2011, 2019). In the case of ophiolitic peridotites, the melting history may involve more complex processes, including ancient melting, sub-ridge melting, and hydrous melting in a SSZ setting (Li et al., 2025a; Wang et al., 2023). In the context of tectonic evolution of the Neo-Tethys Ocean, we tentatively propose three stages of mantle melting events (Fig. 10b), that is, ancient melting dating back to ~2.2 Ga (the oldest T_{RD} age for the YTO peridotites; Xu et al., 2020), sub-ridge melting at the Neo-Tethyan mid-ocean ridge at ~130 Ma (the formation age of the YTO), and a rapid overprinting by hydrous melting in a forearc setting at ~125 Ma. This multi-stage mantle melting model can effectively explain the large compositional variations in the YTO mantle peridotites, which overlap those of abyssal and forearc peridotites (Fig. 2e-g; Fig. 10a-b).

HSE compositions provide additional insights into the melting history of mantle peridotites in the YTO. Due to their extremely high metal/silicate partition coefficients, HSE in the mantle, at least after the so-called "late-veneer hypothesis", are preferentially hosted in sulfides. In a simplified scenario, significant HSE fractionation in mantle peridotites is expected only under conditions of extensive mantle melting (>15-20%) or intense percolation of sulfide-bearing melts, both of which can substantially modify the abundance, composition, and behavior of mantle sulfides (Büchl et al., 2002; Liu et al., 2009; Lorand et al., 1999; Luguet and Reisberg, 2016; Xu and Liu, 2019). The HSE compositions of most YTO mantle peridotites are chondritic and comparable to that of the primitive upper mantle (PUM; Becker et al., 2006) (Fig. 10c, d). In contrast, some samples exhibit fractionated HSE compositions, displaying variable Re and depleted Pt and Pd with respect to the PUM (Fig. 10c). Meanwhile, the YTO mantle peridotites generally have PUM-like $(Pt/Pd)_N$ ratios, while the most refractory peridotites have elevated $(Pt/Pd)_N$ ratio. Such elevated $(Pt/Pd)_N$ ratios, commonly documented in the sub-arc mantle (including forearc peridotites and mantle wedge xenoliths), are attributed to the formation of Pt-Fe alloys during multi-stage mantle melting (Kepezhinskas and Defant, 2001; Xu and Liu, 2019). Although the $(Pt/Pd)_N$ ratios in the refractory YTO mantle peridotites is not as high as those in the sub-arc mantle, it implies that these samples must have experienced higher extents of mantle melting compared to other samples. Therefore, the HSE compositions reinforce our argument based on Os isotopes, indicating that the YTO mantle peridotites are products of multi-stage mantle melting and reflecting a highly heterogeneous mantle beneath the Neo-Tethyan mid-ocean ridge.

Ancient mantle domains responsible for the heterogeneity of Neo-Tethyan asthenosphere have been thoroughly explained as resulting from the recycling of continental (Gong et al., 2016; Griffin et al., 2016), sub-oceanic (Liu et al., 2019; Zhang et al., 2020a, b, 2023a), or subduction-modified peridotites (Liu et al., 2012). Similar hypotheses have also been proposed for the mantle peridotites along the entire Neo-Tethyan ophiolite belt (Liu et al., 2021c and references therein). The occurrence of portion of recycled mantle in the asthenosphere is a common feature at modern slow- and ultraslow-spreading ridges, where abyssal peridotites have been dated to >2.5 Ga (Harvey et al., 2006; Lin et al., 2024; Liu et al., 2008, 2022a; Sanfilippo et al., 2024; Sani et al., 2023; Stracke et al., 2011, 2019). This process would result in a common association of a thin oceanic crust with a highly heterogeneous mantle lithosphere (D'Errico et al., 2016; Zhou and Dick, 2013), highlighting the need for a careful examination of the mantle's nature to better understand the crust-mantle relations. Thin crust underlain by a highly heterogeneous mantle is also a typical feature in modern and fossil magma-poor OCT settings, such as the Iberia-Newfoundland in the North Atlantic Ocean and the Alpine Tethys (e.g., Manatschal et al., 2011; Müntener

