Forearc hyperextension dismembered the south Tibetan ophiolites

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ABSTRACT

Suprasubduction zone ophiolites are relics of oceanic upper plate forearcs and are typically preserved as discontinuous belts with discrete massifs along suture zones. Ophiolites usually contain an incomplete condensed section compared to average modern oceanic lithosphere. The incompleteness and discontinuity of ophiolites are frequently attributed to dismemberment, but tectonic causes remain poorly constrained. Here we show new paleomagnetic and field geological evidence for the preservation of extensional detachment faults that thinned and dismembered the south Tibetan ophiolite belt during the Early Cretaceous. Similar to those documented in modern slow- and ultraslow-spreading ridges, these detachments exhumed lithospheric mantle, and subophiolitic mélange, to the seafloor, which became unconformably covered by Asia-derived forearc strata. We call this mechanism forearc hyperextension, whereby widespread detachment faults accommodate upper plate extension above a subduction zone. We propose that hyperextension is the key mechanism responsible for dismemberment of the south Tibetan ophiolitic belt shortly after its magmatic accretion.

INTRODUCTION

Ophiolites expose oceanic lithosphere, frequently thrust as long and discontinuous belts onto continental margins (Dewey, 1976). Ophiolites have been instrumental in our interpretation of mid-ocean ridge processes (Moores, 1982). Unlike in situ oceanic lithosphere, however, most ophiolites show a condensed pseudostratigraphy dominated by mantle rocks overlain by a thin or even absent crust. Most ophiolites formed by spreading above a subduction zone (suprasubduction zone ophiolites; Pearce et al., 1984). Understanding the causes of ophiolite attenuation and dismemberment is thus essential to assess to what extent they may serve as proxies for typical mid-ocean ridge processes.

Reduced thicknesses of the >2000-km-long south Tibetan ophiolite belt were previously ascribed to stretching of an originally thin, slow-spreading oceanic lithosphere, with mantle units rising diapirically from depth (Nicolas, 1981; Girardeau et al., 1985). Since then, it was discovered that ultraslow-spreading ridges can expose upper mantle rocks in the footwalls of extensional detachment faults (e.g., Smith et al., 2006). Detachment activity results in substantial rotation of their footwalls, which can be identified with paleomagnetic techniques (Garcés and Gee, 2007; Morris et al., 2009; MacLeod et al., 2011; Maffione et al., 2013). Using paleomagnetism, petrography, and field geology at two exposures of south Tibetan ophiolites, we test whether their dismemberment occurred along detachment faults. We discuss possible roles of such faults in the evolution of the Cretaceous forearc developed at the southern margin of Eurasia during northward subduction of Neo-Tethys oceanic lithosphere.

SOUTH TIBETAN OPHIOLITES

The south Tibetan ophiolites are relics of lower Cretaceous oceanic lithosphere formed above a subduction zone within the Neo-Tethys (Hébert et al., 2012). They expose 1–3-km-thick mantle sequences, scarce gabbros, and locally as much as ~500 m of upper crustal pillow basalts and dolerites (Nicolas, 1981). The ophiolites are covered by radiolarian cherts with ages (123–117 Ma; Ziabrev et al., 2003) comparable to those of the ophiolitic crust (128–123 Ma) (Malpas et al., 2003; Dai et al., 2013). The ophiolite overlies a mélange containing garnet amphibolites with $^{40}Ar/^{39}Ar$ cooling ages of 132–127 Ma (Guilmette et al., 2012).

The ophiolites are overlain by ~8-km-thick Asia-derived mudstone and turbiditic sandstone sequences (Xigaze Group) deposited since at least the Aptian (130–125 Ma) in the forearc between the Gangdese magmatic arc and the associated trench (Wang et al., 2012; Huang et al., 2015). The forearc strata locally either interfinger with the epi-ophiolitic cherts (Wang et al., 2012), or unconformably cover mantle peridotites and mélange (Huang et al., 2015). Paleolatitude determinations for the lowermost lower Cretaceous forearc strata (16.5°N ± 0.3°; Huang et al., 2015) and coeval Gangdese arc rocks from the southern Lhasa terrane (15.1°N ± 1.3°; Yang et al., 2015) may suggest post–Early Cretaceous convergence between the ophiolites and southern Tibet, but the distinction between measured paleolatitudes is not statistically significant.

OCEANIC DETACHMENT FAULTS IN THE SOUTH TIBETAN OPHIOLITES?

