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ORIGINAL PAPER

Early Cretaceous wedge extrusion in the Indo-Burma Range accretionary complex: implications for the Mesozoic subduction of Neotethys in SE Asia

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Abstract The Indo-Burma Range (IBR) of Myanmar, the eastern extension of the Yarlung-Tsangpo Neotethyan belt of Tibet in China, contains mélanges with serpentinite, greenschist facies basalt, chert, sericite schist, silty slate and unmetamorphosed Triassic sandstone, mudstone and siltstone interbedded with chert in the east, and farther north high-pressure blueschist and eclogite blocks in the Naga Hills mélange. Our detailed mapping of the Mindat and Magwe sections in the middle IBR revealed a major ~18 km antiformal isocline in a mélange in which greenschist facies rocks in the core decrease in grade eastwards and westwards symmetrically 'outwards' to lower grade sericite schist and silty slate, and at the margins to unmetamorphosed sediments, and these metamorphic rocks are structurally repeated in small-scale imbricated thrust stacks. In the Mindat section the lower western boundary of the isoclinal mélange is a thrust on which the metamorphic rocks have been transported over unmetamorphosed sediments of the Triassic Pane Chaung Group, and the upper eastern boundary is a normal fault. These relations demonstrate that the IBR metamorphic rocks were exhumed by wedge extrusion in a subduction-generated accretionary complex. Along strike to the north in the Naga Hills is a comparable isoclinal mélange in which central eclogite lenses are succeeded 'outwards' by layers of glaucophane schist and glaucophanite, and to lower grade greenschist facies sericite schist and slate towards the margins. In the Natchaung area (from west to east) unmetamorphosed Triassic sediments overlie quartzites, sericite schists, actinolite schists and meta-volcanic amphibolites derived from MORB-type basalt, which are in fault contact with peridotite. Olivine in the peridotite has undulatory extinction suggesting deformation at 600–700 °C, similar to the peak temperature of the amphibolite; these relations suggest generation in a metamorphic sole. The amphibolites have U/Pb zircon ages of 119 ± 3 Ma and 115 Ma, which are close to the zircon ages of nearby calc-alkaline granite and diorite, which belong to an active continental margin arc that extends along the western side of the Shan-Thai block. The IBR accretionary complex and the active continental margin arc were generated during Early Cretaceous (115–128 Ma) subduction of the Neotethys Ocean.

Keywords Myanmar · Indo-Burma Range · Accretionary complex · Wedge extrusion · Early Cretaceous · Neotethys

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Introduction

The Neotethys Ocean closed eastwards in a scissor fashion between the Gondwana and Eurasia continents (Fig. 1a), leading to widespread ophiolite obduction in Asia (Hall 2002; Pan et al. 1997; Scotese and Sager 1988; Şengör 1984). Subduction of the Neotethys Ocean was one of the most important subduction-accretion processes in the Cretaceous along the southern margin of the Eurasian continent. Some Neotethyan ophiolites are preserved along the Yarlung-Tsangpo ophiolitic belt in Tibet (Fig. 1b), whose ages are mainly 120–130 Ma (Liu et al. 2016; Wu et al. 2014). This Cretaceous subduction–accretion belt continues semi-continuously via the Himalaya westwards to the Iranian-Turkish Plateau (Searle et al. 1987) where it contains almost coeval exhumed blueschists and obducted ophiolites (Monié and Agard 2009). However, when traced eastwards, the Cretaceous belt has been disrupted and dismembered mostly by Neogene tectonic events around the eastern Himalayan syntaxis to the Indo-Burma Range on its way to the archipelagic framework in Indonesia (Hamilton 1988; Hennig et al. 2016; Ridd and Watkinson 2013). Because of exposure and insufficient studies it has proved more difficult to reconstruct the complete sequence of subduction–accretion events along the southeastern margin of the Eurasian continent, especially in Myanmar.

The Indo-Burma Range (IBR) in Myanmar and NE India is the southeastern extension of the Yarlung-Tsangpo ophiolitic belt in Tibet (Fig. 1a) (Acharyya 1998, 2015; Brunnschweiler 1966). The IBR is a subduction–accretion complex that contains *inter alia* ophiolitic mélanges, and high-pressure blueschists and eclogites in the Naga Hills (Acharyya 2007, 2015; Bannert et al. 2011; Barley et al. 2003; Ghose et al. 2014; Khogenkumar et al. 2016; Metcalfe 1995, 2006, 2011; Mitchell 1993; Socquet et al. 2002). Although the IBR underwent some modifications during later tectonic events (Acharyya 2007), it is relatively un-dismembered, and thus retains a continuous record of orogenic processes during closure of the Neotethys Ocean, and so it is a key region to address the Cretaceous subduction–accretion system.

In the Kalemyo area (Figs. 1c, 2), where gabbros and metamorphic rocks have U-Pb zircon ages of 130 and 115 Ma, respectively (Liu et al. 2016), the IBR is unconformably overlain by middle/late Cretaceous to Eocene foraminifera-bearing sediments (Acharyya 1998; Bannert et al. 2011; Brunnschweiler 1966; Ghose et al. 2014; Gramann 1974; Socquet et al. 2002; Swe 2012). Mitchell et al. (2015) suggested that the IBR accretionary complex and magmatic arc axis in central West Burma (Fig. 1c) formed during an early episode of subduction. However, to the east of the IBR, the Sibumasu and West Burma (or Myanmar Central Basin) terranes (Fig. 1b, c) (Barber and Crow 2009; Barley et al. 2003; Metcalfe 1995, 2006, 2011; Mitchell 1981, 1993; Shi et al. 2008; Swe 2012) contain Early Cretaceous (114–128 Ma) and Late Cretaceous (<106 Ma) magmatic arcs, respectively (Fig. 1c) (Barley et al. 2003; Gardiner et al. 2015; Liang et al. 2008; Metcalfe 2011; Mitchell et al. 2012; Wang et al. 2014; Swe 2012). Therefore, the question arises: which of these two eastern magmatic arcs developed with the early accretion of the IBR accretionary complex? Further key questions are: how were the HP rocks exhumed structurally, and was the Early Cretaceous subduction polarity eastwards (Acharyya 2007; Metcalfe 2006, 2011) or westwards (Mitchell 1993; Mitchell et al. 2012)?

The aims of this paper are to report our new data from the IBR accretionary complex (AC) and a new sub-ophiolite metamorphic sole in the Natchaung area to the south of Kalemyo to demonstrate the processes of accretion, wedge extrusion, and obduction within the IBR, and to help resolve the subduction polarity in the Early Cretaceous. These results will enable us to present a new tectonic framework for the closure of Neotethys in SE Asia.

Geological outline

Myanmar contains (from east to west) the Sibumasu and West Burma terranes and the IBR accretionary complex (Fig. 1b, c) (Acharyya 1998, 2007, 2015; Metcalfe 1995, 2006, 2011; Mitchell 1981; Mitchell et al. 2012; Swe 2012). These three tectonic units are separated by the Mogok metamorphic belt, and by faults along the eastern margin of the Indo-Burma Range (Fig. 1c). These units were split from the Gondwana continent after the Early Permian (Metcalfe 2011; Mitchell et al. 2015; Ridd 2016) and were accreted to the southern margin of the Eurasia continent from the Jurassic (Metcalfe 1995, 2006, 2011; Mitchell et al. 2015; Swe 2012).

The part of the Sibumasu terrane in Myanmar is called the Shan-Thai block (Metcalfe 2006; Mitchell 1981; Shi et al. 2008; Swe 2012). However, Mitchell et al. (2012), Mitchell et al. (2015), Ridd (2016) and Ridd and Watkinson (2013) suggested that Sibumasu comprises two terranes that are separated by the Medial Myanmar Suture, which formed in the Jurassic along the eastern margin of the Mogok Metamorphic Belt and Mergui Group. Here, we follow the Shan-Thai block definition of the Sibumasu terrane, because re-classification is beyond the subject of this paper and it does not affect our discussion of the early Cretaceous subduction system. The Shan-Thai block is composed of unmetamorphosed or weakly altered Paleozoic, Triassic and Jurassic strata (Fig. 1c) (Cai et al. 2016b; Ridd 2016; Swe 2012). On its western margin is the Mogok Metamorphic Belt (Fig. 1c), which mainly comprises schists and gneisses that are intruded by granite and diorite (Barley et al. 2003; Mitchell et al. 2012; Searle et al. 2007). Some gneissses, granites and diorites have Early Cretaceous zircon ages of 128–114 Ma (Fig. 1c) (Barley et al. 2003; Liang et al. 2008; Mitchell et al. 2012), but others are younger than 100 Ma (Gardiner et al. 2015; Mitchell et al. 2012).