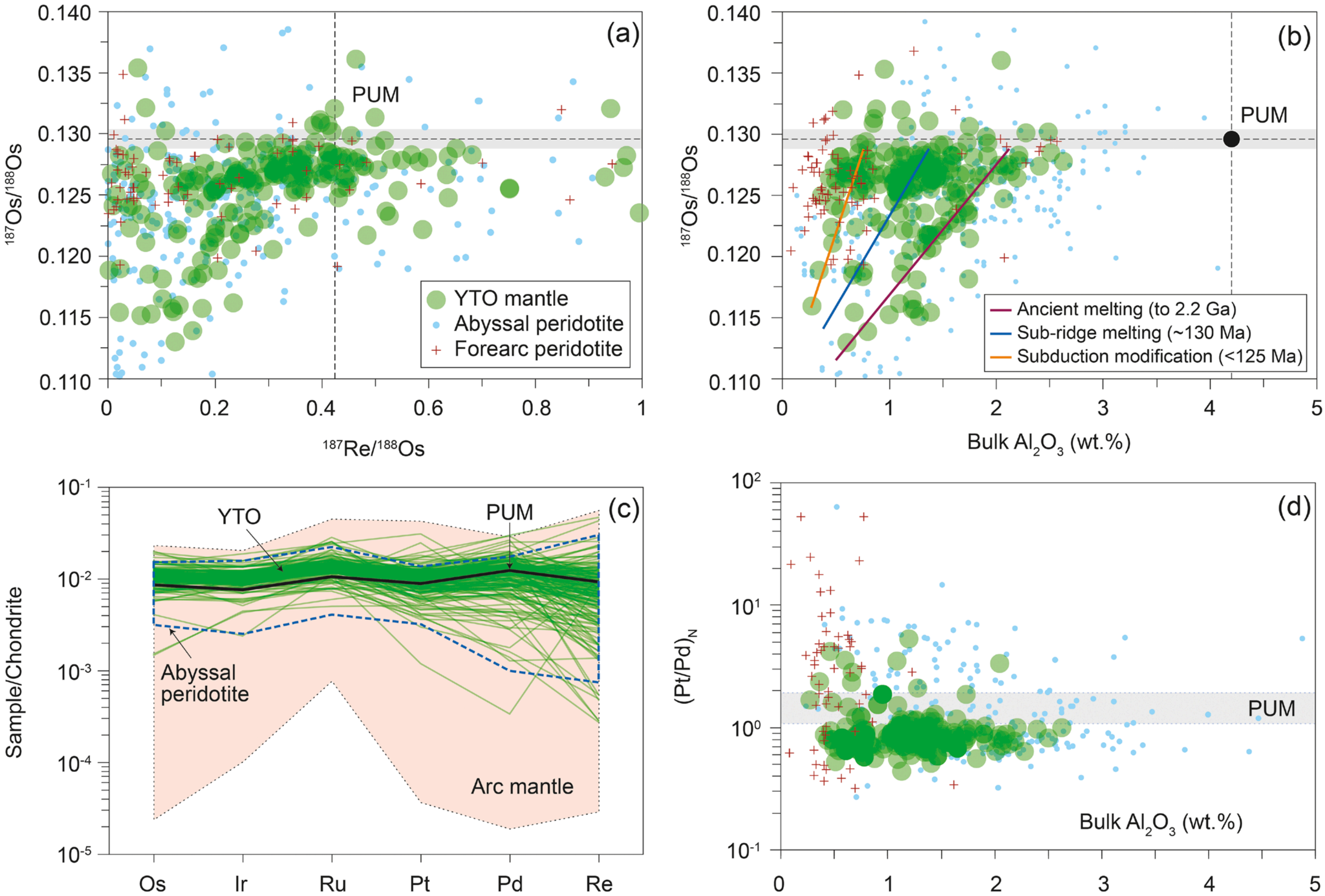

Fig. 10 - Re-Os isotopes and highly siderophile element (HSE) compositions for available data of the mantle peridotites within the YTO. Chondrite values for the normalization of HSE is after Fischer-Gödde et al. (2010). The composition of primitive upper mantle (PUM) is after Becker et al. (2006) and Meisel et al. (2001). Data for abyssal peridotites and forearc peridotites is from the PetDB database (https://search.earthchem.org/).

