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Imbricate structure of the Luobusa Ophiolite and surrounding rock units, southern Tibet

Hiroshi Yamamoto [a,*], Shinji Yamamoto [b], Yoshiyuki Kaneko [c], Masaru Terabayashi [d], Tsuyoshi Komiya [b], Ikuo Katayama [b,1], Tsuyoshi Iizuka [b]

[a] *Department of Earth and Environmental Sciences, Kagoshima University, Kagoshima 890-0065, Japan*
[b] *Department of Earth and Planetary Science, Tokyo Institute of Technology, Meguro, Tokyo 152-8851, Japan*
[c] *Graduate School of Environment and Information Sciences, Yokohama National University, Yokohama 240-8501, Japan*
[d] *Department of Safety Systems Construction Engineering, Kagawa University, Takamatsu 761-0396, Japan*

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Abstract

The Cretaceous Luobusa Ophiolite is a tectonic slice less than 1.2 km thick. The structurally underlying unit is the Tertiary Luobusa Formation and the overlying unit is composed of feebly metamorphosed Triassic sedimentary rocks. The top and bottom contacts of the ophiolite dip gently to the south. The major part of the Luobusa Ophiolite is mantle peridotite, including podiform chromitite. This chromitite has received much attention because it contains an 'unusual mineral assemblage' which includes diamond and moissanite. A serpentinite mélange zone, including clasts of basaltic and sedimentary rocks, occurs underneath the mantle peridotite. Mesoscopic–microscopic structures were observed in the sheared rocks. Shear-indicating structures (C′-type shear bands and σ-type porphyroclasts) in the rocks near the top and bottom boundaries of the Luobusa Ophiolite show consistent top-to-the-north (or northeast) reverse displacement. The results reveal that the Luobusa Ophiolite was overturned and intercalated into an imbricate structure. The thrust faults on the top and bottom of the ophiolite can be correlated with north-vergent back-thrusting which was associated with crustal shortening along the Main Central Thrust due to the continued northward movement of India, after the welding of India to Asia.

Keywords: Ophiolite; Emplacement; Structure; Shear zone; Tibet

1. Introduction

The Indus-Yarlung Zangbo suture zone (IYSZ) separates the Indian subcontinent from the Lhasa Terrane (e.g. Allègre et al., 1984). Ophiolite sequences of Cretaceous age lie along the IYSZ, and radiolarian chert gives an age of 120 ± 10 Ma (Ziabrev et al., 2003). A large ophiolite sequence, called the Luobusa Ophiolite is located in southern Tibet, about 200 km east-southeast of Lhasa. The ophiolite extends 43 km east-west, and its total extent is about 70 km^2 (Zhou et al., 1996). The Luobusa Ophiolite is composed mainly of mantle peridotite (harzburgite), a mélange zone and an intercalated transition zone. Podiform bodies of chromitite are sporadically distributed in the harzburgite (Zhou et al., 1996). The podiform chromitite has received much attention because it contains an 'unusual mineral assemblage' including ultra-high pressure (UHP) minerals such as diamond and moissanite, as well as a number of reduced phases such as graphite, chromium, gold, nickel, copper and silicon (Bai et al., 1993, 2002; Yamamoto et al., 2003). Previous studies of the Luobusa Ophiolite have concentrated on the petrology and mineralogy of the mantle peridotite. However, the mechanism by which the mantle peridotite was emplaced has not been made clear. The difficulty in tectonic interpretation arises from the limited amount of structural data. In this study we analyzed deformation

* Corresponding author. Tel.: +81 99 285 8130; fax: +81 99 259 4720.
E-mail address: hyam@sci.kagoshima-u.ac.jp (H. Yamamoto).
[1] Present address: Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New Haven, CT 06511, USA.

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structures in the boundary zones of the ophiolite to decipher the emplacement process of the Luobusa Ophiolite through the suturing of Asia and India.

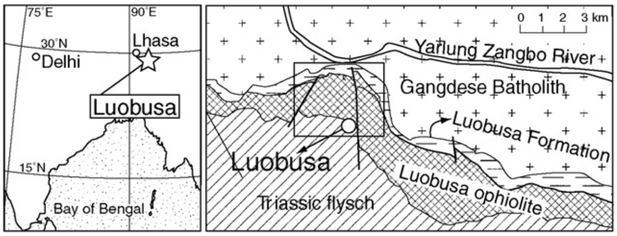

Fig. 1. Left: Index map showing the location of Luobusa. Right: Regional setting of the Luobusa Ophiolite. Lithotectonic boundaries are adopted from Zhou et al. (1996).

