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ORIGINAL PAPER

Indo-Burma Range: a belt of accreted microcontinents, ophiolites and Mesozoic–Paleogene flyschoid sediments

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Abstract This study provides an insight into the litho-tectonic evolution of the N–S trending Indo-Burma Range (IBR), constituting the southern flank of the Himalayan syntaxis. Paleogene flyschoid sediments (Disang–Barail) that represent a shallow marine to deltaic environment mainly comprise the west-central sector of IBR, possibly resting upon a continental base. On the east, these sequences are tectonically flanked by the Eocene olistostromal facies of the Disang, which developed through accretion of trench sediments during the subduction. The shelf and trench facies sequences of the Disang underwent overthrusting from the east, giving rise to two ophiolite suites (*Naga Hills Lower Ophiolite* (*NHLO*) *and Victoria Hills Upper Ophiolite* (*VHUO*), but with different accretion history. The ophiolite and ophiolite cover rock package were subsequently overthrusted by the Proterozoic metamorphic sequence, originated from the Burmese continent. The *NHLO* suite of Late Jurassic to Early Eocene age is unconformably overlain by mid-Eocene shallow marine ophiolite-derived clastics. On the south, the *VHUO* of Mesozoic age is structurally underlain by continental metamorphic rocks. The entire package in Victoria Hills is unconformably overlain by shallow marine Late Albian sediments. Both the ophiolite suites and the sandwiched continental metamorphic rocks are thrust westward over the Paleogene shelf sediments. These dismembered ophiolites and continental metamorphic rocks suggest thin-skinned tectonic detachment processes in IBR, as reflected from the presence of klippe of continental metamorphic rocks over the *NHLO* and the flyschoid Disang floor sediments and half windows exposing the Disang beneath the *NHLO*.

Keywords Indo-Burma Range · Paleogene continental flysch · Olistostromal trench deposits · Ophiolite accretion · Thin-skin tectonics · Crustal structure

Introduction

The Indo-Burma Range (IBR) is a N–S trending, approximately 1,250 km long, arcuate fold-thrust belt that extends between 93°E–95°E longitudes and 19°N–27°30'N latitudes (Figs. 1, 2; term Burma is retained for known geological features). It lies on the east of the subduction zone that extends from the collisional Himalaya on the north to the subduction-related Indonesian arc on the south. The west-verging IBR rocks were popularly interpreted as an accretionary prism of oceanic material, which were accreted during subduction of the Indian plate beneath the Eurasian Burmese plate. The offscraped material of proto-Bay of Bengal fan constituting IBR was postulated to be sourced by the emerging Himalaya to the north (Curray et al. 1979; Hutchison 1989; Curray 2005). Recent provenance studies contend this view and infer more complex setting for IBR. The Paleogene flyschoid Disang sediments of marine distal shelf to deltaic setting are often exposed at altitudes of 1,400–2,000 m in central Naga Hills, possibly overlying the Indo-Burma-Andaman (IBA) microcontinent (Acharyya 1996). IBR represents an accretionary complex, which consists of colliding microcontinents, continental Mesozoic–Paleogene flyschoid sediments and ophiolites. The Paleogene shelf sediments in the west are overridden by two Mesozoic ophiolite suites, accreted in

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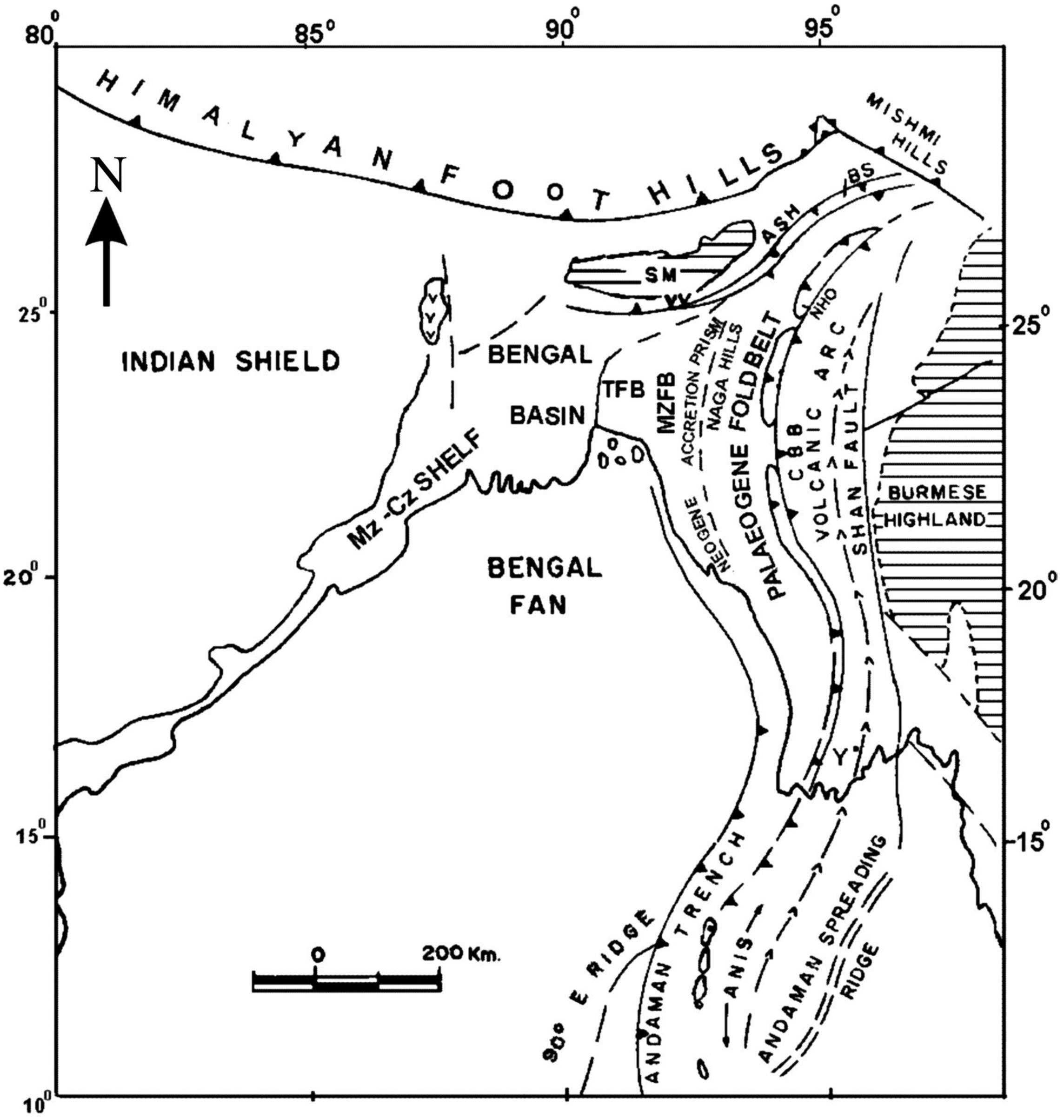

Fig. 1 Geological setting of the Indo-Burma Range. *ANIS* Andaman Island Arc, *ASH* Assam shelf, *BS* belt of schuppen, *CBB* Central Burma Basin, *MZFB* Mizoram foldbelt, *NHO* Naga Hills Ophiolite, *SM* Shillong-Mikir massif, *TFB* Tripura fold belt, *V* mid-Cretaceous volcanics, Inverted V Neogene-Quaternary volcanic line in Central Burma Basin and in Andaman Sea, Y Yangon

different episodes. These ophiolite-bearing complexes are intervened by continental metamorphic rocks, derived from the Burmese continent. Recent studies in IBR are focused mainly on the estimation of present-day tectonic movements from GPS observations (Sahu et al. 2006). However, the evolutionary history of the IBR lithotectonic suites, especially of the ophiolites, is incompletely known. In this study, field investigations were carried out to meet this gap in our knowledge. Based on field data, this contribution aims to provide a new interpretation on the structural evolution of the IBR, including parts of the Andaman Islands.

Regional geological setting

The IBR is located south of the eastern Himalayan syntaxis (Acharyya et al. 1986; Yin et al. 2010; Saha et al. 2012). This convergent tectonic belt bridges the Himalayan collision belt and the Indonesian subduction belt, where the Indian plate is presently undergoing oblique subduction under the Eurasian Burmese plate. The IBR is flanked to the west by the Bengal Basin, which joins with the Tertiary shelf of Assam to the north (Fig. 1). The latter and southeastern margin of the Bengal Basin is floored by the northeast prolongation of the Indian continent. The nature of