At several locations, the Xigaze Group is in direct contact with highly sheared ophiolitic mantle, or mélange (Fig. 1A). The Sangsang area exposes serpentinized harzburgites intruded by doleritic dikes overlying an ophiolitic mélange (Fig. 1B) (Bédard et al., 2009). The ophiolite is cut by a major, approximately northeast-striking, high-angle fault that does not cut India-affinity Tethyan Himalayan strata structurally below, or the Xigaze Group, suggesting that faulting predated forearc sedimentation. The topmost 500 m of the ophiolitic sequence consists of intensely sheared serpentinites unconformably covered by the oldest forearc strata with a maximum depositional age of 128.8 ± 3.4 Ma (Huang et al., 2015) (Fig. 1B; Fig. DR1 in the GSA Data Repository[1]). The forearc strata are unmetamorphosed, weakly deformed turbiditic sandstones with a steep bedding (strike, dip = 265°, 76°N) that is subparallel to the unconformity (strike, dip = 253°, 80°N; Fig. DR1). The lack of radiolarian cherts, observed elsewhere at the base of the Xigaze Group, may be attributed to spatially variable paleoenvironmental conditions. These age, stratigraphic, and structural constraints suggest that at Sangsang, mantle was exhumed to the seafloor and unconformably covered by forearc deposits.

The Qunrang ophiolite (Fig. 1C) exposes mainly serpentinized peridotites and minor gabbros (Hébert et al., 2012), with <500-m-thick upper crustal lavas and sheeted sills (Nicolas, 1981; Girardeau et al., 1985) and ca. 123 Ma radiolarian cherts (Ziabrev et al., 2003). In the study area, serpentinites hosting 10–50 m gabbro pods are in fault contact with sheeted sills. The intervening fault (strike, dip = 220°, 85°N; Fig. DR2a) exposes amphibole-rich rocks that probably resulted from deformation under hydrous, relatively high temperature conditions. To the north, the fault is buried beneath overturned (strike, dip = 085°, 80°N) strata of the Xigaze Group (Fig. 1C; Fig. DR2b), indicating that the ophiolite underwent faulting, which cut out part of the lower crust before forearc basin

[1]GSA Data Repository item 2015167, methods, Table DR1, and Figures DR1–DR7, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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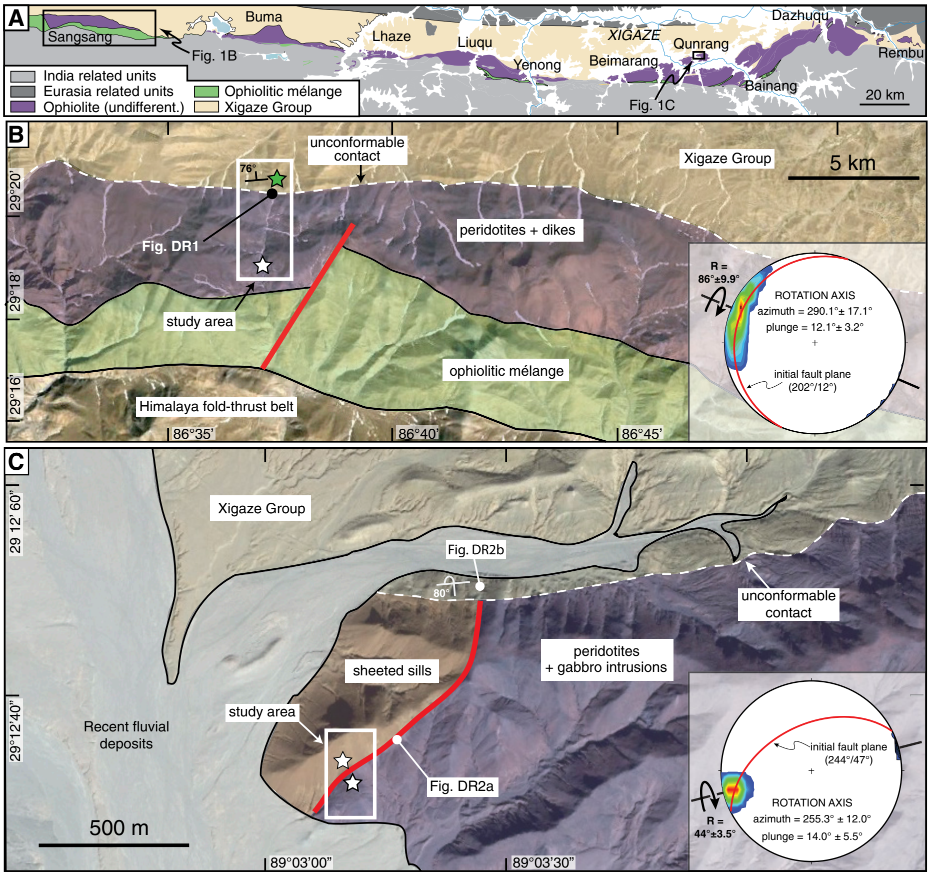