2. Geological setting

Rocks within the IYSZ are subdivided into several tectonic terranes (Aitchison et al., 2000). The Luobusa Ophiolite (Fig. 1) is assigned to the Dazhuqu Terrane. The ophiolite sequence of the Dazhuqu Terrane is regarded as having been derived from the fore-arc of a Late Jurassic to Cretaceous intra-oceanic magmatic arc which is represented by the Zedong Terrane (Aitchison et al., 2000; McDermid et al., 2002; Ziabrev et al., 2004).

The Luobusa Ophiolite sequence is composed of a mantle sequence, a mélange zone and an ultramafic transition zone, partly intercalated with the mélange zone (Fig. 2). The ophiolite is limited by fault contacts. The northern edge of Luobusa Ophiolite in the study area has a fault

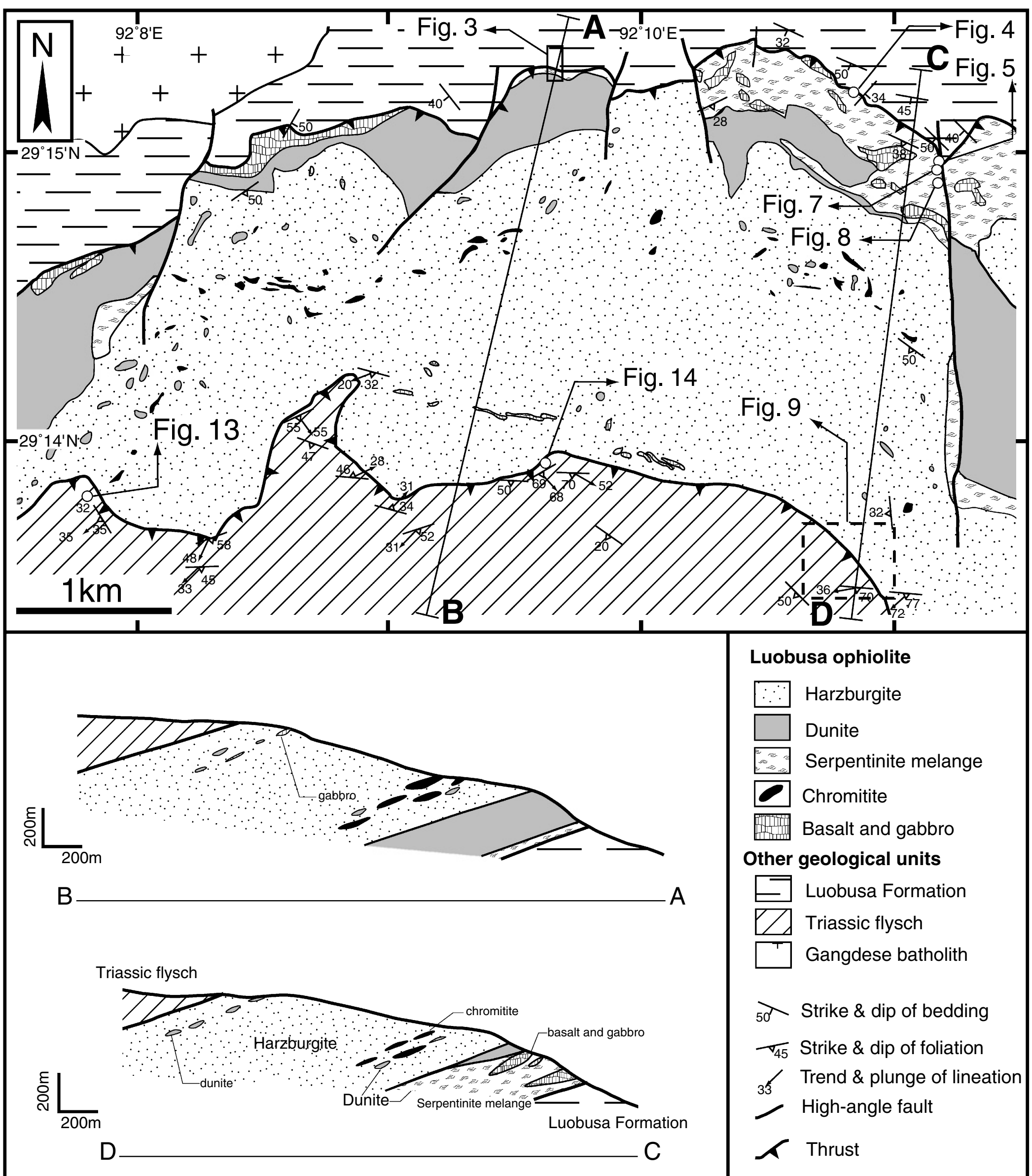

Fig. 2. Geological map and cross-sections of the Luobusa Ophiolite with the adjacent geological units. Geological boundaries are generally adopted from Zhou et al. (1996) and partly modified by the results of our field survey in 2001.

contact with the molasse-type Tertiary Luobusa Formation (Zhou et al., 1996). To the south, Triassic flysch-type sedimentary rocks (Bai et al., 1993) structurally overlie the ophiolite sequence with a fault contact. This fault can be correlated with the Renbu-Zedong Thrust seen elsewhere on the southern margin of Tibet (e.g. Heim and Gansser, 1939; Yin et al., 1994, 1999).The northern (bottom) and the southern (top) boundaries of the ophiolite dip gently to the south (Fig. 2).