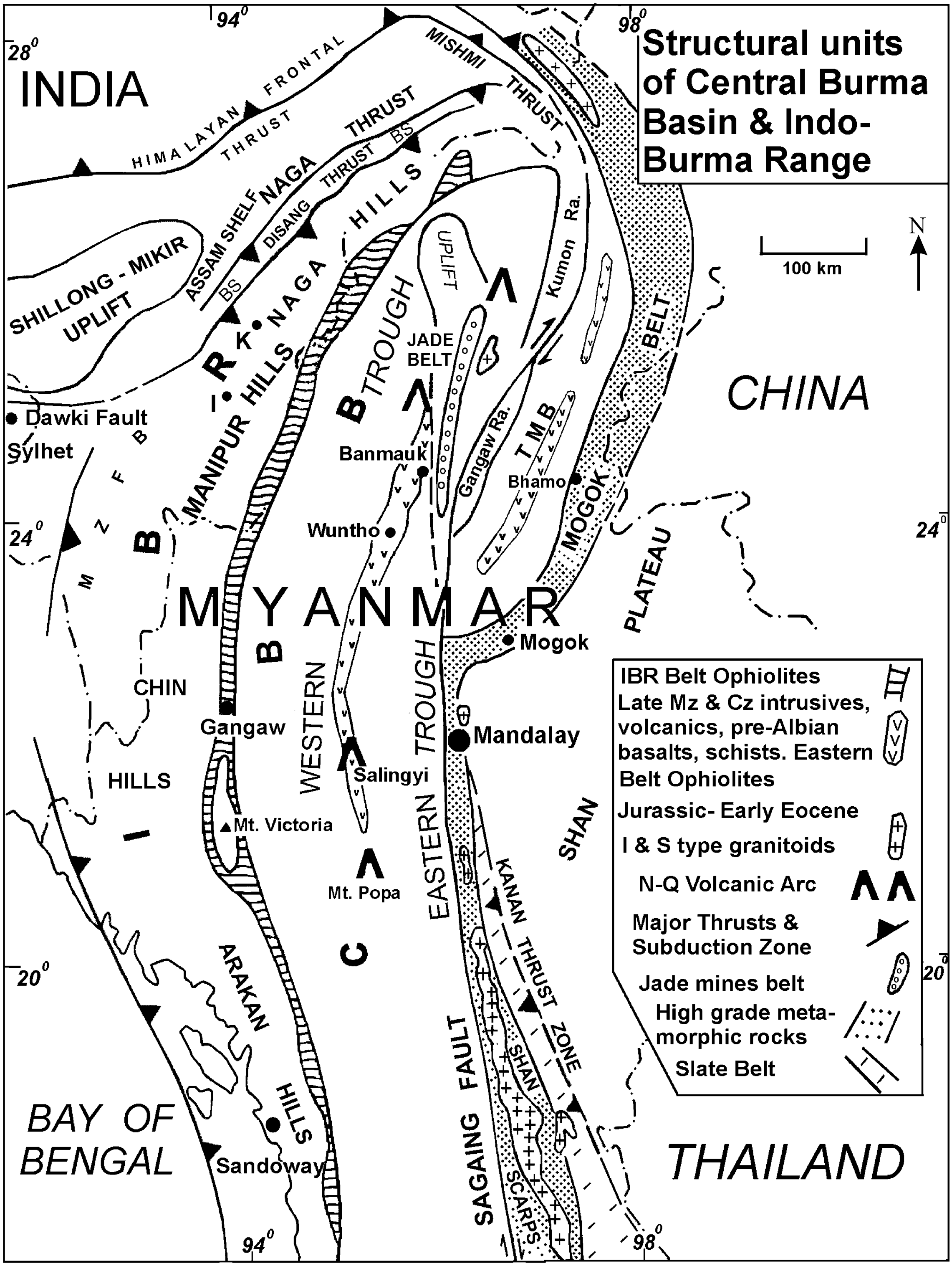

Fig. 2 Geological map of Indo-Burma Range and Central Burma Basin (modified after Mitchell 1993; Mitchell et al. 2004). *I* Imphal, *K* Kohima, *CBB* Central Burma Basin, *TMB* Tagaung–Myitkyna Belt

basement to the Paleogene sediments of IBR and Andaman Island, whether oceanic or continental, is still a debatable issue. The IBR is flanked to the east by the Central Burma Basin which has a central spine of Neogene-Quaternary volcanic chain, and it drains to the Irrawaddy fan and the Andaman Sea (Figs. 1, 2; Acharyya et al. 1986; Mitchell

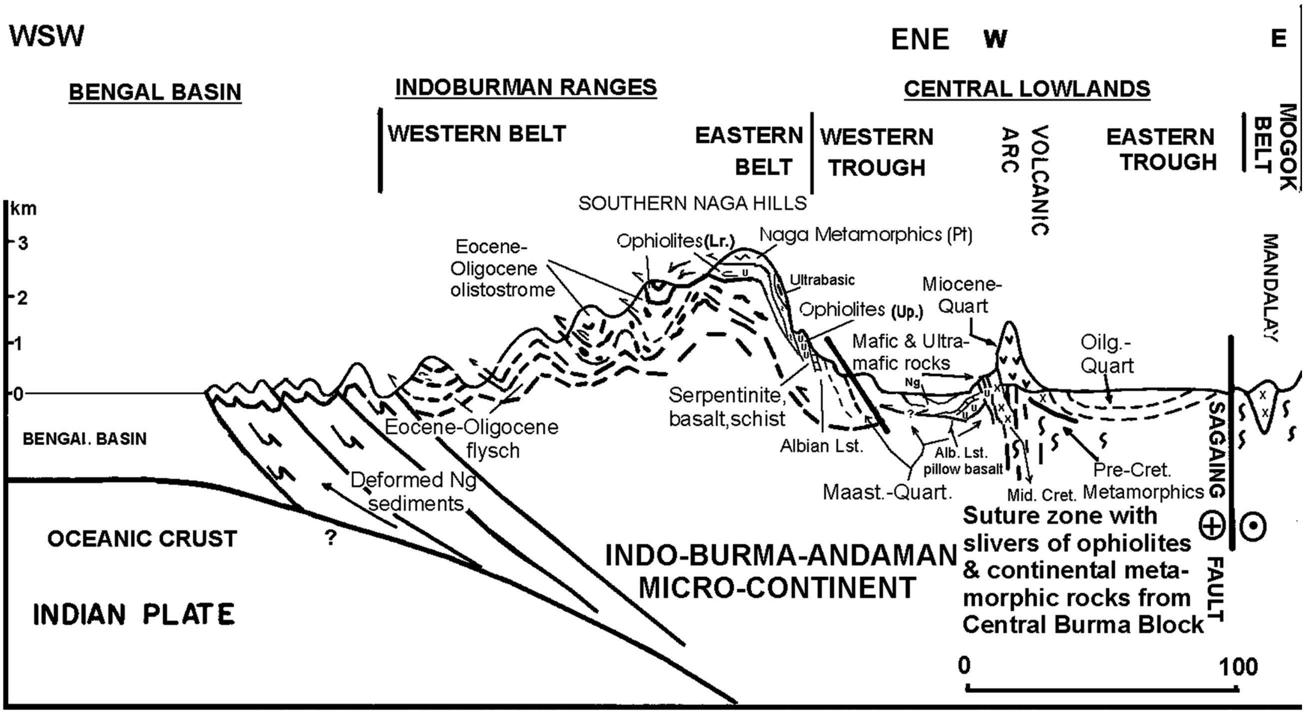

Fig. 3 Schematic composite cross section across IBR and CBB, showing major morphological and structural units (modified after Mitchell 1981, 1993). Presence of two ophiolite nappes: Ophiolite (Lr) and Ophiolite (Up) separated by continental metamorphic rocks shown schematically

1993). The Central Burma Basin is bounded to the east by the Shan-Sagaing strike-slip fault system showing dextral motion. This fault system borders the east Burmese highlands, which comprise the Shan scarp, the Mogok and other metamorphic belts. The north to south sectors of IBR are known as the Naga, Manipur, Chin and Arakan hills (Figs. 2, 3). The present field studies were confined to the Naga-Manipur Hills and Andaman Islands located in India.

Tectono-stratigraphy of Paleogene floor sediments

A simplified and composite tectono-stratigraphic column for IBR is shown in Fig. 4. The west-central segment of IBR exposes the Paleogene flyschoid sediments showing upward coarsening sequence. These sediments can be stratigraphically storied into two broad formations: Disang and Barail. The Disang Formation is over 3,000 m thick and can be divided into upper and lower units. The Disang Formation is overlain by the Barail Formation, which is over 2,000 m thick (Dasgupta and Biswas 2000; Imchen et al. 2014). The IBR shows decreasing elevations westward, where it is flanked by the low hill tracts of the Tripura-Mizoram fold-thrust belt, dominated by the Neogene molasse sediments (Figs. 1, 3; Alam et al. 2003). The western boundary of the Neogene accretionary belt against the Bengal plains is marked by a series of west-verging frontal thrusts.

Recent paleomagnetic studies (Imchen et al. 2014) have corroborated the estimated age of the Disang Formation to be Eocene as inferred from limited biota and stratigraphic evidence (Acharyya 1986; Acharyya et al. 1989). They have also shown that the sediments of the Upper Disang Member were deposited during the Upper Eocene. However, as the studied section is a portion of a much thicker sequence, the Upper Disang Member has been assumed to range in age from the Upper-Middle to Upper Eocene (Imchen et al. 2014).