and Manatschal, 2006; Rampone and Hofmann, 2012; Rampone and Sanfilippo, 2021; Secchiari et al., 2025). Notably, the Alpine-Apennine ophiolites are suggested to contain abundant sub-continental lithospheric mantle (SCLM) that became stranded within the asthenosphere during continental rifting (McCarthy and Müntener, 2015; Rampone and Hofmann, 2012; Rampone and Sanfilippo, 2021). These features are quite similar to those of the YTO. However, there are fundamental distinctions between the Yarlung-Tsangpo Neo-Tethys Ocean and the Piemonte-Ligurian Ocean. The Yarlung-Tsangpo Neo-Tethys was a mature open ocean thousands-of-kilometers wide at the formation time of the YTO, that is, ~130-120 Ma, as evidenced by paleomagnetic data for the Indian and Asian continents (see Hu et al., 2016; Huang et al., 2024). The Yarlung-Tsangpo Neo-Tethys thus is different from the embryonic Piemonte-Ligurian Ocean but more resembles modern ultraslow-spreading open oceans, such as the Southwest Indian Ridge. Accordingly, the YTO should have formed in an ultraslow-spreading ridge, rather than an OCT setting like the Alpine-Apennine ophiolites.

Paradigm shift in understanding the YTO: new models for ophiolite conundrum

The origin of ultraslow-spreading ridges for the YTO and the identification of ancient mantle domains therein provide new insights into the tectonic setting for its formation. In the context of ultraslow seafloor spreading, the observed arc-like features can alternatively be attributed to two new models, rather than the subduction initiation rule typically applied to global SSZ-type ophiolites (Stern, 2004; Whattam and Stern, 2011).

One explanation for the arc-like geochemical signatures in the YTO involves the melting of ancient mantle domains within a heterogeneous asthenosphere under the ultraslow-spreading Neo-Tethyan mid-ocean ridge (Fig. 11a). These ancient peridotites are likely recycled SCLM, arc mantle, or ancient sub-oceanic mantle (e.g., Liu et al., 2021c). This model is supported by the occurrence of anomalous compositions documented in MORBs at modern slow- and ultraslow-spreading ridges. For instance, a refertilized SCLM is thought to have the potential to generate the Dupal isotope anomaly in MORBs observed in both the Southern Hemisphere (Kempton et al., 2002; Mahoney et al., 1992) and the Gakkel Ridge, Arctic Ocean (Goldstein et al., 2008). Moreover, the SCLM has long been recognized as a candidate source for generating enriched MORBs distant from mantle plumes (McKenzie and O'Nions, 1983; Yang et al., 2020), as well as the alkaline, K-rich basalts at the Southwest Indian Ridge and Mid-Atlantic Ridge (Nauret et al., 2011; Wang et al., 2020). In contrast, Urann et al. (2020) argued that recycled arc mantle may be widespread in the oceanic mantle, based on observations from a limited number of peridotites recovered from a section of the Mid-Atlantic Ridge. The widespread contamination of the asthenosphere by arc mantle can result in a hemisphere-scale upper mantle heterogeneity, generating BABB (back-arc