A serpentinite mélange zone, which lies along the northern margin of ophiolite sequence, forms the structural base of the Luobusa Ophiolite (Fig. 2). The serpentinite mélange contains clasts of pyroxenite, gabbroic rocks, basaltic pillow lava, volcanic breccia, chert, marble and shale. These rocks occur as blocks and lenses in a partly serpentinized ultramafic matrix. Individual lithologies are irregularly distributed, and the serpentinite matrix is intensely deformed. An ultramafic transition zone overlies the serpentinite mélange zone. This zone is composed mainly of dunite, locally grading into wehrlite (Zhou et al., 1996), intercalated with serpentinite in places. The mantle sequence overlies the transition zone. The mantle sequence consists of harzburgite, diopsidic harzburgite, chromitite, dunite and gabbro. Many pod-shaped bodies of chromitite (10–50 m long) are distributed within the harzburgite. Harzburgite with dunite–gabbro lenses lies in the structurally upper part of the Luobusa Ophiolite.

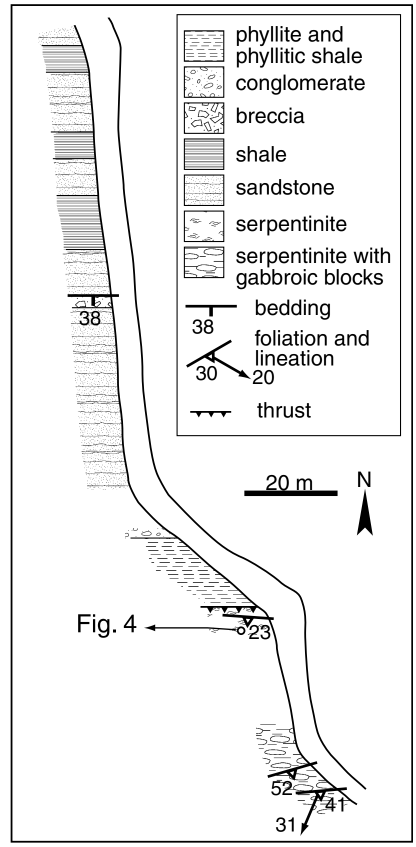

Fig. 3. Route map along road sections through the boundary between Luobusa Formation and Luobusa Ophiolite. See Fig. 2 for location.

3. Lower boundary

The northern border of the Luobusa Ophiolite extends along a fault contact between the serpentinite mélange and sedimentary rocks of the Luobusa Formation. This border corresponds to the structural base of the ophiolite sequence. We found exposures of the boundary zone at three locations. Fig. 3 shows representative strata of the Luobusa Formation near to this boundary. Those are composed of layers of conglomerate, breccia, sandstone, shale and phyllite. The sandstone is medium- to coarse-grained wacke and is generally interbedded with shale. The layers of conglomerate and breccia are composed of poorly sorted (cobble to pebble) clasts of granitic rock, felsic gneiss, mafic volcanic rock, felsic volcanic rock and chert in the matrix of medium- to coarse-grained sand. These layers generally strike east-west and dip moderately to the south. Scaly cleavage occurs in the strata of the Luobusa Formation. The cleavage is composed of minute crystals of sericite and chlorite.

The rocks near to the structural top of the Luobusa Formation grade into phyllitic shale and phyllite with increasing the density of cleavage. In Fig. 3 from the fault contact with the serpentinite the phyllite (or phyllitic shale) is about 9 m thick. Along the boundary between the Luobusa Ophiolite and the Luobusa Formation the thickness of the phyllite and phyllitic shale varies laterally from 1 to 20 m. The attitude of the cleavage in the phyllite is subparallel to the fault contact with serpentinite. Serpentinite of the Luobusa Ophiolite lies on the phyllite of the Luobusa Formation with a zone of sheared serpentinite along the contact. The serpentinite is well foliated in this zone defined by the subparallel alignment of flaky serpentine. Mesoscopic structure of sheared serpentinite was observed on an outcrop surface which was nearly perpendicular to the foliation and nearly parallel to the lineation. Sets of subparallel shear bands and minor shear zones are distributed within the foliated serpentinite (Fig. 4). The shear