The Upper Disang Formation is characterized by shale, mudstone and fine-grained sandstone, the frequency of the latter increasing, thickening and coarsening upward. Rare presence of benthic arenaceous foraminifera, pteropod juvenile fauna coexisting in association with *Nummulite* bearing larger foraminifera, plant fragments and common occurrence of Ophiomorpha-type burrows suggests that the Disang and the Barail formations were deposited in shallow marine to deltaic sedimentary environments (Acharyya 1986; Lokho and Kumar 2008; Imchen et al. 2014). The combined evidence of uvigerinid foraminifers and pteropods suggests a palaeobathymetry of ~500 m for the Upper Disang Formation. Benthic microgastropods, bivalves and larger foraminifers, including *Nummulites* that also occur in the

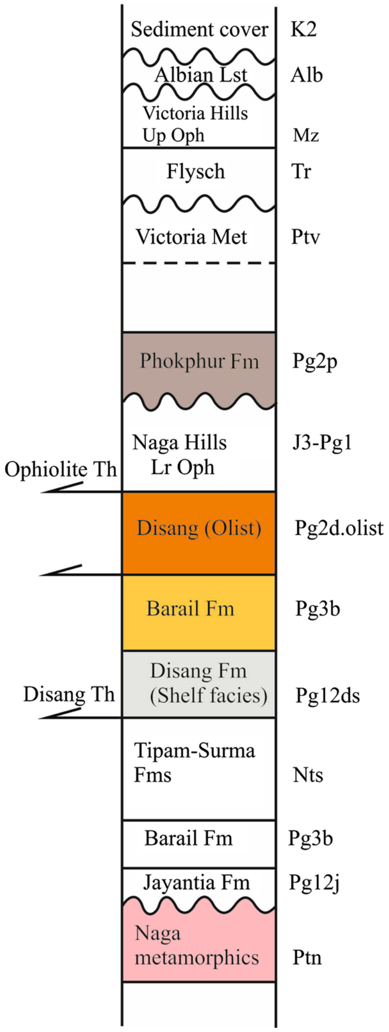

Fig. 4 Simplified and synthetic tectono-stratigraphic column for IBR. Equivalent stratigraphic units are similarly colored in Figs. 5 and 6. Stratigraphic units are indicated by standard stratigraphic symbols and first letter of formation name in lower case, e.g., *Pt* Proterozoic, *Tr* Triassic. NHO J3-Pg1 stands for Late Jurassic to Early Eocene age range for the ophiolite unit; Pg—Paleogene subdivided to three units, Paleocene–Eocene–Oligocene, Pg12 stands for Paleocene–Eocene; Naga Hills and Victoria Hills Ophiolites represented by several components are not colored. Units not exposed in study area are also *not colored*

pteropod-yielding samples, might have been transported into the bathyal zone from near-coastal shallow marine areas. *N. chavannesi* and *N. pengaronensis* are morphologically similar to *N. venosus*, which lives in present-day oceans between 15 and 80 m depth (Lokho and Kumar 2008).

Consequently, the shallow marine to deltaic Paleogene sequence overlies a continental crust (Acharyya 1996), as against conventional view of deep water origin (Brunnschweiler 1966; Bender 1983).

Provenance studies have been done on the Tertiary sediments and on modern river sediments draining the Arakan coastal hills by Allen et al. (2008) and on the Paleogene sediments from central Naga Hills east of Kohima by Imchen et al. (2014; Fig. 2). Provenance of the Paleogene sediments from South Andaman Island was also studied by Allen et al. (in Curray and Allen 2008).

The west-verging IBR was so far inferred to have formed by offscraped material from a proto-Bay of Bengal fan, supplied by the emerging Himalaya to the north (Curray et al. 1979; Curray 2005). Provenance studies on the contrary indicate that the Paleogene sediments in IBR were unlikely to have been sourced by the nascent Himalaya (Curray and Allen 2008). In contrast, the Neogene rocks from outer IBR belt show dominant derivation from the Himalaya. The proto-IBR during the Paleogene time was inferred to be located in lateral continuity of the Himalayan microcontinent and locally associated with magmatic arc (Acharyya 2007b; cf. Curray and Allen 2008). The Upper Disang sandstone from central Naga Hills belt is composed of monocrystalline, polycrystalline quartz and rock fragments, with minor plagioclase and negligible K-feldspar. The latter dominantly consists of volcanic and subordinate metamorphic rocks. A QFL plot of the Upper Disang sandstone indicates recycled orogenic material. Heavy mineral contents are in general scarce and include zircon, rutile, garnet, tourmaline, corundum, scapolite and opaque. The coexisting angular and subrounded clastics in same sample indicate textural immaturity involving short- and long-distant transport. Zircon occurs as euhedral, subrounded and well-rounded grains, with all three types noted in most samples. Source of euhedral zircon is postulated by Imchen et al. (2014) to be from granite and granite gneiss in the Naga Metamorphics (Proterozoic), which are assumed to have been exposed and eroded during mid-Eocene time. The Naga Metamorphics override the mid-Eocene accreted Naga Hills Ophiolite (*NHO*) possibly during the Late Eocene Oligocene nappe movement, as would be discussed later. The Naga Metamorphics thus appear to be unlikely source for euhedral zircon in Upper Disang sediments. The presence of dioritic plutons intruding the ophiolitic rocks of possible mid-Cretaceous–Eocene age is reported from southern Chin Hills by Brunnschweiler (1966). Such subduction-related mid-Cretaceous–Eocene aged intrusives would be more suitable source of euhedral zircon in the Upper Disang sediments. This postulation is strengthened by common presence of U–Pb detrital zircon ages reported by Allen et al. (2008) from the Paleogene sediments of Arakan sector, which are predominantly of Paleocene and Cretaceous in age, and minor component of Cambro-Ordovician and Precambrian ages.

Provenance studies on the Upper Disang rocks from the central Naga Hills (Imchen et al. 2014) revealed the presence of dual source of felsic and mafic characters with minor contribution from low- to medium-grade metamorphic rocks. Most of the felsic components were transported from distant source as evidenced by extensive reworking of grains. Felsic source rocks were possibly granite and granite gneisses from the Mikir Hills Proterozoic complex, which belonged to the Indian continent and located to the west of the Naga Hills (Fig. 1). Equivalent Eocene sediments also flank the shelf of the Mikir Hills. On the other hand, the bulk source of the sediments was from nearby mafic and ultramafic rocks. The sediments from nearby eastern source were rapidly dumped causing mixing and textural immaturity. Imchen et al. (2014) postulate that near-source mafic and ultramafic rocks were derived from *NHO* that emerged above sea level during mid-Eocene. Although *NHO* was accreted just prior to mid-Eocene and ophiolite-derived mid-Eocene shallow marine sediments rarely have local intercalations of terrestrial sediments (Jena and Acharyya 1986), it is unlikely that the Naga Hill Lower Ophiolite (*NHLO*) and its cover sediments, which were then palinspastically located further east (their pre-thrust position relative to present configuration), could not be the bulk source of mafic and ultramafic rocks to the contemporaneous Upper Disang shelf sediments that were then ill exposed and located far west. It is more likely that the Mesozoic upper ophiolite (*UO*) from the IBR that was accreted during the Albian to be better suited source rocks for the Upper Disang rocks.

The provenance of study of the Paleogene rocks by Allen et al. (2008), on the other hand, was located near the southern end of IBR and close to exposed ophiolite belt. The area of study by Imchen et al. (2014), on the other hand, was located further west and away from the present location of the ophiolite belt of IBR. There are no exposed pre-Tertiary rocks in the latter area other than that of IBR. However, it should be noted with caution that the present position of the ophiolitic rocks in IBR is not at their initial basinal position but at their tectonically transported position westward over the Paleogene shelf rocks, as would be discussed later.

Thermochronological analyses on detrital grains, isotopic analyses on bulk rock, and petrographic and heavy mineral data indicate that the Paleogene sediments from Arakan area were significantly sourced by an arc located to the east. The bedrock petrographic data also show significant proportion of lithic volcanic rock detritus, which plot within ‘Magmatic Arc’ field in QFL diagram. Older crustal components may have been sourced from the Himalaya or the Indo-Burmese margin. Low negative epsilon Nd values are indicative of magmatic source. Arc-derived Paleogene–Cretaceous detrital zircon fission track ages are common with only minor Paleozoic ages (Curray and Allen 2008). There is no evidence of substantial Trans-Himalayan input. U–Pb zircon ages were predominantly of Paleocene–Cretaceous age with minor Cambro-Ordovician and Precambrian ages, as mentioned earlier. The presence of older continental crust component is indicated by old Proterozoic U–Pb ages and fission track ages older than 300 Ma. These Paleogene sediments were possibly deposited over a continental/transitional crust and might be derived from rising south flank of the Himalaya or more likely from the east Burmese orogen (Allen et al. 2008; Curray and Allen 2008).

These Paleogene sediments although located to the west of the ophiolite belt, they resemble more to the ophiolite-derived mid-Eocene sediments in *NHO* that are exposed to its east and characterized by common presence of contemporaneous and older clastics rocks of volcanic and ultramafic nature. The dominance of mafic and ultramafic components is relatively less in the Paleogene sediments from the central Naga Hills belt that is located relatively away from the exposed ophiolite belt. Clasts of mafic volcanic rocks are also recorded as minor component from the Barail sediments from inner and outer belt Naga Hills (Acharyya 1986; Acharyya and Roy 1986).

The east-central parts of IBR expose a belt of olistostromal Paleogene flysch (Figs. 3, 4). The Late Cretaceous age component for the Disang Formation has been inferred mainly based on olistolithic faunal record (cf. Brunnschweiler 1966; Acharyya et al. 1989). Typical sections of this facies are well exposed in Manipur, Chin, Arakan Hills and Arakan coast (cf. Brunnschweiler 1966). However, this facies is poorly exposed in the Naga Hills, possibly due to tectonic reshuffling. Similar facies is also well exposed in the Andaman Islands. The argillaceous host sediments of the olistostrome are unfossiliferous, whereas the olistoliths consist of different dimensions and types of ophiolitic rocks, fossiliferous limestone and also continental metamorphic rocks (Acharyya et al. 1989, 1990). Earlier workers reported *Globotruncana*-bearing limestone as exotic blocks from Chin Hills (Brunnschweiler 1966 and Bender 1983). The olistolithic blocks, on the other hand, were inferred to occur as large boudins within the younger flyschoid succession (Mitchell 1993). Varied nature of olistoliths from several outcrop and adjacent sectors confirms olistostromal nature of these sediments.