Along its central axis the West Burma terrane contains schist, diorite, granite and basalt (Fig. 1c) (Mitchell et al. 2012; Shi et al. 2008; Swe 2012), which were generated in a magmatic arc younger than 106 Ma (Mitchell 1993). The youngest detrital zircons in a schist near Salingyi to the south of Monywa, are younger than 120 Ma (Personal communication of Professor Lin Ding from the Institute of Tibetan Plateau Research of the Chinese Academy of Sciences) and negate the hypothesis that Precambrian rocks crop out in the West Burma terrane (Acharyya 2007; Metcalfe 1995, 2006, 2011). Liu et al. (2016) suggested that the Shan-Thai block collided with the West Burma terrane in the Jurassic along the Myitkyina suture zone, which contains an ophiolite dated at ~170 Ma. However, we found that km-size peridotites and massive intrusive plutons containing gabbro, massive basic diorite, diorite, leucogranitic diorite and biotite granodiorite. An associated chert-like tuffaceous siltstone contains abundant zircons (we selected more than 500 grains from a 1 kg sample); no pillow basalts or thin-bedded cherts were found. Trace element geochemistry shows that these rocks have a supra-subduction zone (SSZ) fingerprint (Liu et al. 2016; Yang et al. 2012). To the east and west of the Myitkyina belt there are pre-Mesozoic meta-sediments. Accordingly, we conclude that the Myitkyina intrusions are components of an active continental margin arc, rather than an ophiolite, but further elaboration is beyond the scope of this paper.

The IBR (Acharyya 2015; Bannert et al. 2011; Mitchell et al. 2012; Swe 2012) is divisible into two belts based on rock assemblages (Allen et al. 2008; Brunnschweiler 1966; Curray 2005; Curray et al. 1979; Hutchinson 1989; Mitchell 1974). The western belt consists of Cenozoic and minor Upper Cretaceous sediments that contain many leaf fossils (Brunnschweiler 1966), but the eastern belt is more complex. In the sections below we will present details of the eastern belt, and briefly discuss the relationships between the two belts.

Lithology

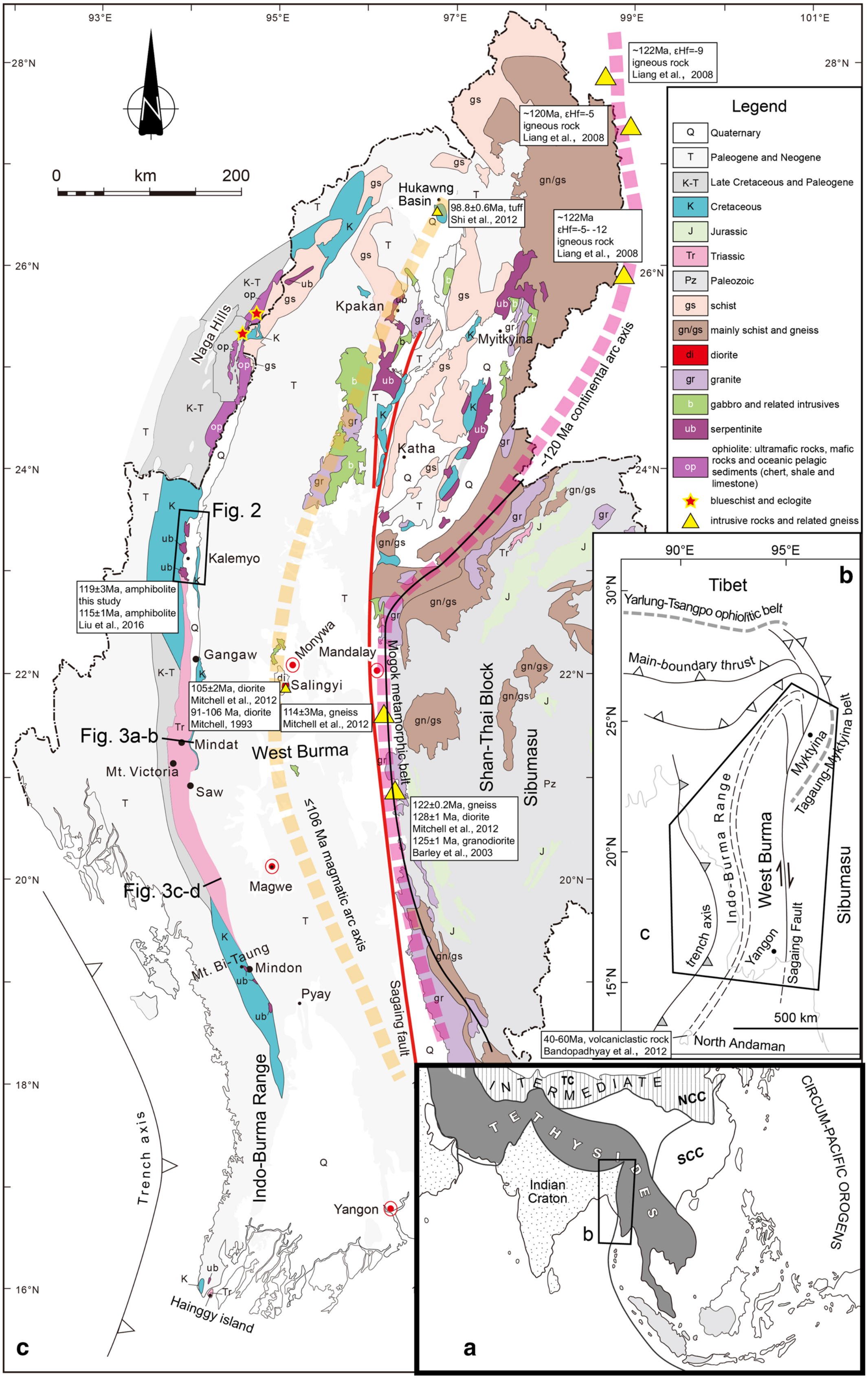
The eastern IBR extends for more than 1000 km from the Naga Hills along the international border between Myanmar and India in the north to Hainggy island and the Andaman sea in the south (Fig. 1c). It mainly contains Mesozoic and Paleogene sediments, low-grade metamorphic rocks, and ophiolitic mélanges (Acharyya 2015; Ao and Bhowmik 2014; Bannert et al. 2011; Baxter et al. 2011; Brunnschweiler 1966; Gramann 1974; Khogenkumar et al. 2016; Mitchell 1981, 1993; Ningthoujam et al. 2012; Sarkar et al. 1996; Singh 2013; Swe 2012), but also high-pressure metamorphic rocks in the Naga Hills (Acharyya 2007; Ao and Bhowmik 2014; Ghose et al. 2010, 2014; Venkataramana et al. 1986).

Sedimentary and metamorphic rocks

Triassic and Cretaceous sediments crop out along the eastern side of the IBR (Figs. 1c, 3). Jurassic terrigenous sediments have so far not been found in the IBR except for some blocks of red thin-bedded pelagic chert in ophiolitic mélanges in the Naga Hills (Fig. 1c) (Acharyya 2015; Baxter et al. 2011; Mitchell 1981; Sarkar et al. 1996).

There are two types of Triassic unmetamorphosed sediments. The first one is thin-bedded siltstones and mudstones intercalated with gray cherts (Fig. 4a), which are of limited extent. They only crop out in the Mindat section (Figs. 2a, 3b) and to north of Kalemyo. They are in fault contact and surrounded by low-grade sericite schist and interbedded quartzite, which are metamorphosed siltstone and chert (Figs. 3, 4b) (Bannert et al. 2011; Socquet et al. 2002). The sericite schists are widespread along the eastern side of the IBR from Mindon to the Naga Hills (Fig. 1c). These low-grade metamorphic rocks, which are commonly termed the Kanpetlet Schist near Mindat-Saw area (Swe 2012), were earlier regarded as Precambrian basement (Brunnschweiler 1966; Swe 2012). Brunnschweiler (1966) pointed out that some of the highest mountains in the Naga Hills are composed of "Klippen" of metamorphic rocks lying on Cenozoic flysch. However, the youngest detrital zircons from the sericite schists have U-Pb ages of 228–239 Ma in the Mindat and Magwe sections (Fig. 5a, b). In contrast, in the Naga Hills, these low-grade metasediments are still considered to be Proterozoic, originating from the West Burma terrane (Acharyya 2015). Because of the inaccessibility of the Naga Hills, we are unable to constrain or confirm the age of these metamorphic rocks.