Fig. 4. Sheared serpentinite on the hanging wall of the boundary thrust between Luobusa Ophiolite and Luobusa Formation. The attitude of foliation is N60°E, 30°S. Broken lines indicate C′-type shear bands (N53°W, 25°N) suggesting top-to-the-north displacement. See Fig. 2 for location.

bands are oblique to the foliation and are regarded as 'C′-type shear bands' (Berthé et al., 1979; Lister and Snoke, 1984; Passchier and Trouw, 1996). Monoclinic symmetry of the combination of the foliation and the shear bands indicates sense-of-shear (Simpson and Schmid, 1983; White et al., 1986). Shear bands (C′) located several meters from the contact with the Luobusa Formation indicate top-to-the-north displacement (Figs. 3 and 4).

Fig. 5 shows a south-dipping fault which separates the Luobusa Ophiolite from the Luobusa Formation. The strata of the Luobusa Formation consist of layers of conglomeratic sandstone, sandstone, shale (in reddish color) and phyllite on the structural top. These layers generally strike NE and dip gently or moderately to the SE. The hanging wall of the fault consists of sheared serpentinite of the Luobusa Ophiolite. The sheared serpentinite is well foliated and the attitude of foliation is concordant with the attitude of cleavage in phyllite of the Luobusa Formation.

Fig. 6 shows another occurrence of south-dipping fault separating the Luobusa Ophiolite from the Luobusa Formation. The strata of the Luobusa Formation consist of layers of sandstone, shale (partly in reddish color) with phyllitic shale at the structural top. In this location a direct contact between the Luobusa Ophiolite and the Luobusa Formation is not exposed. The hanging wall of the fault consists of serpentinite of the Luobusa Ophiolite. A basalt layer structurally overlies the serpentinite and serpentinite enclosing basaltic blocks overlies the basalt layer structurally.

Minor shear zones are sporadically distributed in serpentinite mélange near to the base of Luobusa Ophiolite. Shear bands (C′) in foliated serpentinite were observed on outcrop surfaces nearly perpendicular to the foliation and nearly parallel to the lineation at two separate locations in the northeastern part of the study area. Fig. 7 shows C′-type

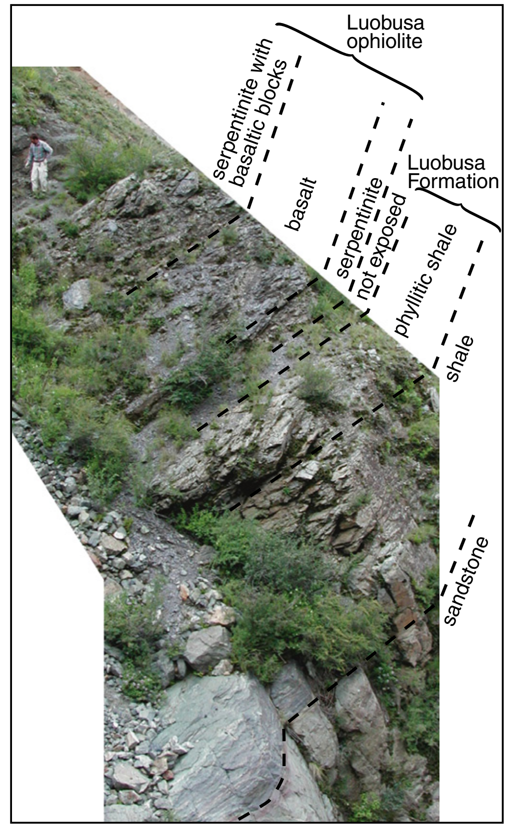

Fig. 6. Photograph of an exposure of the boundary zone between the Luobusa Formation and the Luobusa Ophiolite. See Fig. 2 for location.