Common presence of olistostromal facies is noted close to the tectonic floor of the ophiolite thrust sheet. Similar olistostromal rocks are also exposed at the Andaman Islands (Lipa Shale of Karunakaran et al. 1968), but they are tectonically inter-banded with the ophiolite-derived clastics (Namunagarh Sandstone of Karunakaran et al. 1968) and constituted a sedimentary mélange, called the ‘Mithakhari Group’ (Acharyya et al. 1989; Sengupta et al. 1990; Acharyya 2007a).

Similar olistostromal sediments have been also reported from the Sunda outer-arc islands as mélange, called the Oyo Complex (Karig et al. 1980) in Nias Island (south of Nicobar Is. in Mentawi Outer-Island Arc). Karig et al. (1980)

interpreted them as trench-fill deposits, with slumped blocks of accreted ophiolite and sedimentary rocks possibly derived from trench shoulder and those lying on the tectonic floor of the accretionary complex. No stratigraphic contacts have been established between the Oyo Complex and the bedded sedimentary units at Nias. However, the mélange is assumed to represent the oldest unit, forming the basement of the overlying bedded sequence (Acharyya 2007a). Mobilization and diapirism of Neogene or younger shale and mudstone were recognized as a possible mechanism for the origin of mélange at Nias (Samuel et al. 1995, 1997).

In the Manipur Hills and Andaman Islands, the olistostromal sediments are interpreted as subduction-related trench-fill sediments, which are often located close to the base of an accretionary complex (Acharyya 2007a; cf. Karig et al. 1980). There are no Neogene sediments exposed in or around exposures of these olistostromal rocks, and there is no evidence of shale diapirism (cf. Samuel et al. 1995, 1997). The presence of mid-Eocene olistolith representing the youngest element in the olistostrome is inferred to indicate the age for the main component of the trench sediments. The olistostromal trench deposits, together with dismembered ophiolites, and continental metamorphic rocks are inferred to represent an older accretionary complex, the products of which were thrust westward over the Paleogene Disang–Barail flyschoid sediments of IBR (Acharyya et al. 1989, 1990; Sengupta et al. 1990).

Ophiolite suites

Two suites of dismembered ophiolite comprising assemblages of ultramafic–mafic rocks consisting of hartzburgite, dunite, gabbro and volcanic rocks including pillow lava are recorded from Naga-Manipur Hills and Andaman Islands. They, however, reveal different accretion history. The oceanic pelagic sediments like chert, mudstone-phyllite, and limestone are closely associated mainly with pillow lava and other volcanic rocks. The assemblages of radiolarian, nanno-cocolith and foraminifera in *NHLO* indicate Late Jurassic to Early Eocene (say 150–55 Ma) age (Roy et al. 1988; Acharyya et al. 1989). The Mt Victoria region of the Chin Hills and northward, on the other hand, expose bodies of harzburgite, dunite and gabbro, which overlie the continental Triassic flysch. The largest ultramafic body of Webula Tung is underlain by an amphibolitic metamorphic sole up to 2 km wide (Mitchell et al. 2010). At the eastern margin of the southern Chin Hills, the pillow basalt, other ophiolitic rocks and the Triassic flysch are overlain unconformably with a basal conglomerate and limestone containing planktonic foraminifera and ammonite indicating an Upper Albian and Cenomanian age (Figs. 4, 7b; Mitchell 1993; Mitchell et al. 2010). The latter in turn is unconformably overlain by the Kabaw Formation having local conglomerate, glauconitic sandstone and shallow marine fossils of Campanian, Maasrtichtian and Paleocene ages (Mitchell et al. 2010).

Consistent geochronological dates are reported from Naga, Chin Hills and Andaman ophiolites. Sarkar et al. (1996) dated fine-grained basalt from the NHO location (28°38′ 0″N/94°44′ 40″E) juxtaposed with red and green chert at 148 ± 4 Ma (WR, K–Ar). Hornblende–plagioclase-bearing pegmatite vein intruding serpentinites from southern Chin Hills ophiolites has yielded 158 ± 20 Ma K–Ar hornblende age (in Mitchell 1981 and in Mitchell et al. 2010). Plagiogranite from eastern margin of South Andaman Island (92°44′30″N/11°34′05″E) has yielded 93.6 ± 1.3 Ma U–Pb ionprobe age on zircon (Sarma et al. 2010).

The ophiolitic rocks occupy synformal cores over the Disang floor rocks as exposed to the west of Kamjong (Fig. 5). The continental metamorphic rocks at places also occur at the cores of detached synformal klippe over a terrain of exposed ophiolites and its cover sediments, as observed in Kamku hill (Figs. 6, 7a). The low-dipping and thin-skinned disposition of west-verging ophiolite nappes has been thus modified by later structures (Acharyya 2007, 2010; Acharyya et al. 1990) (Fig. 6).

In the Chin-Victoria Hills, continental metamorphic rocks (quartz muscovite, biotite schist, termed ‘Kanpetlet Schists’ by Brunnschweiler 1966) occur beneath the cover of continental Triassic flysch, which in turn underlies Mesozoic ophiolite *VHUO* (Fig. 7b; Mitchell 1993). Along the eastern margin of IBR, in Naga-Manipur Hills, the Naga Metamorphics sheet dips gently eastward. The lithotectonic unit is unconformably overlain by the Miocene molasse sediments that extend to the Central Burma Basin (Figs. 16 and 17 in Brunnschweiler 1966).

Ophiolite cover and olistostromal trench sediments

The ophiolitic rocks are associated with two types of closely associated sedimentary rocks. One type includes shallow marine to paralic ophiolite-derived and plagioclase-dominant clastic cover rocks (mid-Eocene) in the Naga-Manipur Hills. The other type includes olistostromal flyschoid sediments recorded from Manipur, Chin, Arakan Hills and Andaman Islands, which often tectonically underlie the dismembered ophiolites. At a few locations, e.g., Phokphur area in Naga Hills, the ophiolite-derived clastic sediments show angular unconformity against the underlying accreted ophiolites (Fig. 8; Acharyya 1986; Jena and Acharyya 1986). This stratigraphic relation is, however, mostly obscured by imbricate thrusting. In the southern Chin Hills, the pillow basalt and Triassic flysch occur