The second type of Triassic sediment is unmetamorphosed, interbedded sandstone, mudstone and limestone containing *Halobia* and *Daonella* (Figs. 3, 4e) (Bannert et al. 2011; Mitchell 1993; Swe 2012), which are termed the Pane Chaung Group in the geological map of Mindat-Saw Area edited by Burma United Nations DGSE GSE-Project BUR/72/002 (1978) (Bannert et al. 2011; Bender 1983). The Daonella-bearing limestones and calcareous sandstones crop out to the west of Gangaw (Swe 2012) and on the western side of the Magwe section (Fig. 3c). These sandstones and mudstones correlate with the Langjiexue Group to the south of the Yarlung-Tsangpo ophiolitic belt in


93°E
95°E
97°E
99°E
101°E
28°N
26°N
24°N
22°N
20°N
18°N
16°N
0 km 200
~122Ma, εHf=-9
igneous rock
Liang et al., 2008
~120Ma, εHf=-5
igneous rock
Liang et al., 2008
~122Ma
εHf=-5- -12
igneous rock
Liang et al., 2008
Hukawng Basin
98.8±0.6Ma, tuff
Shi et al., 2012
Naga Hills
Kpakan
Myitkyina
Katha
~120 Ma continental arc axis
Fig. 2
Kalemyo
119±3Ma, amphibolite
this study
115±1Ma, amphibolite
Liu et al., 2016
Gangaw
Monywa
Mandalay
Salingyi
105±2Ma, diorite
Mitchell et al., 2012
91-106 Ma, diorite
Mitchell, 1993
114±3Ma, gneiss
Mitchell et al., 2012
Fig. 3a-b
Mindat
Mt. Victoria
Saw
West Burma
Mogok metamorphic belt
Shan-Thai Block
Sibumasu
122±0.2Ma, gneiss
128±1 Ma, diorite
Mitchell et al., 2012
125±1 Ma, granodiorite
Barley et al., 2003
≤106 Ma magmatic arc axis
Fig. 3c-d
Magwe
Mt. Bi-Taung
Mindon
Pyay
Sagaing fault
40-60Ma, volcaniclastic rock
Bandopadhyay et al., 2012
Trench axis
Indo-Burma Range
Yangon
Hainggy island
c
Legend
Q Quaternary
T Paleogene and Neogene
K-T Late Cretaceous and Paleogene
K Cretaceous
J Jurassic
Tr Triassic
Pz Paleozoic
gs schist
gn/gs mainly schist and gneiss
di diorite
gr granite
b gabbro and related intrusives
ub serpentinite
op ophiolite: ultramafic rocks, mafic rocks and oceanic pelagic sediments (chert, shale and limestone)
★ blueschist and eclogite
▲ intrusive rocks and related gneiss
b
90°E
95°E
30°N
25°N
20°N
15°N
Tibet
Yarlung-Tsangpo ophiolitic belt
Main-boundary thrust
Myktyina
Tagaung-Myktyina belt
Indo-Burma Range
West Burma
trench axis
Yangon
Sagaing Fault
Sibumasu
c
500 km
North Andaman
a
INTERMEDIATE
TC
NCC
TETHYSIDES
SCC
Indian Craton
b
CIRCUM-PACIFIC OROGENS

◂**Fig. 1** *a* Schematic map of East Asia (Şengör 1990) showing the location of the Tethysides (Himalayas) and SE Asia. *TC* Tarim craton, *NCC* North China craton, *SCC* South China craton. *b* Main tectonic units extending from southern Tibet to Myanmar (Acharyya 1998; Searle et al. 2007; Shi et al. 2008). *c* Simplified geological map of Myanmar and the Naga Hills [modified from geological maps of Myanmar (1977), Acharyya (2015), Ghose et al. (2010) and Singh (2013)]. The ages of Early Cretaceous igneous rocks along the western margin of the Shan-Thai block are indicated, and the *pink* and *yellow dashed lines* mark the Early Cretaceous and Late Cretaceous continental and magmatic arcs, respectively. The positions of Figs. 2, 3a–d are marked

southern Tibet (Cai et al. 2016a; Wang et al. 2016). Some sediments occur as block-in-matrix mélanges (Fig. 6b), and locally some calcareous sandstones have clear herringbone cross-bedding (Fig. 4d), suggesting deposition in a shallow marine environment. Primary way-up structures show that some sediments are overturned (Fig. 4c).

The above two types of unmetamorphosed Triassic sediments are separated by sericite schists and are not in direct contact (Fig. 3), but their sedimentary structures suggest that they were deposited at different water depths, confirming they are now in fault contact.

Ophiolitic mélange

The ophiolitic mélanges contain serpentinized peridotite, gabbro, pillow basalt, and chert, and some exotic metamorphic rocks (Acharyya 2015; Ao and Bhowmik 2014; Bannert et al. 2011; Brunnschweiler 1966; Liu et al. 2016; Ningthoujam et al. 2012; Singh 2013). Except in the Naga Hills (Acharyya 2015; Ghose et al. 2014), most outcrops do not contain all these rocks together.

Peridotites and serpentinites are widespread along the eastern margin of the IBR from the Naga Hills in the north to near Hainggy island in the south (Fig. 1c) (Bannert et al. 2011; Baxter et al. 2011; Brunnschweiler 1966; Ghose et al. 2014; Ningthoujam et al. 2012; Sarkar et al. 1996; Singh 2013; Venkataramana et al. 1986). Generally, the peridotites in the Kalemyo region are fresh (Fig. 2) (Liu et al. 2016), although the margins of some peridotites are altered to serpentinite and weakly deformed (Fig. 3c). Some strongly sheared serpentinites within block-in-matrix structures are commonly mixed with other components of ophiolitic rocks (Fig. 3b). The gabbros are limited in extent, mostly as small size blocks in a serpentinite matrix. For example, there are no gabbros in the Magwe section, and only one outcrop in the Mindat section (Fig. 3). But in the Yazagyo area to the north of Kalemyo (Fig. 2a) the mélange contains gabbroic diorites, and Liu et al. (2016) reported limited rodingites derived from gabbro, and their exposures are smaller than 10 m^2.

Basalts and cherts are widespread and occur together in the IBR (Figs. 1c, 2b, 3). There are two types of occurrence: (1) Some pillow basalts are associated with thin-bedded radiolarian red cherts, and generally have fault contact with serpentinites and unmetamorphosed sedimentary rocks in the Mindat section and in the Yazagyo area (Figs. 2a, 3b). (2) Some basalts and cherts that have been metamorphosed to greenschist, sericite quartzite and amphibolite (Figs. 2b, 3) (Bannert et al. 2011; Liu et al. 2016) generally occur in blocks less than 1 m to tens of meters across, as in the block of greenschist within meta-siltstone sericite schist in the Magwe and Mindat sections (Fig. 4g). The basalts are fine- to medium-grained (Fig. 4h), and contain phenocrysts of augite and hornblende (Bannert et al. 2011). In the Naga Hills they have MORB and OIB trace element signatures (Khogenkumar et al. 2016; Sengupta et al. 1989; Venkataramana et al. 1986), suggesting they are derived from oceanic crust or a seamount/oceanic plateau (Acharyya 2015). Locally they are in fault contact with unmetamorphosed Triassic rocks (Fig. 7a).

Exotic blueschist and eclogite occur as blocks in the ophiolitic mélange of the Naga Hills (Acharyya 2015; Ao and Bhowmik 2014; Bannert et al. 2011; Ghose et al. 2010, 2014; Singh 2013). The blueschists contain fine-grained (0.3-2mm) crystalloblasts and needles of pleochroic glaucophane (Bannert et al. 2011). Metabasites have a low-K tholeiitic signature possibly derived from a mid-ocean ridge, and the peak P-T conditions of blueschists are ~11.5 kbar and ~340 °C and ~10 kbar and ~325 °C that suggest metamorphism during cold subduction (Ao and Bhowmik 2014; Bannert et al. 2011). Ophiolites are overlain unconformably by the mid-Eocene Phokphur Formation of shallow marine tuffaceous greywackes, conglomerates and shales (Acharyya 2015). No high-pressure metamorphic rocks have been found in Myanmar.

Amphibolite and related pelagic sediments

Along the IBR in Myanmar we found only one outcrop of amphibolite in the Natchaung area south of Kalemyo (Figs. 1c, 2b) (Bannert et al. 2011; Liu et al. 2016), where unmetamorphosed Triassic sandstones and mudstones (Fig. 6b) occur with quartzites and sericite schists (Fig. 6d), actinolite schists (Fig. 6e, f), amphibolites (Fig. 6g, h) and peridotites (Fig. 6c). Their occurrences from west to east (Fig. 2b) suggest that the metamorphic grade increases eastwards. Some serpentinites with a "block-in-matrix" structure are thrust onto unmetamorphosed Triassic sediments (Fig. 6a).

Thinly bedded quartzites (1–3 cm thick beds) are intercalated with thinly bedded sericite schists (beds are less than 1 mm thick) and do not contain detrital zircons. These features suggest their derivation from cherts and pelagic mudstones (Fig. 6d).