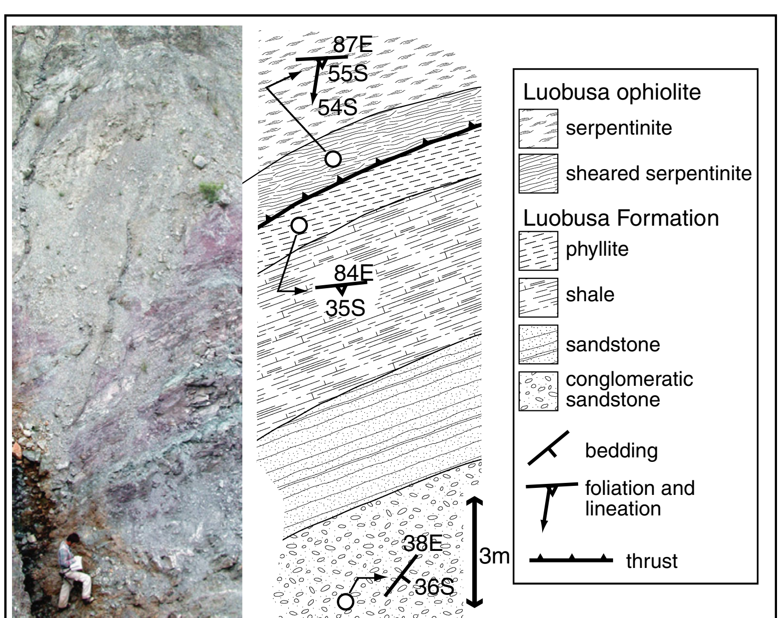

Fig. 5. Left: Photograph of an exposure of the boundary zone between Luobusa Formation and Luobusa Ophiolite. Right: Sketch of the Left. See Fig. 2 for location.

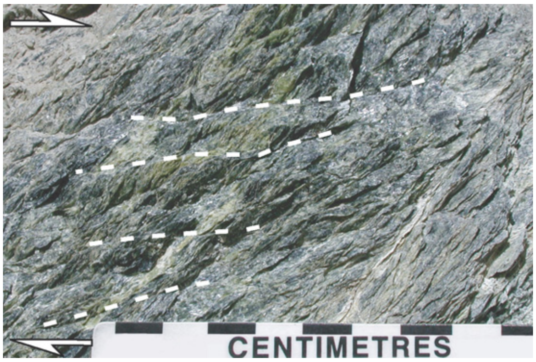

Fig. 7. Sheared serpentinite near to the base of the Luobusa Ophiolite. The attitude of foliation is N58°W, 41°S and striation lineation on the foliation trends N6°E. Broken lines indicate C′-type shear bands (N33°W, 30°SW) suggesting top-to-the-north displacement. See Fig. 2 for location.

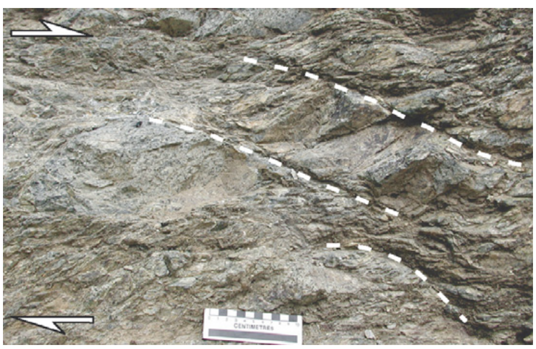

Fig. 8. Sheared serpentinite near to the bottom of Luobusa Ophiolite. The attitude of foliation is N20°W, 34°S. Broken lines indicate C′-type shear bands (N80°E, 31°N) suggesting top-to-the-north displacement. Scale bar on the bottom of view is 10 cm. See Fig. 2 for location.

shear bands oblique to the foliation, recognized by the subparallel alignment of flaky serpentine. The monoclinic arrangement of the shear bands (C′) and the foliation suggests top-to-the-north displacement. Fig. 8 shows C′-type shear bands which displace less deformed lens- or lozenge-shaped blocks of serpentinite. The monoclinic arrangement of the shear bands (C′) and long axes of lens- or lozenge-shaped blocks also indicate top-to-the-north displacement.

4. Upper boundary

The southern border of the Luobusa Ophiolite is traceable between serpentinized harzburgite and flysch-type Triassic sedimentary rocks (Fig. 2). The rocks near this boundary are not well exposed, because of the flat and grassy ground surface in the southern part of study area. Although the direct contact between serpentinite and sedimentary rocks is not exposed, the boundary is inferred to be a south-dipping low-angle fault, based on the trace of rocks of the hanging and footwall.

Serpentinization and carbonatization are ubiquitous in the rocks near to structural top of the Luobusa Ophiolite (Figs. 9 and 10). Carbonatization has totally obliterated the previous structure of the rocks of the Luobusa Ophiolite. Carbonate veins are sporadically distributed in serpentinite, generally running at high angles to the trace of the boundary between the serpentinite and the sedimentary rocks. The largest example of a carbonate vein is shown in Fig. 9.