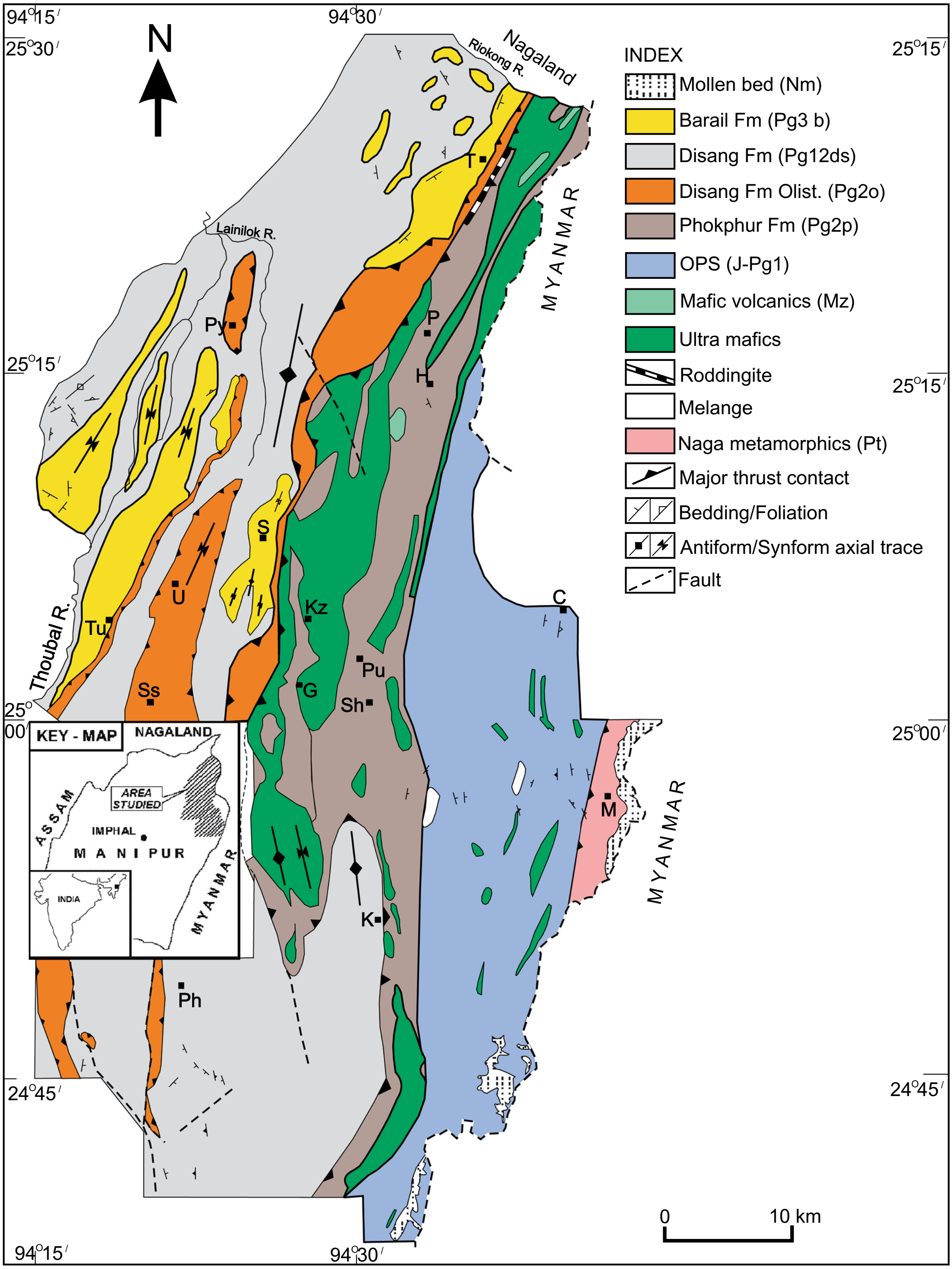

Fig. 5 Geological map of Lower Ophiolite Belt, northern Manipur bordering Naga Hills. Geological maps by Joshi and Vidyadharan (2008) and Das et al. (2008) have been integrated and reinterpreted by author. Disang Fm. is represented by two facies (non-olistostromal shelf and olistostromal trench of Early and mid-Eocene ages, respectively). The Ophiolite-derived clastics comprise Phokphur Fm., the unit shown in figure also include minor components of volcanics and oceanic pelagic sediments; *OPS* oceanic pelagic sediments; ultramafics mainly comprise serpentinite and harzburgite; mélange mainly comprise serpentinite. *C* Chammu Thankul, *G* Gamnom, *H* Huishu, *K* Kamjong, *Kz* Kazing Malung, *M* Mollen, *P* Poi, *Ph* Phungyar, *Pu* Pushing, *Py* Paoyi, *S* Siruhi, *Sh* Shingcha, *Ss* Shangshak, *T* Tusom, *Tu* Tushar, *U* Ukhrul

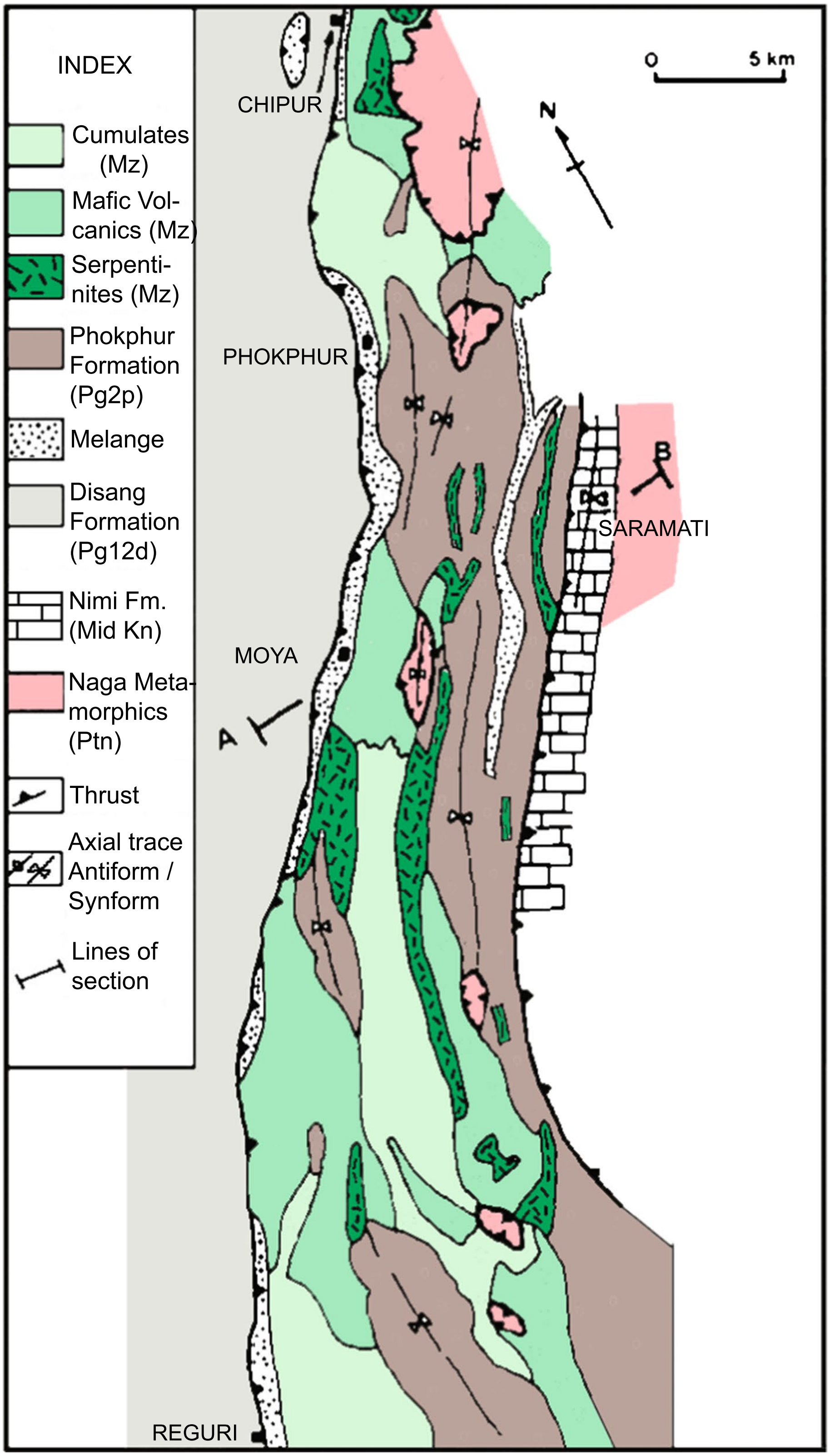

Fig. 6 Geological map of Lower Ophiolite Belt, Nagaland (modified after Anon 1986). Mafic volcanics closely associated with oceanic pelagic sediments are shown together in the diagram. The oceanic pelagic sediment ranges in age from Late Jurassic to Early Eocene. Phokphur Fm. comprising ophiolite-derived clastics is mid-Eocene in age. Mélange involving mixture of tectonized rocks shown by stippled white unit

unconformably below a basal conglomerate and limestone. Planktonic foraminifera and ammonite indicate Upper Albian and Cenomanian age (Figs. 4, 7b; in Mitchell 1993; Mitchell et al. 2010). The Albian–Cenomanian limestone of the Chin Hills is again overlain unconformably by the Kabaw Formation. The latter consists of local

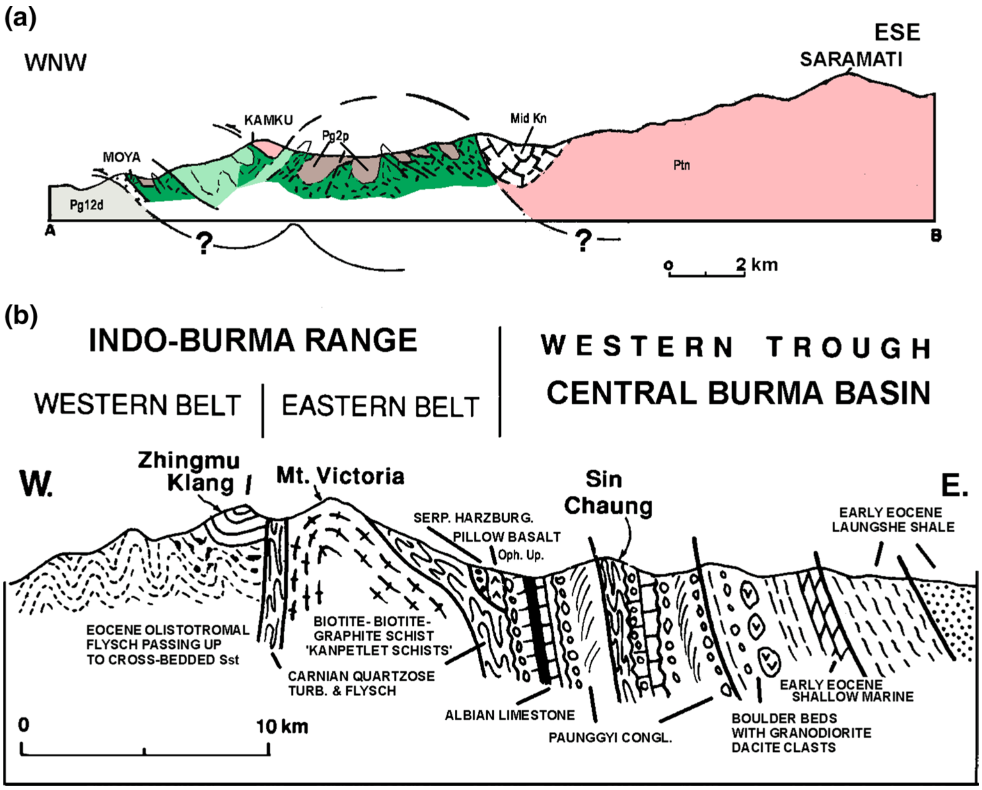

Fig. 7 **a** Geological cross section across Naga Hills Ophiolite (lower ophiolite). Section line shown in Fig. 6, **b** shows schematic cross section across Mt Victoria area and parts of 'Western Trough' (modified after Mitchell 1993)