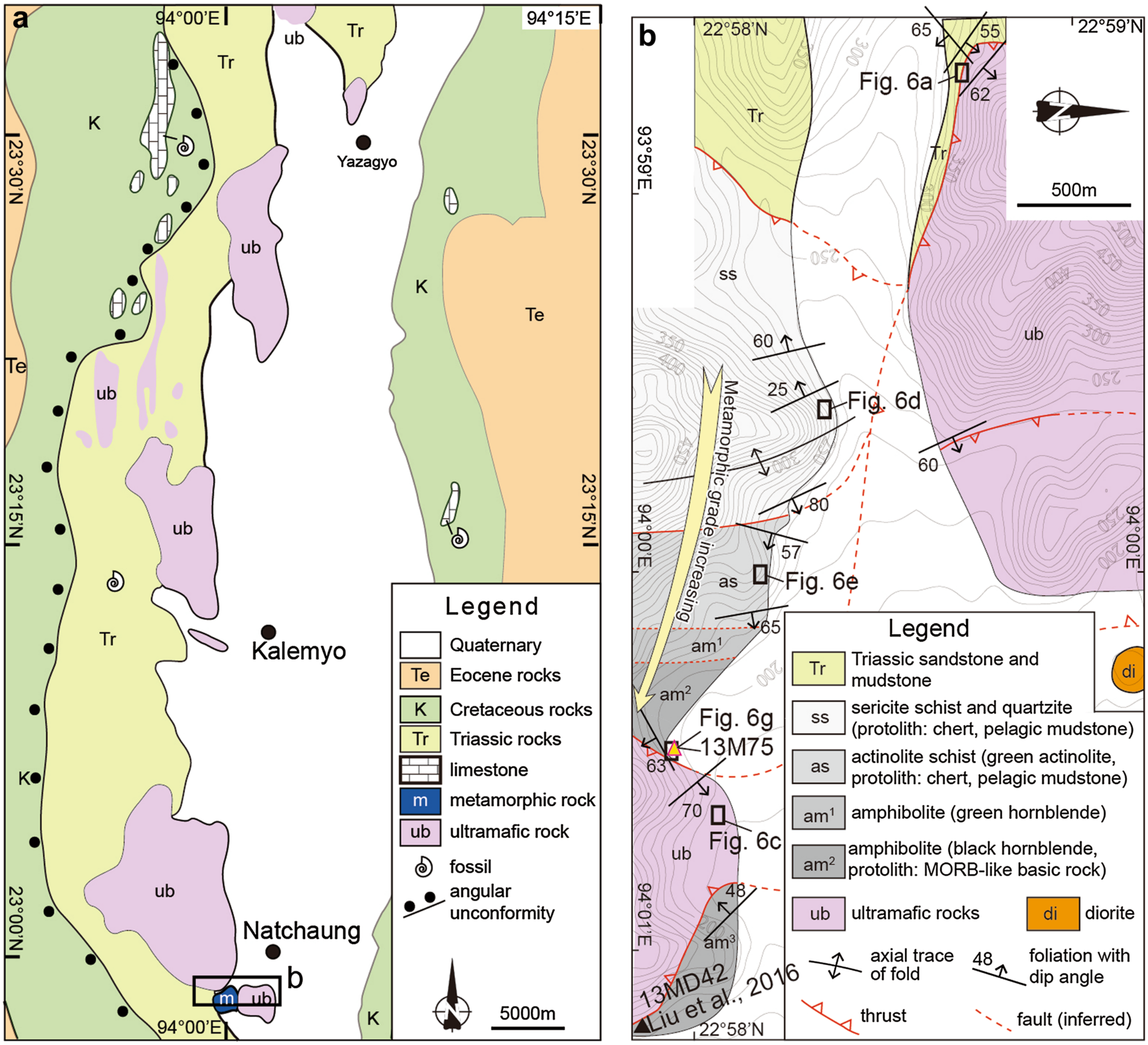


Fig. 2 **a** Geological map of the Kalemyo area (Fig. 1c) (modified after Burma Department of Geological Survey and Mineral Exploration, 1977 of the Geology of the Falam-Kalemyo area, northern Chin Hills), showing the relationship between Cretaceous strata and the IBR accretionary complex composed of Triassic strata, metamorphic rocks, peridotite and serpentinite. Position of 2b is marked. **b** Geological map of the Natchaung metamorphic sole, showing that the metamorphic grade increases from untamorphosed Triassic sandstone and mudstone to sericite schist and quartzite, actinolite schist and amphibolite from west to east. See text for details. The dated amphibolite 13M75 is marked. The amphibolite (13MD42) studied by Liu et al. (2016) is indicated with a *triangle*. The location of the diorite is based on Bannert et al. (2011)

The grain size of amphibolites, which are in direct contact with peridotites, increases from the boundaries with actinolite schists to the peridotite contacts (Fig. 2b) (the largest amphiboles are 5–8 mm long), and amphibole colors change from green to black (Fig. 2b). Amphibolites have flat REE patterns and are slightly depleted in LREEs, and their zircons have low Th contents, low Th/U ratios, and depleted Hf isotopes and their $\delta^{18}O$ values are remarkably higher than mantle values; these variations suggest that the amphibolite protolith was a low-temperature altered MORB-like basalt (Liu et al. 2016). This would be consistent with the idea that the protolith of the associated quartzite was pelagic chert, and that these rocks were part of ocean plate stratigraphy (OPS), which would be an expected provenance in such an ophiolitic mélange (Kusky et al. 2013). We envisage that the top basalts and overlying

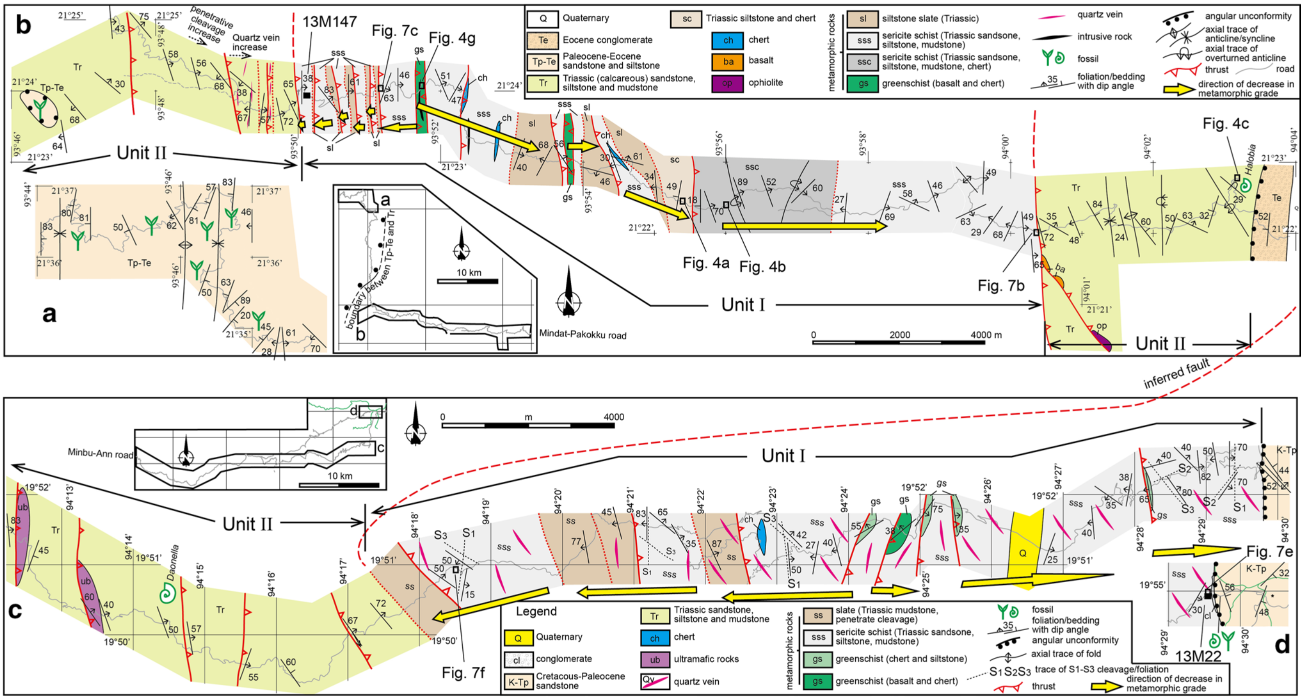


Fig. 3 Detailed geological and structural maps of the Mindat (**a, b**) and Magwe (**c, d**) sections. Their locations are marked in Fig. 1c. Samples for detrital zircon dating are marked as 13M22 and 13M147. *Red dashed lines* are inferred faults. The decrease in metamorphic grade (indicated by *yellow arrows*) westwards and eastwards from the central higher grade-core of greenschists of both sections suggests the presence of isoclinal folds and exhumation by wedge extrusion. Figure 8b shows a cross-section of the Mindat section. Positions of Figs. 4a–c, g, 7b, c, e, f are marked. See text for details

pelagic sediments were scraped off the subducting Neotethys Ocean crust, and accreted to the accumulating mélange, in a similar way to other greenschists in the IBR.