Figure 1. A: Simplified geological map of the eastern south Tibetan ophiolite belt (after Yin and Harrison, 2000); locations of B and C are indicated. B: Detailed geological map of the Sangsang ophiolite (after Wang et al., 1984). Red line is fault; symbol indicates strike and dip. White star is sampling locality (29°19′4.80″N, 86°37′12.36″E). Green star is sampling site of Huang et al. (2015). C: Detailed geological map of the Qunrang ophiolite (after Pan et al., 2004). White stars are sampling localities (gabbros, 29°12′29.43″N, 89°3′11.20″E; sills, 29°12′30.73″N, 89°3′10.62″E). Stereonets in B and C show the reconstructed initial fault planes and associated rotation axes with relative rotation magnitude (R). Contours of the 500 permissible rotation axes solutions are also shown.

deposition. The occurrence of radiolarian cherts at the base of the Xigaze Group here (Fig. DR2b) confirms the regionally documented (Wang et al., 2012; Huang et al., 2015) unconformable contact between this unit and the ophiolite.

Stratigraphic and age constraints from Sangsang and Qunrang suggest that the ophiolite underwent attenuation and mantle denudation within an oceanic environment before or during forearc sedimentation. In analogy with similar processes operating at modern slow-spreading ridges, producing mantle uplift to the seafloor (e.g., Smith et al., 2006), disruption of the south Tibetan ophiolites may have been caused by extension along detachment faults. To further test this, we performed paleomagnetic analyses.

METHODS AND RESULTS

Whereas oceanic detachments are characterized by brittle fault rocks with greenschist facies mineralogical assemblages (serpentine, chlorite, prehnite, talc, and tremolite; e.g., Escartín et al., 2003), not all such fault zones are detachments. A critical test for the presence of detachments is establishing whether horizontal axis tectonic rotations of the fault footwall occurred (Garcés and Gee, 2007; Morris et al., 2009; MacLeod et al., 2011). We therefore used paleomagnetism, integrated with rock magnetic experiments and petrographic observations on polished thin sections [scanning electron microscopy (SEM) coupled with energy-dispersive X-ray (EDX) elemental analysis], to analyze the kinematics of the faults cutting the ophiolite and to test for the existence of oceanic detachments (for a description of the methods, see the Data Repository).

In the Sangsang ophiolite, 96 paleomagnetic cores were collected at 7 sites within mantle-hosted mafic dikes (Fig. 1B). In the Qunrang ophiolite, 58 and 73 cores were collected from the sheeted sills (1 site) and the mantle-hosted gabbros (4 sites), respectively (Fig. 1C; Table DR1; see the Data Repository). From the Sangsang dikes, 81 well-resolved characteristic remanent magnetization (ChRM) directions were isolated at 520–570 °C and alternating fields (AF) of 25–100 mT (Fig. DR3). At Qunrang, stable ChRMs were isolated at 520–600 °C and AF of 15–70 mT (Fig. DR3). Mean paleomagnetic poles were calculated for the Sangsang dikes (declination/inclination, D/I = 328.4°/28.9°, α_{95} = 4.8°), and Qunrang gabbros (D/I = 197.3°/25.3°, α_{95} = 4.2°) and sills (D/I = 151.8°/27.8°, α_{95} = 5.7°) (Fig. DR4; Table DR1).

Diffuse chlorite and prehnite within a weathered, isotropic, clinopyroxene- and plagioclase-rich matrix was identified in all studied thin sections (Fig. DR5), indicating mild greenschist facies metamorphism. These mineralogical assemblages and structures are typical of low-temperature (200–400 °C) seafloor hydrothermal alteration. SEM observations coupled with EDX analyses recognized discrete, 1–100 µm, magmatic titanomagnetite crystals homogeneously dispersed within the rock matrix, and occasionally showing Ca-rich alteration rims that may relate to mild low-temperature alteration (rodingitization) (Fig. DR6). These observations exclude major secondary magnetic mineral growth after initial cooling below the Curie temperature.

ROTATION ANALYSIS

Reliable paleomagnetic analyses require that the remanence of the rock was not reset after cooling below the Curie temperature of their carriers. This is likely in our rocks because (1) remanence carriers characterized by high Curie temperatures (~580 °C) are stable during greenschist seafloor metamorphism (possible thermoviscous secondary magnetizations acquired at this stage would be parallel to the primary components); (2) the in-situ ChRM directions do not resemble the present-day field (Fig. DR4); (3) paleosecular variation is adequately represented in all data sets (Fig. DR4) (the elongated ChRM distribution of the Qunrang sills may be related to minor folding, not dramatically affecting the reliability of the mean value); and (4) magnetic minerals are fresh and dispersed within the rock matrix, indicating a primary magmatic origin.