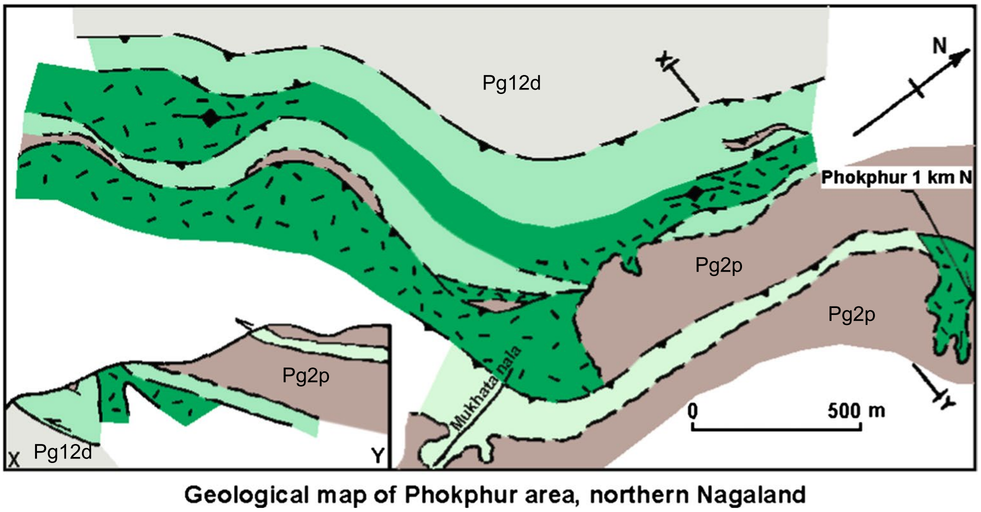

Fig. 8 Geological map of Phokphur area, Tuensang district, Nagaland, showing accreted ophiolite rocks (comprising cumulate, mafic volcanics and serpentinites) are unconformably overlain by the ophiolite-bearing Phokphur Fm. The latter along with associated ophiolitic rocks are also affected further by thrust imbrication. Location of Phokphur is shown in Fig. 6

conglomerate, glauconitic sandstone and shallow marine fossils of Campanian, Maasrtichtian and Paleocene age (in Mitchell et al. 2010).

At Mt Victoria region the ophiolites overlie the continental Triassic flysch and basement rocks. The *VHUO* was thus accreted prior to the Late Albian time. On the other hand, the ophiolites from the Naga Hills that are tectonically overridden by similar continental metamorphic rocks were accreted prior to mid-Eocene *NHLO*. The Naga Metamorphics and the Kanpetlet schists exposed along the Indo-Myanmar border are equivalent rocks, if not laterally connected (Acharyya 2007a). In the Manipur Hills, olistostromal sediments often occur beneath the dismembered ophiolitic rocks (Figs. 4, 7b). Olistoliths floating in the Disang mudstone slate consist of variable sized and mixed up blocks of limestone, ophiolite and continental metamorphic rocks (Acharyya 1986; Mitra et al. 1986; Acharyya et al. 1989; Sengupta et al. 1990). Limestone olistoliths even in a single outcrop often contain marine fauna of diverse age and facies. They show diverse ages, indicating mixed nature of the trench deposit. Olistoliths of ophiolites and limestones of Late Cretaceous and Early-mid-Eocene ages are possibly derived from accreted rocks at the trench shoulder. Such relationship is typically recorded from Paoyi area (Fig. 5).

In the Mt Victoria region, the western boundary of continental metamorphic rocks bordered mainly by an assemblage of the Triassic flysch, other sedimentary and ophiolitic rocks, which are truncated by the east-dipping Kheng Thrust (in other words ophiolite thrust; Fig. 2 in Mitchell et al. 2010). The assemblage of these rocks in turn overrides the flyschoid Paleogene sediments to its west. The latter is represented by a sequence of feldspathic grit, mudstone with olistolithic blocks of Triassic sandstone, Cretaceous limestone, ophiolites and rare biotite schist. The assemblage is inferred to represent lower Eocene debris flow (Fig. 7 in Mitchell 1993). This sequence grades up to the Barail-like cross-bedded sandstones of Eocene or Early Oligocene age (Fig. 7b; Mitchell 1993; Mitchell et al. 2010).

Concurrent presence of lower-mid-Eocene fossils in the ophiolite-derived sediments, and among the olistolith from the olistostromal facies from the Naga-Manipur belt and the Mt Victoria area, respectively, indicates a common episode of ophiolite accretion during mid-Eocene period (Acharyya et al. 1989). The packet of thrust stack, comprising the Albian accreted Mesozoic ophiolite *VHUO* at the Mt Victoria and Chin Hill area; and the mid-Eocene accreted ophiolite *NHLO* at the Naga Hills; together with sandwiched continental metamorphic rocks are thrust westward as thin-skinned thrust sheets over the Disang–Barail shelf sequence or equivalent floor rocks (Fig. 7b).

The Eocene 'Mithakhari Group' from South Andaman Island shows dominant contribution from arc, and positive epsilon Nd values are indicative of a juvenile magmatic source. Cretaceous–Eocene fission track ages are also present. Subordinate continental source is also present possibly derived from continental margin of Shan-Thai Block (Allen et al. in Curray and Allen 2008). Curray and Allen (2008) did not differentiate the two diverse but contemporaneous sedimentary components that are mixed up tectonically in the 'Mithakhari Group.' The samples studied by Allen et al. possibly belong to the ophiolite-derived Namunagarh sandstone facies (Karunakaran et al. 1968), which has distinct volcanic arc input. The Oligocene aged Andaman Flysch, on the other hand, shows recycled orogenic setting and negative epsilon Nd values, which are typical of continent-derived sediments. The provenance signature for the Andaman Flysch is thus markedly different to that revealed by the 'Mithakhari Group.' Recycled orogenic source was possibly derived from northeastern continental region of Myanmar, and subordinate magmatic source was likely from the eastern Myanmar arc (in Curray and Allen 2008). The Andaman Flysch occurs as a tectonic floor beneath the Mithakhari and the ophiolite mélange. Tectono-stratigraphically, the Andaman Flysch can be compared and correlated with the Paleogene (Disang–Barail equivalent) shelf sediments of the IBR to the north (Acharyya et al. 1990; Acharyya 2010). Their provenance setting is also similar. On the south, the Victoria Hills ophiolite of Mesozoic age is overlain by shallow marine Late Albian sediment (Fig. 7b).

The Neogene rocks from the outer IBR, as distinct from non-Himalayan-provenanced Paleogene rocks, represent Himalaya-sourced Neogene accretionary prism comprising sediments offscraped from the down-going Bengal fan component (Allen et al. 2008). Thus, there was a sharp change in provenance setting during the initiation of the Neogene sedimentation following the Late Oligocene collision. The Neogene sediments largely constituted the outer IBR Tripura-Mizoram accretionary wedge (Figs. 1, 3).

Discussion

Nature of crust flooring IBR and parts of Andaman Islands

The nature of crust underlying IBR and Andaman Islands is debated, but it is an important issue. IBR is generally inferred to be floored by oceanic crust; however, some postulate it to be continental (Hutchison 1989; Acharyya et al. 1990; Acharyya 1996).

Shallow marine to deltaic nature of the Disang–Barail sequence as revealed from their setting and rarely present fauna (Lokho and Kumar 2008) and similar nature of rocks further south suggests them to overlie a continental crust (Acharyya 1996), as mentioned before. Concurrent presence of lower-mid-Eocene fossils in the ophiolite-derived shallow marine to deltaic sediments, and among the olistolith from the underlying olistostromal trench facies from the Naga-Manipur belt and the Mt Victoria area, respectively, indicates a common phase of ophiolite accretion predating mid-Eocene period (Acharyya et al. 1989). The packet of thrust stack, comprising the Albian accreted Mesozoic ophiolite *VHUO* around the Mt Victoria area; and the mid-Eocene accreted ophiolite *NHLO* at the Naga Hills; together with sandwiched continental metamorphic rocks were thrust westward and emplaced as thin-skinned thrust sheets over the Disang–Barail shelf sequence or equivalent floor rocks (Fig. 3). The low-dipping, open-folded nature of the accreted ophiolite-bearing thrust stack, subduction-related trench sediments and the sandwiched continental metamorphic rocks occurring between the ophiolites were tectonically emplaced over the Paleogene shelf rocks. The low-dipping, open-folded thin-skin geometry of the thrust stack necessitates the presence of continental floor.

Kieckhefer et al. (1981) inferred that the outer-island arc of Sumatra, representing southeast continuity from the Andaman and Nicobar outer-island arc, is probably underlain by a mélange, including ultramafic rocks, or by a continental crust. A different model for origin of mélange in Nias Island, involving shale and mud diapirism and injection from Neogene-Quaternary sand silt, has been proposed by Samuel et al. (1995, 1997). In the Manipur Hills, the olistostromal facies is not associated with any Neogene sediments and was interpreted to represent a tectonically modified sedimentary deposit in a subduction-related trench (cf. Karig et al. 1980). These trench sediments were later attached to the base of the accretionary complex.