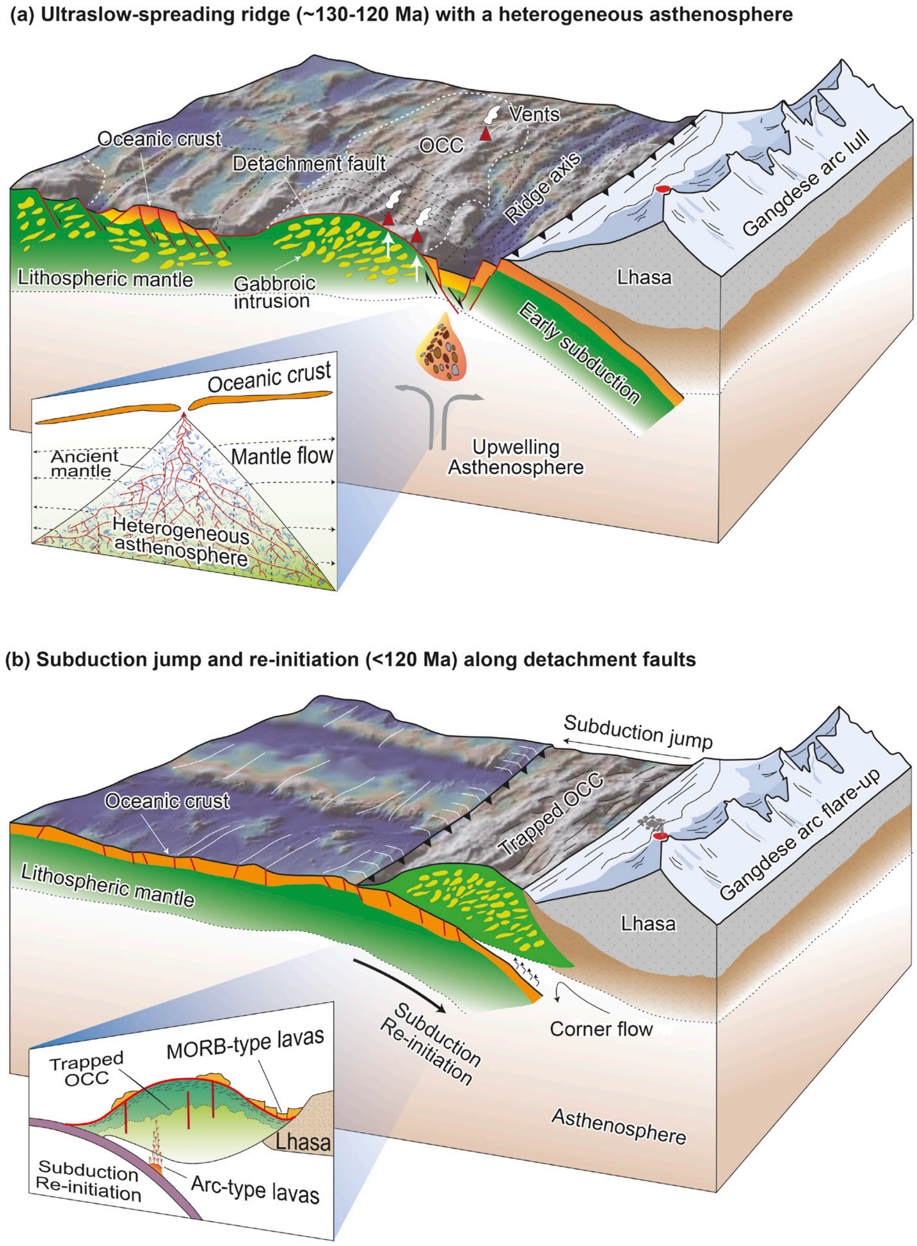

Fig. 11 - Two new conceptual models for alternative explanations of the YTO ophiolite conundrum. (a) Re-melting of the ancient mantle domains in the Neo-Tethyan heterogeneous asthenosphere at ~130-120 Ma (context of the melting regime is modified after Stracke, 2021); (b) Subduction jump and re-initiation along detachment faults of the Neo-Tethyan ultraslow-spreading ridge and subsequent overprinting of arc-like magmatism onto the previous MORB-like oceanic crusts (modified after Liu et al. (2022b), Ou et al. (2025), and Zhang et al. (2019)). See the text for details.

basin basalt)-like MORBs frequently encountered at global ocean ridges barring the Pacific Ocean as inferred for instance by Yang et al. (2021). It should be noted that these findings from modern ocean ridges do not imply that the pervasive occurrence of arc-like lavas in global ophiolites can be accounted for by the melting of recycled mantle in the asthenosphere. Nonetheless, it provides an additional perspective for studying certain ophiolites, suggesting that caution should be exercised when using basalts to discriminate the tectonic setting of ophiolites (Liu et al., 2021c).