Feebly metamorphosed sedimentary rocks (siliceous, pelitic and calcareous) overlie the serpentinized–carbonatized harzburgite. This unit occupies the structural bottom of flysch-type Triassic sedimentary rocks (Bai et al., 1993) and includes siliceous phyllite, chloritic phyllite and crystalline limestone (Fig. 9). Among these rock types siliceous phyllite predominates, composed of micaceous layers with included carbonaceous material. Scaly cleavage composed of fine-grained sericite, chlorite and opaque minerals occurs in the siliceous phyllite. In highly sheared rocks, the cleavage is subparallel to the compositional layering. Microscopic observations were made on polished slabs and thin sections of oriented samples taken from the structural base of the Triassic sedimentary rocks. The slabs and

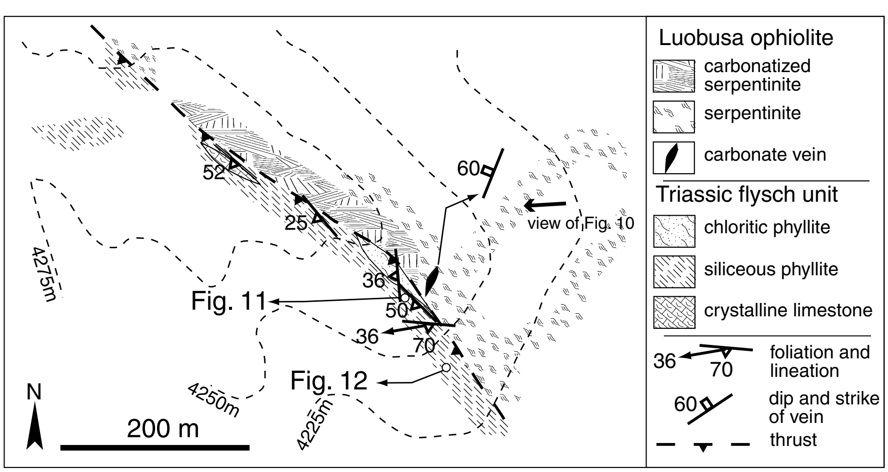

Fig. 9. Geological route map along the boundary between the Luobusa Ophiolite and the Triassic flysch unit in the southeastern part of study area. See Fig. 2 for location.

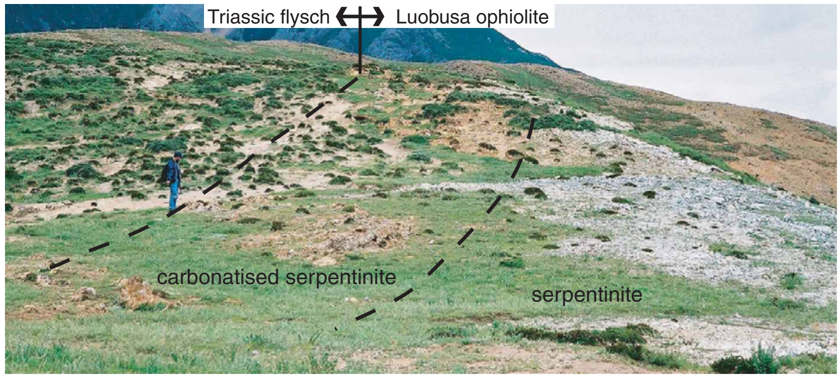

Fig. 10. Field photograph showing the occurrence of the upper boundary of the Luobusa Ophiolite. See Fig. 9 for location.

thin sections were made on the section perpendicular to the compositional layering and parallel to the mineral–striation lineations.

Small-scale shear zones oblique to the compositional layering are observed in siliceous phyllite. The small-scale shear zones displace compositional layering and quartz veins. The geometric pattern of these shear zones is comparable to that of the C′-type shear bands. Shear bands (C′) were observed in four oriented samples taken from separate locations (Figs. 2 and 9). In the eastern part of study area shear bands (C′) in well-laminated siliceous phyllite consistently indicate top-to-the-northeast displacement (Figs. 11 and 12). Some quartz porphyroclasts in siliceous phyllite are mantled by asymmetric 'tails' to form 'σ-type' porphyroclasts (Passchier and Simpson, 1986). Monoclinic symmetry of σ-type porphyroclasts, with respect to the center of the porphyroclast, indicates the sense-of-shear. A representative σ-type porphyroclast in a sample (sili-

Fig. 11. Polished surface of sheared siliceous rock near to the top of mantle peridotite. C′-type shear bands displacing compositional layering indicate top-to-the-northeast displacement. The attitude of foliation is N74°W, 54°S and the trend of mineral lineation is N46°E. See Fig. 9 for location.

Fig. 12. Polished surface of sheared siliceous phyllite near the top of the mantle peridotite. C′-type shear bands displacing compositional layering and quartz vein indicate top-to-the-northeast displacement. The attitude of foliation is EW, 58°S and the trend of mineral lineation is N75°E. See Fig. 9 for location.