The root zones of thin-skinned west-directed thrust packets of IBR ophiolites are located farther east. The geological setting of Central Myanmar belt is not well known because of poor exposure condition, obliterations due to magmatic activities, and lack of the related literature. Certain features from the Central Myanmar belt, however, resemble suture zone like rock assemblage such as the presence of narrow outcrops of steep-dipping mafic–ultramafic rocks, ophiolitic sediments, mid-Cretaceous and younger plutons and continental metamorphic rocks. This rock assemblage is exposed along a narrow central belt and partly beneath the Neogene-Quaternary volcanic rocks. Higher gravity value also characterizes this belt. The assemblage and setting possibly mark ophiolitic suture zone (Acharyya et al. 1989, 1990; Acharyya 2007a; Sengupta et al. 1990).

Several interpreted seismic sections have been presented by ONGC geoscientists (Roy 1992 and others) portraying the subsurface on-shore and off-shore structure in and around the Andaman outer arc. The Miocene and younger strata in these sections unconformably overlie the Oligocene Andaman Flysch, which in turn overlie older formations. Interpreted cross sections depict the presence of thrust faults affecting low-dipping formations, maintaining their stratigraphic order. Such tectono-stratigraphic setting is unlikely to develop in an offscraped accretionary prism located adjacent to a subduction zone. Instead, these domains possibly represent uplifted and thrust fault affected forearc basin (Curray and Allen 2008).

Kumar et al. (2013) have used the Bouguer coherence (Morlet isostatic response function) technique to compute the spatial variation of effective elastic thickness (Te) of the Andaman subduction zone. The subduction geometry (depth section) is derived from forward modeling of the Bouguer gravity anomaly across the Andaman arc. A close match is noted between observed and calculated curve. The recovered Te map resolves regional-scale features that correlate well with known structures of the subducting Indian plate, the overthrust Burmese continent, major structures on the Indian plate and the ninety east ridge (NER). The computed crust geometry suggests partially subducted NER topography at the crust interface between the down-going Indian plate and the overriding Burmese crust (Fig. 9). The latter placed beneath the Andaman Islands is imaged to be about 24 km thick and with 2.7 g/cm^3 gravity, which are typical values for continental crust.

The nature, settings, disposition and geometry of the lithotectonic units of IBR, as presented above, indicate IBR lithotectonic units to be floored by the IBA continental crust.

It may be noted that the creation of IBA microcontinent possibly dates back to early history of brake up of the Gondwana supercontinent. The SIBUMASU (Siam-Burma-Malaysia-Sumatra) microcontinent cluster was rifted from the northern margin of Indo-Australian continent during the Permo-Carboniferous (Audley-Charles 1988; Metcalfe 1988), whereas, the Indo-Burma-Andaman microcontinent and some others did so during the Late Jurassic (Powel et al. 1988; Fang 1994). The Indo-Burma-Andaman (IBA) microcontinet was later accreted to the NE prolongation of the Indian continent during the Pliocene (Acharyya 1998) as would be discussed later.

Evolution of Indo-Burma Range and emplacement history of ophiolites

The ophiolitic rocks at IBR were postulated to be composed of steep-dipping thick-skinned body that represents the Indo-Eurasian suture (Curray et al. 1979; Curray 2005; Mitchell 1993; Mitchell et al. 2010). The shallow, orogen parallel, open-folded geometry of the IBR ophiolites, as well as the presence of ophiolites and overriding metamorphic rocks as klippe and half klippe over the Paleogene flyschoid floor sediments, on the other hand, indicates low-dipping fold-thrust geometry of the IBR ophiolites.

Two assemblages of ophiolite rocks with different accretion history have been recognized in the IBR. These ophiolite bodies, however, have not been mapped separately. They represent Naga Hills Lower Ophiolite unit (*NHLO*)

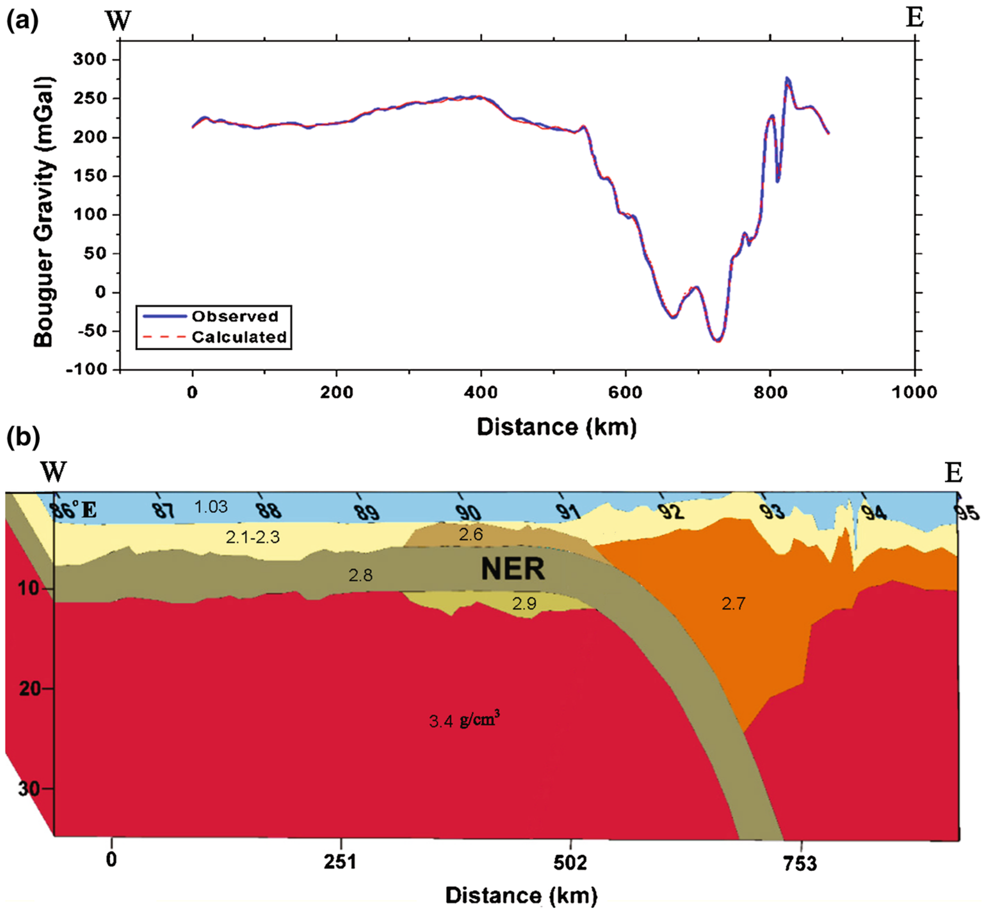

Fig. 9 Schematic section across the Andaman subduction zone along 10°N latitude. Longitudinal range of the area is also shown. Subduction geometry (depth section) derived from forward modeling of the Bouguer gravity anomalies across the Andaman arc. There is close match between observed and calculated curves of Bouguer anomaly. Depth shown in km; gravity (g/cm^3) values of mantle, normal crust and NER crust, overriding Burmese crust and sediment cover are shown. The figure shows the subduction of the NER topography beneath the overriding Burmese crust that floor the Andaman Island (modified after Kumar et al. 2013). The overriding Burmese crust is ~24 km thick and has a gravity value of 2.7 g/cm^3

and the Victoria Hills Upper Ophiolite unit (*VHUO*). The continental Triassic turbidities tectono-stratigraphically overlying quartz-mica schist at Mt Victoria in turn underlie a section of Mesozoic ophiolites (Mitchell 1993; Mitchell et al. 2010), representing the UO unit. The accreted ophiolite unconformably underlies shallow marine Late Albian limestone. The ocean basin located between the Sino-Burma and the Central Burma microcontinents closed in response to an east-dipping subduction activity, which was followed by collision (Fig. 10). The Early Cretaceous suture represented by UO is designated Suture-I. The accreted ophiolites were intruded by mid-Cretaceous and younger granodiorite plutons, which were possibly generated because of an east-dipping subduction activity that flipped to the western margin of the amalgamated Burmese microcontinent.

The mid-Eocene aged ophiolite-derived shallow marine to paralic cover rocks unconformably overlie the imbricated ophiolite *NHLO* of Naga-Manipur Hills. The olistostromal trench sediments tectonically underlying the accreted ophiolites from Manipur, Chin Hills and Andaman Islands contain olistoliths of various types and ages. The youngest lower-mid-Eocene elements present among the olistoliths mark the age of the main component of the trench sediments. The coinciding mid-Eocene age of these two contrasting facies of sedimentary rocks marks the common phase of subduction-related ophiolite accretion that closely preceded the mid-Eocene time (Fig. 10; Acharyya et al. 1989; Sengupta et al. 1990).