The ophiolite conundrum of the YTO can also be elucidated by a subduction jump and re-initiation model proposed by recent studies on the Yarlung-Tsangpo metamorphic soles (Zhang et al., 2019). Metamorphic soles associated with ophiolites are widely regarded as geological indicators for subduction initiation (e.g., Wakabayashi and Dilek, 2003). It is shown that metamorphic soles along the YTS are compositionally similar to the magmatic crust of the YTO (e.g., Zhang et al., 2019). Their protolith and metamorphic ages are also coeval with the formation ages of ophiolites (Fig. 1c; Duan et al., 2022; Guilmette et al., 2009, 2012; Zhang et al., 2019, 2023b). These features thus suggest a rapid tectonic transition from an ultraslow-spreading ridge to a subduction zone (Duan et al., 2022; Liu et al., 2022b; Zhang et al., 2019, 2023b). A notable feature of slow- and ultraslow-spreading ridges is the highly heterogeneous crustal structures on the seafloor. It has been established that detachment and transform faults both can lead to significant exhumation of the mantle, forming topographic highs with respect to the ambient oceanic crust (Baines et al., 2003; Ligi et al., 2022), such as the Atlantis Bank, which was uplifted >3 km above adjacent seafloor (Baines et al., 2003). The subduction of such ocean ridges would result in a ridge-trench collision and the subsequent juxtaposition of oceanic core complexes at the continental margin (Fig. 11b; Liu et al., 2022b; Zhang et al., 2019). In such a scenario, a new subduction zone may re-initiate on the opposite side due to jump of the subduction front (Fig. 11b). Dehydration of the slab from this new subduction zone, along with the subsequent flux melting of the overlying mantle wedge (the fossil oceanic core complex), can generate arc-like magmatism superimposed on the pre-existing MORB-type oceanic crust. Such a model can also explain the rapid transition from mid-ocean ridge to subduction zone, during which the metamorphic soles were generated and had similar compositions and ages with the magmatic crusts of the YTO.

The aforementioned models provide a new perspective for resolving the long-standing debate regarding the tectonic setting of the YTO. Many geological and geochemical features of the YTO can be more effectively explained in the context of ultraslow seafloor spreading and its subsequent evolution, rather than simply relying on the previously accepted model of subduction initiation. This insight has the potential to lead to a paradigm shift in our understanding of this renowned, extensively studied ophiolite belt. Moreover, the YTO is not an isolated case, because slow- and ultraslow-spreading oceanic lithospheres, as described in the Chapman model, are likely to be prevalent within global ophiolites, particularly those associated with the Neo-Tethys extending from the Alps to Southeast Asia (Liu et al., 2024). Therefore, comparative studies with modern slow- and ultraslow-spreading ridges should emerge as a new area of research, paving the way for a transformative shift in our knowledge of global ophiolites from the Penrose model to Chapman model.

CONCLUDING REMARKS

The understanding of ophiolites has been significantly reshaped since the pioneering work that innovatively linked ophiolites to island arcs (Miyashiro, 1973). This marked a paradigm shift, positioning ophiolites as geological records for subduction initiation, rather than products of seafloor spreading at mid-ocean ridges. If this hypothesis is valid, it means that the vast oceans that existed in Earth's geological history have completely subducted back into the deep mantle. However, the notion of a SSZ origin for ophiolites has been called into question, as it is suggested that MORB can display arc-like geochemical signatures. The key to resolving this issue lies in a comprehensive understanding of the underlying mantle. The extent and heterogeneity of mantle depletion serve as critical factors that modulate the thickness, composition, and characteristics of oceanic crusts. This knowledge, obtained from studies of modern slow- and ultraslow-spreading ridges, should be applied to ophiolite research, to identify those that may have formed under similar conditions. Ophiolites, in turn, are valuable supplements for the study of oceanic lithospheres at modern ocean ridges, as they typically provide continuous observations of lithology, composition, and structures of oceanic lithospheres.

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