An in situ inclination shallowing–corrected mean paleomagnetic direction was recalculated for the Xigaze Group at the Sangsang area (Fig. 1B) by applying the local deformation (strike, dip = 265°, 76°N) to the predeformation and inclination shallowing-corrected direction (D/I = 351°/30.2°; α_{95} = 3.5°; computed by Huang et al., 2015). The obtained value (D/I = 186.8°/72.9°) differs from the mean in situ remanence of the Sangsang dikes (Fig. DR4), and indicates relative rotation of the two units. Similarly, at the Qunrang area the statistically different in situ mean directions of the gabbros and sheeted sills (Fig. DR4) can be explained by relative rotation of the two units across the intervening fault.

Analyzing the kinematics of these rotations requires definition of the rotation axes (azimuth, plunge, and magnitude of rotation) that bring the remanence vector of the fixed block toward the one of the rotated block. Without additional constraints, infinite solutions exist for the rotation axes that displace the two vectors, defining a locus that forms the great circle bisectrix of them (Fig. DR7). For simple coaxial deformations where the rotation axes are in the fault plane, a unique solution for the rotation pole is given by the intersection of the fault plane and the great circle bisectrix. To model the uncertainties associated to the remanence directions (α_{95}), and the potential for more complex, noncoaxial deformations, we adopted a Monte Carlo approach (see the Data Repository).

In the Sangsang ophiolite, we constrained the rotation axis to be parallel to the unconformity above the ophiolite, interpreting this plane as the flat-lying detachment fault (or a secondary plane parallel to it) that exposed the peridotites to the seafloor. The in situ solutions of the fault kinematic analysis indicated that the ophiolite underwent 86° ± 9.9° of rotation around an approximately west-southwestward, shallowly plunging (~20°) rotation axis (Fig. DR7b). In Qunrang, our results revealed 44° ± 3.5° of rotation of the mantle units with respect to the crustal sequence around a subvertical axis (Fig. DR7g). The original rotation poles, corrected for the local deformation (Figs. 1B and 1C; Fig. DR7; also see the Data Repository), are subhorizontal (12°–14°) and approximately east-west trending (255°–290°), and producing an approximately southward tilt (counterclockwise rotation looking in the direction of the axis azimuth) of the ophiolite's mantle sections. The original faults (corrected for the local deformation) accommodating these rotations were subhorizontal at Sangsang (strike, dip = 201°, 12°) and approximately east-west–striking (strike, dip = 243°, 43°) in Qunrang (Figs. 1B and 1C; Fig. DR7).

FOREARC HYPEREXTENSION MODEL

Field analyses from the Sangsang and Qunrang ophiolite (Fig. 1) have documented the presence of major faults active before deposition of the Xigaze Group (i.e., before 125–120 Ma). Our kinematic analysis revealed substantial subhorizontal axis rotations along approximately east-west–striking faults, producing southward tilt of the analyzed mantle sequences (Fig. DR7). The fault rotations documented in the south Tibetan ophiolites are comparable with those associated with oceanic detachment faults, where unloading and uplift of the detachment footwalls result in a progressive rollover and flattening of the exhumed fault plane around subhorizontal axes (Morris et al., 2009; MacLeod et al., 2011). This suggests that the south Tibetan ophiolites were cut along detachments, which resulted in rotated mantle portions exposed on the seafloor, and lithospheric attenuation associated with at least tens of kilometers of extension. The thin crust of the ophiolites has long been suggested to reflect slow spreading (Nicolas, 1981), and the detachments recognized in this study, as well as in the Purang ophiolite further west (Liu et al., 2014), are consistent with this inference.

Our results show that magmatic activity that produced the thin ophiolitic crust was followed by a phase of north-south "tectonic spreading," accommodated by approximately east-west–striking detachment faults (subparallel to the preexisting spreading axis), thinning and dismembering the ophiolites during the Early Cretaceous (Fig. 2). We term this process forearc hyperextension, i.e., pervasive stretching and detachment faulting in the upper plate at a magma-starved forearc spreading center due to slow spreading, but perhaps also due to ultradepletion of the mantle wedge below the forearc.