Glaucophane- and jadeite-bearing schists occur within the metavolcanics, and ophiolite mélange from the ophiolites of Naga Hills indicates subduction process to be responsible for ophiolite accretion (Acharyya et al. 1990). Pal et al. (2003) have reported the presence of metasediments and metavolcanics of greenschist to amphibolite facies in mélange zone of Andaman ophiolites, indicating

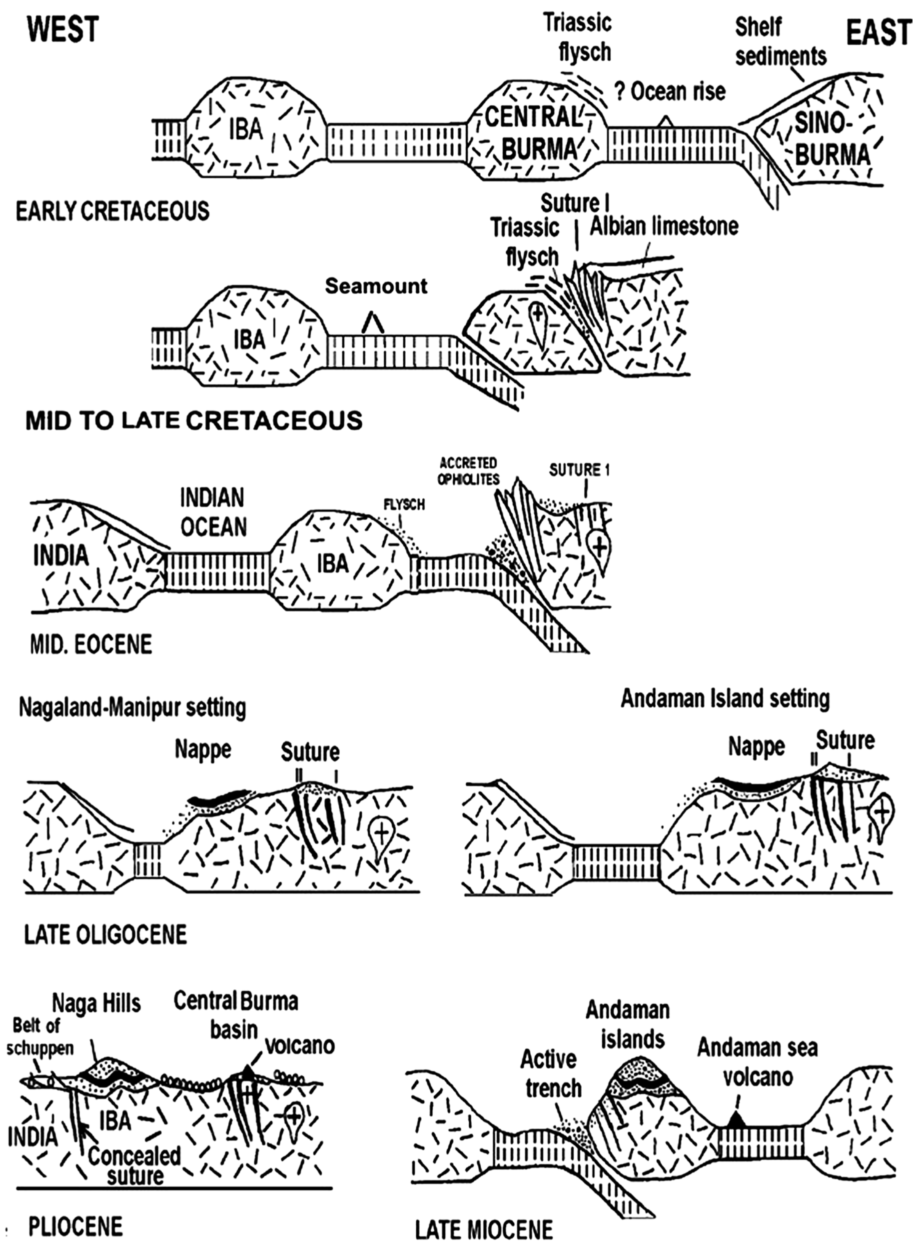

Fig. 10 Schematic cartoons showing successive closures of ocean basins located between the Burmese and the Indo-Burma-Andaman microcontinents, leading to the emplacement of Naga-Andaman ophiolites, development of Andaman subduction activity and finally collision between northern ends of IBA with northeast prolongation of the Indian continent

effects of post subduction metamorphism. The presence of several mid-Cretaceous and Eocene granodioritic plutons and related volcanic rocks close to the Central Burmese magmatic arc possibly indicates the location of the subduction zone. This early subduction activity has no straightforward relationship with the presently active Andaman-Java subduction.

The chemistry of basalts from the Naga Hills ophiolites indicates that ocean islands were important constituent of the subducting ocean crust (Fig. 10; Sengupta et al. 1989). This is corroborated further by the prevalence and close association of limestone, and calcareous chert occurring in close association with the ophiolitic volcanics, indicating a depositional process to be operating at shallower depth than CCD (Acharyya et al. 1989). The ocean-floor volcanics associated with radiolarian chert without any carbonate association indicate a depositional process operating at greater than CCD basin depth. The entry of seamounts to the subduction zone possibly temporarily jammed subduction activity. Continued convergence clipped off seamounts and also imbricated slivers from ocean floor, which were accreted to the leading margin of the overriding Burmese continent. The *NHLO* unit predates mid-Eocene accretion and caused the closure of the ocean basin located between IBA and the amalgamated Burmese microcontinent (Fig. 10).

During the Late Oligocene terminal collision, the accreted ophiolites, associated sediments and the sandwiched continental basement rocks, emanating from composite suture zones, were thrust westward and emplaced as thin-skinned thrust bodies over the Eocene–Oligocene flyschoid sediments, which was possibly floored by the IBA microcontinent. The suture zone for the ophiolite nappe of IBR appears to be tentatively located along and beneath the Cenozoic volcanic belt of the Central Myanmar as mentioned before (Fig. 10).

Mitchell et al. (Fig. 7, in 2010), on the other hand, postulated the presence of a thick-skinned ophiolite slab along the eastern margin of IBR. Because of the Sagaing dextral fault, the dislocated part of this ophiolite body is inferred to be exposed at the Central Burma belt. Thick-skinned nature of IBR ophiolite, however, is not favored by their map pattern and open-fold geometry, as mentioned earlier (Figs. 6, 10).

A Late Oligocene regional unconformity affects the IBR and the South Andaman Islands, possibly marking the time of terminal collision between IBA and amalgamated Burmese microcontinents. Major parts of the Indian plate being located far away from the site of the Late Oligocene collision, there was uninterrupted sedimentation during Late Eocene to Late Miocene at the deeper and eastern part of the Bengal Basin (Dasgupta 1997; Shamsuddin and Abdullah 1997), as well as at the northeastern part of the Indian Ocean (Curray and Munasinghe 1989).

During much of the Oligocene time, uninterrupted flyschoid sediments were deposited over the Indo-Burma-Andaman (IBA) microcontinent (Acharyya 1996). These areas are located at the eastern segment of the Indian Ocean. Continued subduction brought the Burmese and IBA microcontinents closer and finally caused collision of the Burmese continental block with IBA, which was marked by the lower ophiolite (*NHLO*) and Suture-II (Fig. 10; Acharyya 2007a).

At the Andaman outer-island arc, the accreted lower ophiolite (*LO*) and ophiolite-derived mid-late Eocene shallow marine sediments are exposed facing the Andaman-Java subduction zone. Some workers believe that the subduction activity along this zone was continuing since the Cretaceous and the activity also extended northward to the proto-IBR (Bender 1983; Curray et al. 1979; Curray 1992; Wajzer et al. 1991). However, the Andaman ophiolites predate the intrusion of plagiogranite (dated 93.6 Ma, Ub-Pb; zircon age; Sarma et al. 2010). Shallow marine, ophiolite-derived clastics copiously exposed at Andaman Islands also indicate pre-mid-Eocene age for the Andaman ophiolites. Thus, Eocene and older oceanic elements were already present as accreted features associated with the Andaman ophiolite. Therefore, these rock assemblages could not be produced by the current Andaman-Java subduction activity.

The current subduction activity is inferred to have been initiated since Miocene and resulted in opening up of the Andaman Sea and similar back-arc basins since the Late Miocene (Acharyya et al. 1990; Khan and Chakraborty 2005). The Pliocene–Holocene volcanism in the Central Burma Basin and the Andaman inner arc corroborates initiation of subduction activity only since Late Miocene. The ophiolites in the Andaman belt are emplaced as west-directed low-dipping thin-skinned nappes that emanated from a suture in the east and were emplaced over the Late Oligocene Andaman Flysch (Acharyya 2007a).

During the Oligo–Miocene, the northeast prolongation of the Indian continent was located close to the IBA and the Burmese microcontinents in the north, but they were separated in the south by the wide Indian Ocean. The Paleogene sediments from central Naga Hills record the presence of dual provenance: long-distant one from the Proterozoic Mikir Hill massif in the west and short-distance one supplying mafic and ultramafic products from uplifted ophiolite to the east. The Paleogene sediments in the Naga Hills were possibly overlying the IBA microcontinent and were flanked to the east by the Albian accreted UO *VHUO*.

The convergence following the Late Oligocene continental collision developed a new subduction activity flipping to the western margin of the IBA. The convergence caused collision of the northeastern ends of the Indian continent with the northern segment of the amalgamated IBA–Burma block to the north, during the Pliocene. This caused thrust imbrications of the Pliocene molasse sediments in the 'belt of schuppen' that flank the Naga foothills to the north (Figs. 1, 2).

The Paleogene sediments in IBR were unlikely to have been sourced by the nascent Himalaya. The Late Oligocene collision, however, caused major change in basin configuration and sedimentary setting. Under such changed setting, the Himalaya-sourced offscraped sediments from proto-Bay of Bengal became a major component for the Neogene accretionary wedge that flanked the western margin of IBR.

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