Structural geology

Imbricated thrust stack

Based on metamorphic grade, we divide the IBR into two units: ca 18 km-wide Unit I (silty slate, sericite schist and greenschist) and ca 10 km-wide Unit II (unmetamorphosed Triassic sandstone and mudstone) (Fig. 3). In the Magwe section, Unit I occurs to the east of Unit II in which a transfer zone along the road near 94°18′E, is accompanied by an increase (from west to east) in metamorphic grade from unmetamorphic to slate (Fig. 3c, d). In the Mindat section, Unit II is repeated twice and Unit I separates the two on the road at 93°50′E and 94°00′E (Fig. 3b). Because of heavy forest cover, we were unable to trace the extensions of the units, so we do not know their total length. However, the fact that Unit II crops out twice in the Mindat section and once in the Magwe section demonstrates that several OPS-mélange units are imbricated in the Indo-Burma Range. Here we assume that Units I and II extend along their strike from north to south. The boundary between Unit I and the eastern Unit II in the Mindat section is located near 94°00′E, west of the boundary between Unit I and Unit II in the Magwe section at 94°18′E. This Unit II occurs between 94°00′E and 94°18′E; its eastern boundary is shown as a red dashed line in Fig. 3, which also shows that Units I and II are repeated two and three times, respectively, in these sections. Considering the fact that the units may vary along strike and have different lengths, Units I and II should be repeated several times in the eastern IBR, suggesting major accretion of imbricated thrust stacks in a trench (Acharyya et al. 1989; Mitchell 1974).

Unit I is internally subdivided into greenschist, sericite schist, slate and unmetamorphosed rocks (Fig. 3), which are arranged with increasing metamorphic grade and repeated several times in the Magwe and Mindat sections, suggesting the polarity of their imbrication as shown with yellow arrows in Fig. 3. This is the typical structural architecture of accretionary prisms worldwide (Fujisaki et al. 2015; Hashimoto and Kimura 1999; Kawai et al. 2007; Kusky et al. 2013; Sawaki et al. 2010).

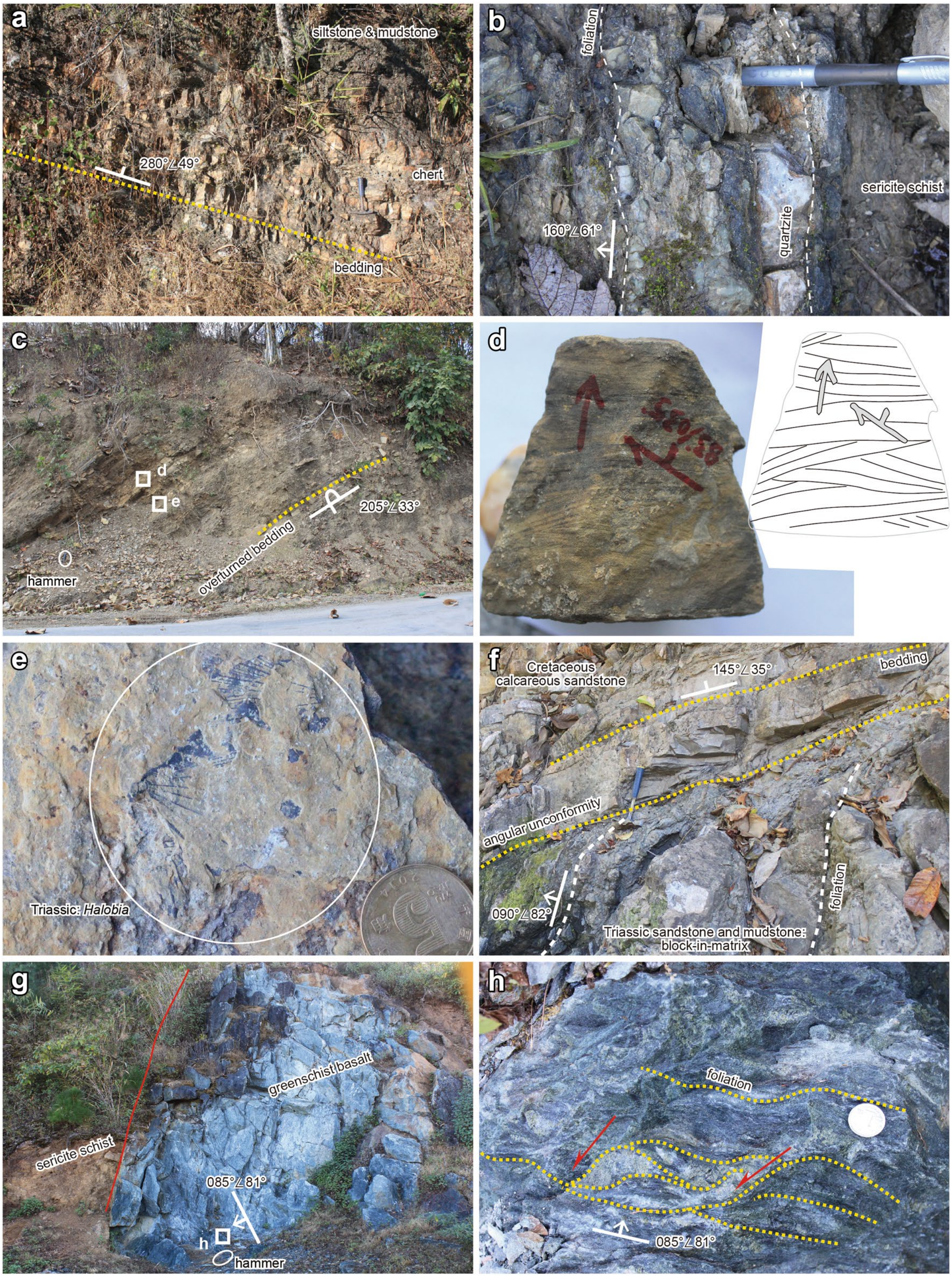


Fig. 4 Field photos of rocks and structures in the IBR. **a** Triassic siltstone and mudstone intercalated with thinly bedded chert in the Mindat section. **b** Quartzite and sericite schist in the Mindat section, which are metamorphosed from chert and siltstone. **c** In the eastern Mindat, overturned Triassic calcareous mudstone and sandstone with herringbone cross-bedding (**d**) and the fossil *Halobia* (**e**). **f** Near the Saw area, Late Cretaceous calcareous sandstone unconformable on Triassic sandstone and mudstone, which has "block-in-matrix" structure. **g** Greenschist basalt, surrounded by sericite schist, develops a minor extensional shear zone duplex (**h**) in the Mindat section. The locations of Figs. 4a–c, g are marked in Fig. 3