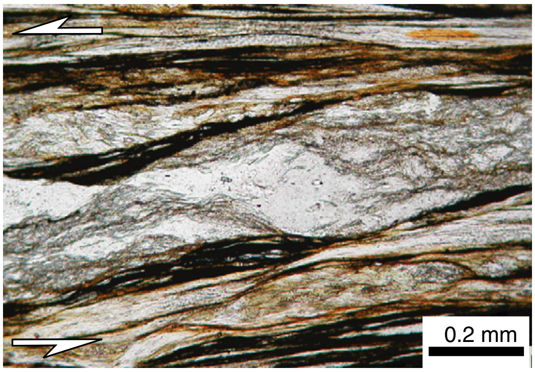

Fig. 13. Photomicrograph (open polarized light) of sheared siliceous phyllite near to the top of the mantle peridotite. Asymmetric σ-type strain shadows on a quartz porphyroclast indicate top-to-the-north displacement. The porphyroclast is associated with shear bands (C′) on the top-left and bottom-right sides. The attitude of the foliation is N60°W, 29°S and the trend of the mineral lineation is N25°E. See Fig. 2 for location.

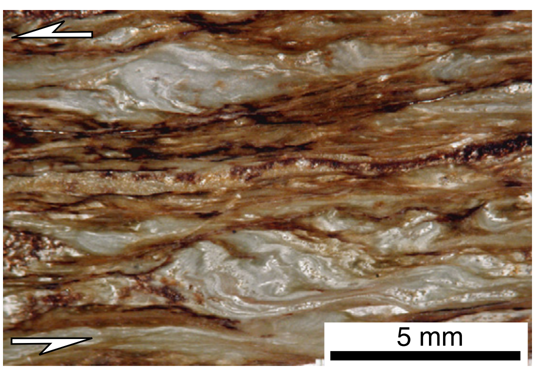

Fig. 14. Photomicrograph (open polarized light) of sheared siliceous phyllite including carbonaceous material near to the top of the mantle peridotite. C′-type shear bands displacing compositional layering indicate top-to-the-northeast displacement. The attitude of the foliation is N60°E, 69°S and the trend of the mineral lineation is N42°E. See Fig. 2 for location.

ceous–carbonaceous phyllite) is associated with shear bands (C′). The shear sense indicated by these coexisting structures shows consistent top-to-the-north displacement (Fig. 13). In the western part of study area laminated siliceous–calcareous phyllite C′-type shear bands displacing compositional layering indicate top-to-the-northeast displacement (Fig. 14).

5. Summary and tectonic implications

The Luobusa Ophiolite in the study area is a tectonic slice less than 1.2 km thick bounded by thrust faults at the base and top. The hanging walls of these thrust faults are to the north. The structurally underlying unit is the molasse-type Tertiary Luobusa Formation and the structurally overlying unit is feebly metamorphosed flysch-type Triassic sediments. The Luobusa Ophiolite and its underlying and overlying units form a northward-vergent imbricate structure. The mantle sequence dominated by harzburgite forms the structural top of the ophiolite, and serpentinite mélange, including clasts of basaltic and sedimentary rocks, occurs beneath the mantle sequence. The stratigraphic sequence of the ophiolite and the adjacent geological units has been overturned (Fig. 15).

North-directed thrust faults are described elsewhere in the IYSZ (e.g. Heim and Gansser, 1939; Valdiya, 1988; Ratschbacher et al., 1994; Yin et al., 1994, 1999). Heim and Gansser (1939) named the north-directed thrust ‘the Great Counter thrust’ and Yin et al. (1999) collectively referred to the north-directed thrust faults as ‘the Great Counter Thrust System’. The origin of Great Counter Thrust System is considered to be back-thrusting, associated with crustal shortening along the Main Central Thrust (Yin et al., 1994, 1999). Based on the structural observations, the thrust fault on the top of Luobusa Ophiolite can be correlated with the Renbu-Zedong Thrust which is the most prominent fault in the Great Counter Thrust System (Heim and Gansser, 1939; Yin et al., 1999). The thrust faults on the top and bottom of the Luobusa Ophiolite are probably part of the Great Counter Thrust System. It is inferred that the north-vergent imbricate structure was assembled during the Miocene, because the Renbu-Zedong Thrust is estimated to have been active between 19 and 10 Ma (Yin et al., 1999) , and granite samples related to shearing within the IYSZ in the Namche Barwa area have been dated at 21 Ma (Booth et al., 2004).