Although significant Cenozoic deformation affected the suture zone of south Tibet (e.g., Burg and Chen, 1984), in many places leading to thrusting of the ophiolite over the Xigaze Group, in our study areas the primary stratigraphic contacts between the forearc strata and the ophiolite are preserved. While the ophiolites were likely further disrupted during obduction and subsequent India-Asia collision, our study provides evidence for their primary dismemberment via detachment faults prior to deposition of the Xigaze Group. Possible analogues are the Izu-Bonin-Mariana (Ishizuka et al., 2011), Tonga (Bloomer and Fisher, 1987), and South Sandwich (Pearce et al., 2000) forearcs, where mantle peridotites are widely exposed at the inner trench walls. Forearc hyperextension can begin shortly after subduction initiation, as may be the case in our study area: mélanges below the south Tibetan ophiolites contain garnet amphibolites with 132–127 Ma $^{40}Ar/^{39}Ar$ ages, which are interpreted to date subduction initiation (Guilmette et al., 2012). Forearc hyperextension may, however, continue during mature subduction, e.g., at the Sumatran arc (McCaffrey, 1991). Ophiolite dismemberment is a process that is intrinsically related to the dynamics that created suprasubduction zone ocean floor, therefore in an extensional setting, well before their emplacement onto continental margins. The causes of forearc hyperextension may be slow spreading, or perhaps relate to ultradepletion of the forearc mantle wedge, and need to be taken into account when studying ophiolites as analogues of lithosphere generated at mid-ocean ridges.

Our study has important implications for tectonic scenarios explaining ultrahigh-pressure metamorphic minerals in the Luobusa ophiolite, which may come from as deep as the upper-lower mantle transition zone (e.g., Xu et al., 2015). To explain the occurrence of such minerals in an intraoceanic setting, Xiong et al. (2015) invoked the interaction between a plume rising below a spreading ridge along which subduction started, all within a short time span. Huang et al. (2015), however, showed that the south Tibetan ophiolites formed proximal to the Lhasa terrane instead of far offshore. This study shows that hyperextension played a key role in ophiolite formation, with only minor melting involved. These constraints open the possibility that the ophiolites may represent subcontinental mantle

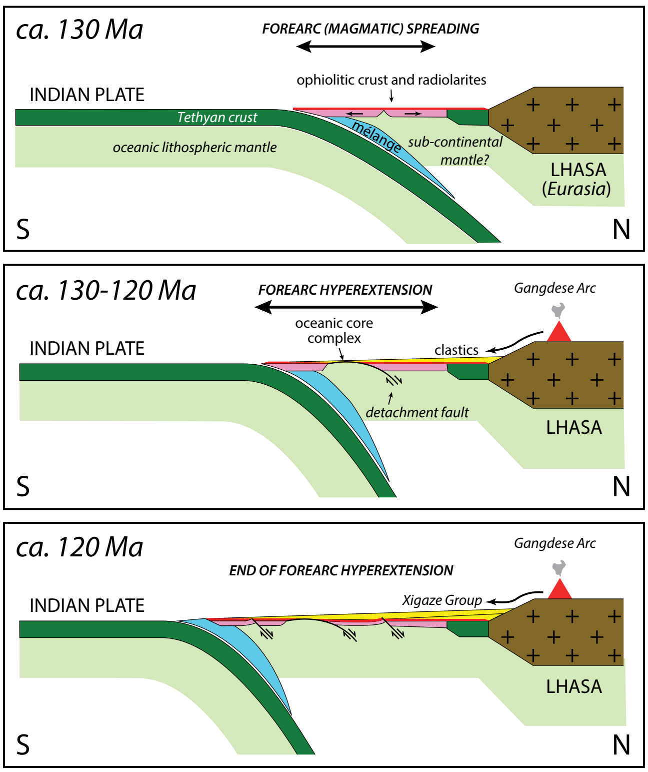

Figure 2. Schematic model (not to scale, not balanced) for forearc hyperextension in the south Tibetan ophiolites. The main extensional phase in the forearc occurred at 130–120 Ma, synchronous with the initial input of the Xigaze Group forearc sediments. This caused detachment faulting, crustal attenuation, and mantle uplift to the seafloor. Forearc hyperextension stopped ca. 120 Ma, and was followed by continuous sedimentation of the Xigaze Group, which unconformably covered the dismembered ophiolite. The dynamics of the subducting slab during forearc hyperextension did not affect the magmatic activity at the Gangdese arc, which persisted from the Early Cretaceous until the Eocene.

of the Lhasa terrane. If correct, the exhumation of the Luobusa ultrahigh-pressure minerals to lithospheric depths through plume activity (Xiong et al., 2015) may have long predated their incorporation into the south Tibetan ophiolites.

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