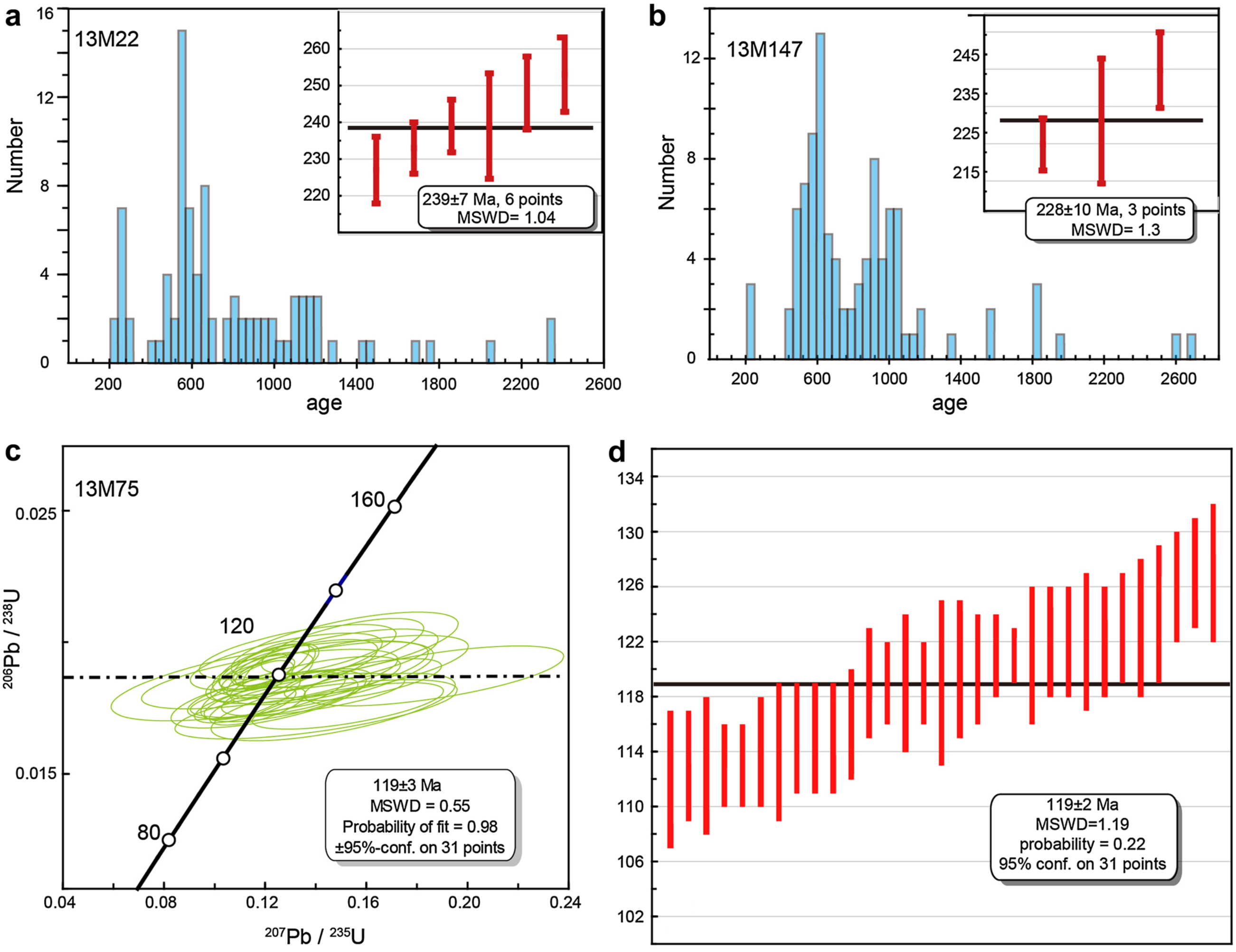


Fig. 5 **a, b** Detrital zircon ages of 13M22 and 13M147 from the Magwe and Mindat sections, showing that the youngest groups have Triassic ages of 239 and 228 Ma, respectively. **c, d** U-Pb zircon ages of amphibolite 13M75, showing that they are close to the age of 115 Ma of amphibolite (13MD42) of Liu et al. (2016). The locations of these amphibolites are marked in Fig. 2b. The data of 13M75 are in the Supplementary file. See Liu et al. (2016) for more details of $\delta^{18}O$, CL images and *εHf*(*t*) of the amphibolite

Antiformal isoclinal structure

In both sections, there are isoclinal antiforms in which the highest metamorphic grade greenschists or HP eclogites and blueschists are located in the centre or core of the structures (Figs. 3, 8b) (Acharyya 2015; Chatterjee and Ghose 2010), and the imbricated (in Unit I) lower metamorphic grade sericite schists and silty slates are situated in the limbs. The yellow arrows in Fig. 3 and the black arrows in Fig. 8b points to the directions of metamorphic grade decrease.

In the Mindat section the greenschists are repeated twice, and in Fig. 8b we mark G1 and G2 as the central greenschists in the western and eastern folds, respectively. To west of G1 in Unit I there are silty slates and sericite schists, which lie above a basal thrust on unmetamorphosed Triassic Pane Chaung Group sediments of Unit II. To east of G2 the metamorphic grade decreases eastwards (shown by pink dashed arrows in Fig. 8b). In general, the highest metamorphic grade rocks occur in the fold cores of the Mindat and Magwe sections, and the metamorphic grade decreases toward the east and west on the fold limbs, respectively (shown by orange dashed arrows in Fig. 8b). The fact that the metamorphic grade decreases symmetrically outwards from the central higher grade rocks suggests the presence of symmetrical isoclinal folds.

On the western lower boundary of Unit I in the Mindat section (Fig. 8b) sericite schist (foliation dips east at 38°), is thrust onto unmetamorphosed Triassic Pane Chaung Group sediments (bedding attitude is S26°E/65°NE) (Fig. 3b). The thrust dips equally to the east (Fig. 3b). At the eastern boundary of Unit I (Fig. 8b), the juxtaposed unmetamorphosed Triassic Pane Chaung Group sediments dip at S7°E/78°NE and the underlying sericite schists dip at

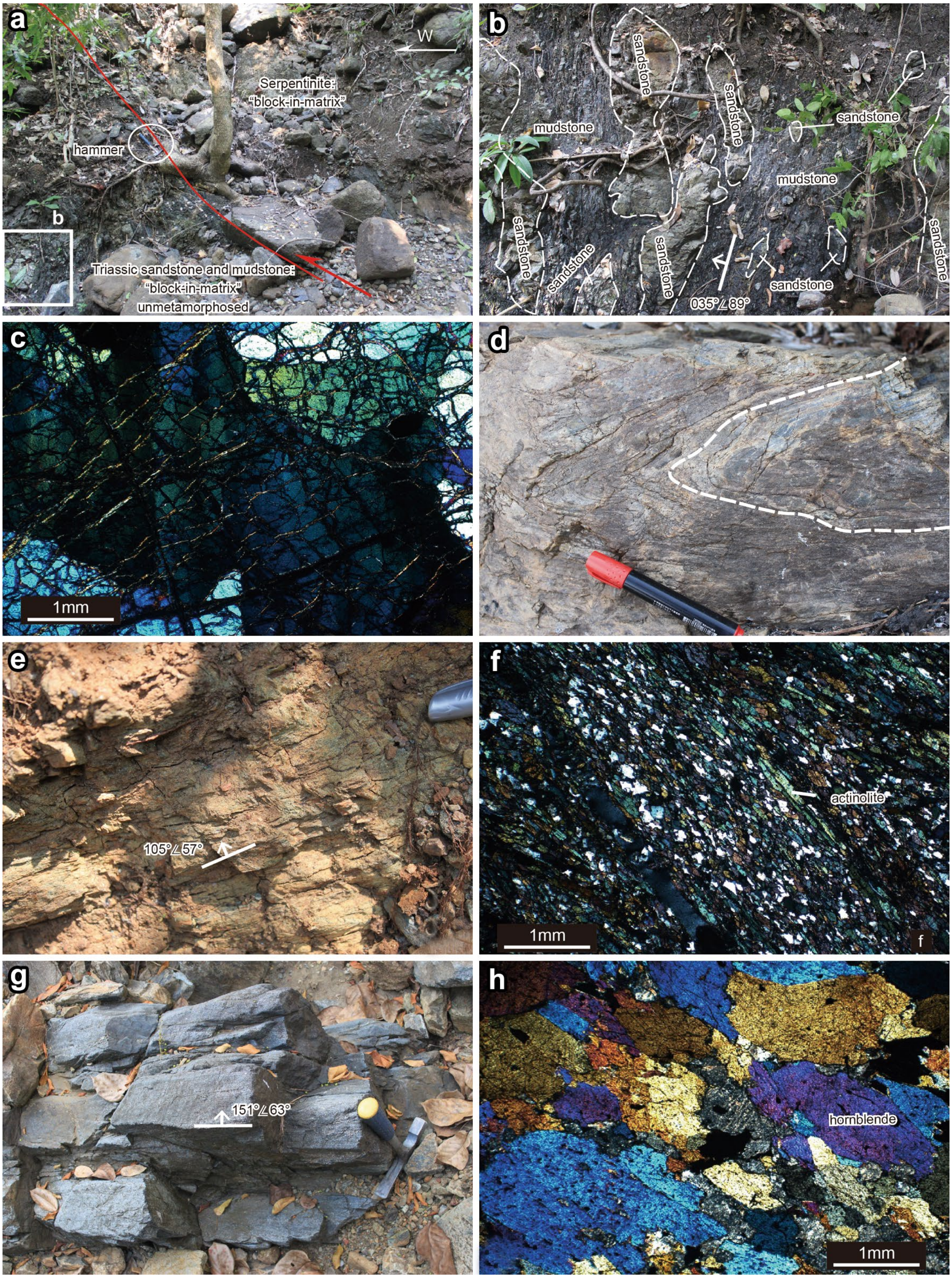


Fig. 6 Structures and lithologies of the Natchaung metamorphic sole. **a** Serpentinite thrusts onto unmetamorphosed Triassic strata with a "block-in-matrix" structure shown in detail in **b**. **c** Microtexture shows olivines with undulatory extinction, suggesting that the peridotite has undergone low-temperature deformation at 600–700 °C. **d** Folded thinly bedded quartzitic schist that may be metamorphosed chert and pelagic mudstone. **e, f** Outcrop and microscope features of actinolite schist show that the actinolites have a preferred orientation. **g, h** Outcrop and microscopic views of amphibolite showing that hornblendes have a preferred orientation parallel with the main foliation, suggesting that the amphibolite was generated in a compressional regime. Photo locations are marked in Fig. 2b. See text for details