The results of this study, combined with the previously reported tectonic framework of the IYSZ (e.g. Molnar, 1984; Thakur, 1987; Zhou et al., 1996; Kaneko, 1997; Yin et al., 1999; Aitchison et al., 2000) lead to an interpretative model for the process of emplacement of the Luobusa Ophiolite (Fig. 16). In the Early Cretaceous crust and mantle of a fore-arc were situated along an intra-oceanic subduction zone. The Mesozoic continental shelf sediments on the northern margin of India became juxtaposed

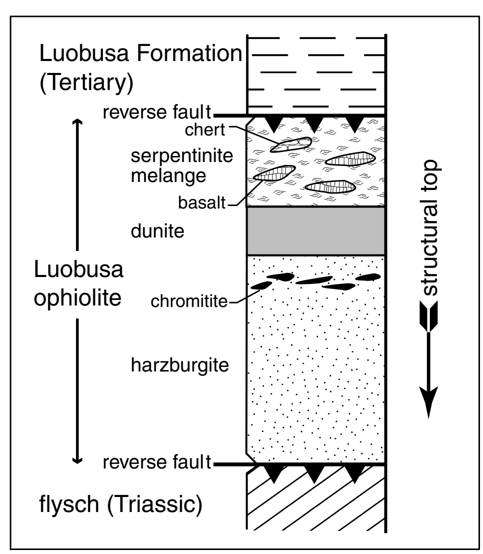

Fig. 15. Tectonostratigraphic column of the Luobusa Ophiolite and adjacent geological units. Diagram not to scale.

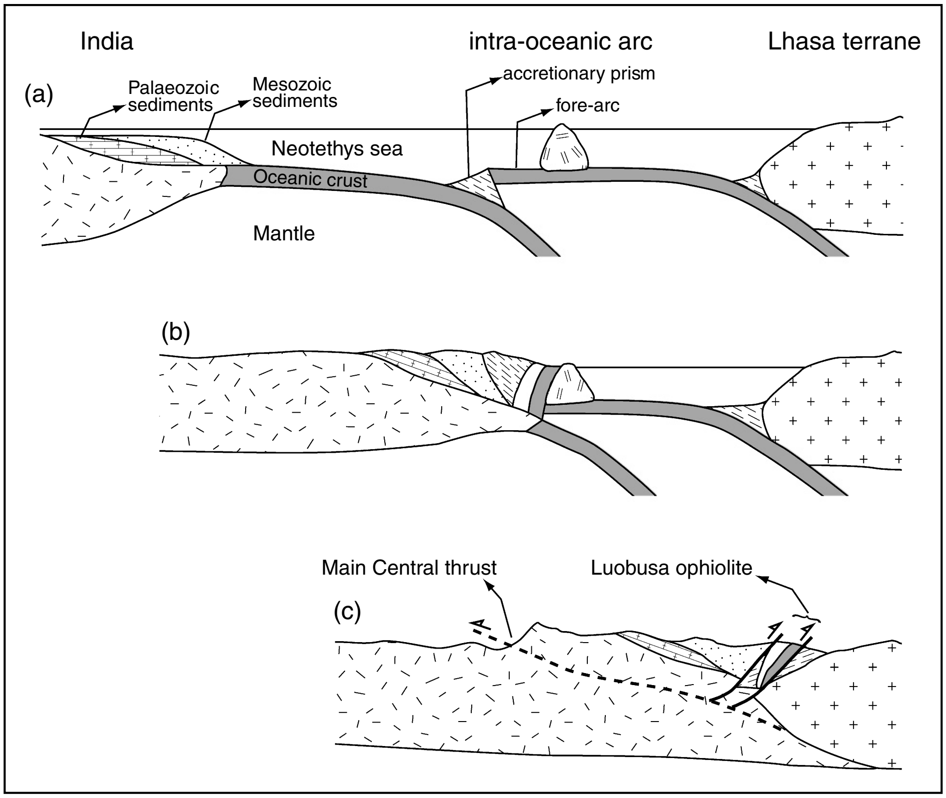

Fig. 16. Interpretative model for the process of emplacement of the Luobusa Ophiolite. (a) Early Cretaceous; (b) Late Cretaceous; (c) Miocene, not all tectonic unit appears in this section across the Luobusa Ophiolite. Tectonic framework refers to Molnar (1984), Thakur (1987), Zhou et al. (1996), Kaneko (1997), Yin et al. (1999) and Aitchison et al. (2000). Diagrams not to scale.

with this intra-oceanic arc in the Late Cretaceous. The Luobusa Ophiolite was scraped off the fore-arc and overturned. Suturing of India and Asia took place in the Early Eocene (Klootwijk et al., 1992; Rowley, 1998). The Main Central Thrust and its back-thrust system were activated due to the continued northward movement of India after the India–Asia collision (Yin et al., 1999). The Luobusa Ophiolite and adjacent units were finally incorporated in a north-vergent imbricate structure.

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