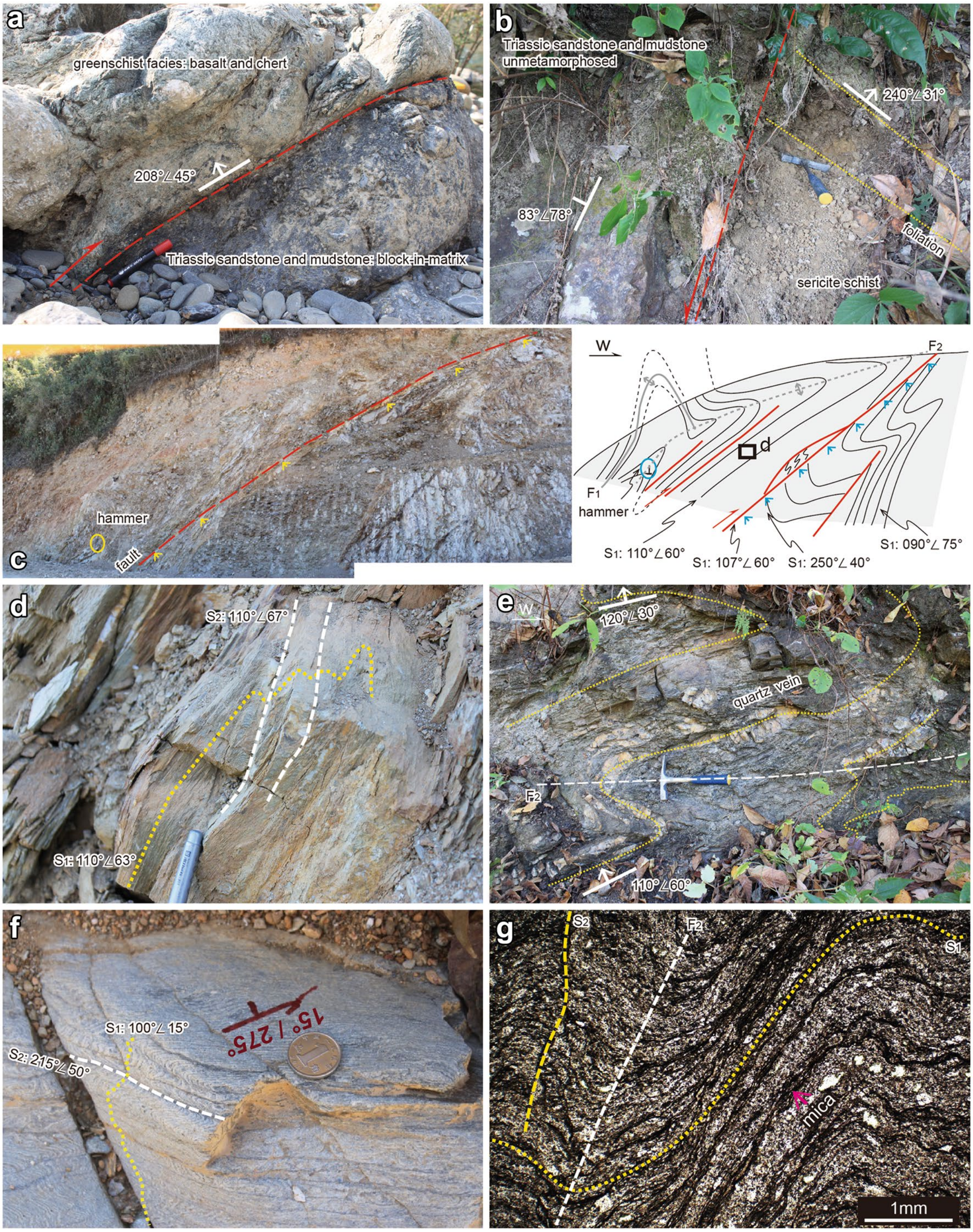


Fig. 7 Field photos of structures in the IBR. **a** Greenschist facies basalt and chert thrust over unmetamorphosed Triassic sandstone and mudstone in the Yazagyo area, north of Kalemyo. **b** Normal fault between unmetamorphosed Triassic sandstone and mudstone and underlying discordant sericite schist. **c** Superimposed folds in sericite schist showing a first-phase fold refolded by a top-to-W verging fold. For clarity, the structures are outlined in the right-hand figure. **d** Axial planar crenulation cleavage. Fold limbs are parallel to the cleavage. Mindat section. **e** Minor folds in sericite schist. A quartz vein is parallel with the schistosity. Magwe section. **f** In the Magwe section, crenulation cleavage in sericite schist showing different orientations of foliation (S_1) and cleavage (S_2). The *red arrow* shows orientation of an oriented sample, whose (g) microscopic view showing that the basal planes of micas are parallel with the foliation (S_1) and are cut by a new cleavage (S_2). The locations of Fig. 7b, c, e, f are marked in Fig. 3

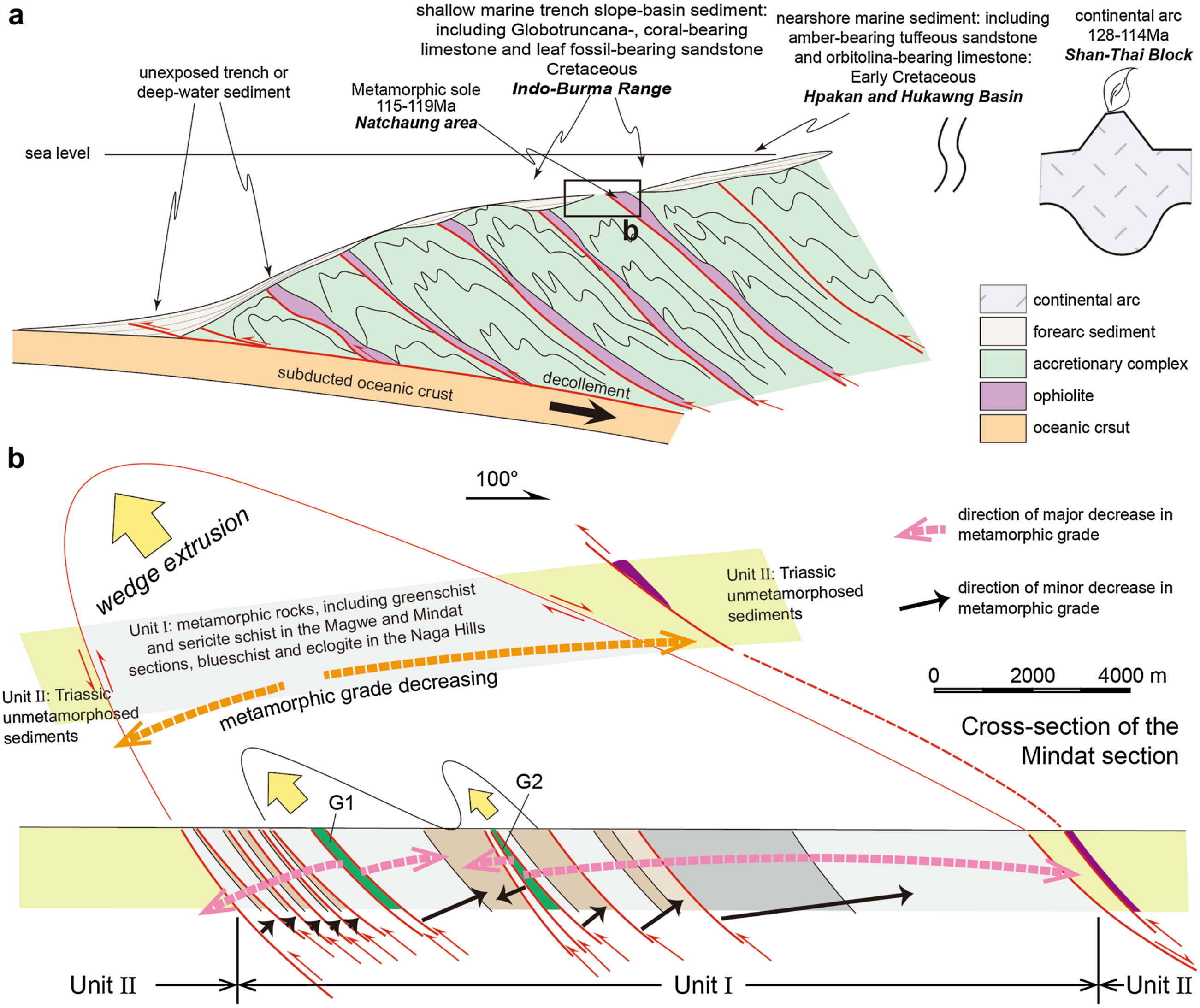


Fig. 8 **a** Tectonic model of the Early Cretaceous (114–128 Ma) subduction system in Myanmar, consisting of the accretionary wedge of the IBR and the active continental margin arc along the western margin of the Shan-Thai block (see Fig. 1c). The accretionary wedge is covered by late Early Cretaceous trench-slope basin sediments deposited in a nearshore marine to shallow marine semi-pelagic environment. Deeper water sediments may be unexposed to the west. **b** Cross-section of the Mindat section; same legend as Fig. 3. Note that the metamorphic grade decreases symmetrically outwards from greenschist or blueschist/eclogite in the central fold core of the accretionary complex to unmetamorphosed sediments in the limbs. The bottom western boundary is a thrust, whereas the top eastern boundary is an extensional fault; these dual structures enabled the accretionary complex to be exhumed via wedge extrusion. The legend of the cross-section is the same as in Fig. 3. See text for more discussion

N30°W/31°SW, and the intervening extensional fault dips east. Figures 7b and 8b show that the unmetamorphosed Pane Chaung Group sediments overlie the sericite schists on a normal fault.

Superimposed folds, faults and crenulation cleavage

Inside Units I and II there develops superimposed folds, minor faults and crenulation cleavages.

The superimposed folds and minor faults can be observed in tens of meters to hammer-size outcrops (Fig. 7c, e). The original bedding in some lithologies has been completely transposed to a foliation that is commonly intruded by quartz veins (Fig. 7e). In Fig. 7c in the Mindat section the first axial trace (F_1) has been refolded by a second overturned F_2 fold, which dips E (Fig. 7c) suggesting top-to-W shear. These folds are transected by later minor east-dipping thrusts (Fig. 7c).

Crenulation cleavages (Fig. 7d) and minor shear zones have developed on some foliation planes and on the limbs of superimposed folds (Fig. 4h). Under the microscope micas that lie with their basal planes on the first foliation

(S_1) are refolded and cut by a new axial plane cleavage (S_2) (Fig. 7g). Some S_2 crenulation cleavages, which have the same orientation (S20°W/63°SE) as the earlier S_1 foliation (S20°W/67°SE) (Fig. 7d), but other foliations (S10°W/15°SE) and cleavages (N55°W/50°SW) have different orientations (Fig. 7f). Based on these cross-cutting relationships, a deformation sequence can be established. The first foliations strike N–S, and the foliations and cleavages of the second and third folds strike NE–SW and NW–SE, respectively (Fig. 3c). The first F_1 deformation may be related to the regional metamorphism of the sericite schists.

Discussion

Wedge extrusion: mechanism of exhumation of an accretionary complex

Accretionary complexes accumulate through trench off-scrape and underplating to the base of the prism. (1) Some parts of the oceanic crust are scraped off from the down-going slab and accumulate in the frontal trench, where they may be dismembered into block-in-matrix structures, but may retain their fossils and original sedimentary structures. However, typically all the peridotites, gabbros, sheeted dykes, and most of the basalts from the oceanic crust are subducted, and only the uppermost basalts and the pelagic-clastic sediments are accreted (Kimura and Ludden 1995). (2) Some rocks enter the subduction channel and are accreted into the base of the growing accretionary prism/complex (Kawai et al. 2007), where they may undergo elevated temperatures and pressures, and develop different grades of metamorphism, such as low-middle-grade sericite schist and greenschist, to high-pressure blueschist and eclogite (Wakabayashi 2015).

In Unit II, some unmetamorphosed limestones and calcareous siltstones are intercalated or interbedded with sandstones and mudstones (Fig. 4c), which contain well-preserved *Halobia* and *Daonella* (Fig. 4e) and herring-bone cross-bedding (Fig. 4d) (Bannert et al. 2011; Mitchell 1993; Swe 2012). They were scraped off at very shallow level of accretion and not carried to a deep level in the subduction channel. In the Mindat section an ophiolitic peridotite is in fault contact with unmetamorphosed Pane Chaung Group sediments within the eastern Unit II (Figs. 3b, 8b).

Unlike Unit II with its unmetamorphosed Triassic sediments, Unit I comprises metamorphic sericite schist, quartzite and greenschist, such as the Kanpetlet Schist near Mindat-Saw or Mt. Victoria (Swe 2012). They were recrystallized from siltstone, chert and basalt, respectively, suggesting that the protoliths of Units I and II were different, and derived from different environments. The different metamorphic grades and rock assemblages confirm that Units I and II have been juxtaposed on a thrust. The different juxtaposed metamorphic rocks were exhumed from different levels of the accretionary complex by wedge extrusion in sub-horizontal nappes, explaining why there are “Klippen” of Cretaceous metamorphic rocks thrust onto Cenozoic flysch in some of the highest mountains in the Naga Hills (Brunnschweiler 1966).

Within Unit I, the highest metamorphic grade rock is greenschist located in the core of the isoclinal anticlines in the Mindat and Magwe sections. Though there are several repeated subunits (shown as yellow arrows in Fig. 3 and black arrows in Fig. 8b), the major decrease in metamorphic grade from greenschist to sericite schist/slate to unmetamorphosed sediments developed in the eastern and western limbs separated from the core of Unit I (shown as orange dashed arrows in Fig. 8b). The antiformal isoclinal structure in Unit I (Fig. 8b) is demonstrated by the symmetrical decrease in metamorphic grade in both limbs from the central higher grade core of greenschist and by the thrust on the lower boundary and the extensional fault on the upper boundary. The metamorphic rocks in the Mindat and Magwe sections are packaged by the fossil-bearing Triassic Pane Chaung Group sediments, because the lower thrust transported them over any available rocks such as the Triassic sediments, and the upper normal fault brought down any available lower grade rocks such as the Triassic sediments.

This exhumation model further explains the presence of the blueschists and eclogites in the Naga Hills. The eclogite lenses are surrounded by successive layers of glaucophane schist, glaucophanite and greenschist (Ao and Bhowmik 2014; Ghose et al. 2010). Exhumation anticlines can be demarcated by the dip-and-strike structure around the hinge of the isocline, but also by the structure of the metamorphic isogrades around blueschists as in Anglesey-Lleyn, UK (Kawai et al. 2007) and by high-pressure mafic granulites in the Trans-North China Orogen (Trap et al. 2011). This mechanism of HP wedge extrusion is known worldwide (Agard et al. 2009; Maruyama et al. 1996) and is illustrated by Fig. 8b.

Metamorphic sole and its age

The IBR accretionary complex develops complicated structures such as imbricated thrusts and duplexes, superimposed folds and crenulation cleavages, but their age is not yet known (Acharyya et al. 1989; Allen et al. 2008). To help resolve this problem, we studied amphibolites in the Natchaung area, south of Kalemyo (Figs. 1c, 2), which were previously marked as a metamorphic sole (Bannert et al. 2011; Liu et al. 2016; Mitchell et al. 2010).

The peridotites that are in contact with amphibolites (Fig. 2b) contain olivine that has undulatory extinction (Fig. 6c), suggesting the peridotite underwent low-temperature deformation at 600–700 °C (Passchier and Trouw 2005). Amphiboles in the amphibolites have a preferred orientation (Fig. 6h), indicating they underwent compressional deformation at ca. 600 °C, which is close to the deformation temperature of the olivine. From these relations we conclude that the amphibolite was derived from a metamorphic sole related to the emplacement of the peridotite (Bannert et al. 2011; Liu et al. 2016; Mitchell et al. 2010). Our new isotopic age of the amphiboles is 119 ± 3 Ma (LA-ICP MS zircon U-Pb age) (Figs. 1, 7c, d), which is close to the age obtained by Liu et al. (2016), suggesting that the metamorphic sole formed in the Early Cretaceous.

To the north of the Saw area (Fig. 1) late Early Cretaceous calcareous sandstones and limestones overlie Triassic sandstones and mudstones with an angular unconformity (Fig. 4f) (Gramann 1974). A limestone, at the base of which contains pebbles of pillow basalt, is Upper Albian (~100 Ma, Gramann 1974; Mitchell 1981) and lie unconformably on the Triassic strata and pillow basalts and lavas (Mitchell et al. 1978). West of Mindon the base of the Cretaceous Paunggyi conglomerate contains reworked serpentinite pebbles on the eastern slope of Mt. Bi-Taung (Bannert et al. 2011). These relations suggest that the late Early Cretaceous sediments were originally deposited unconformably on the Early Cretaceous accretionary complex, which consists of tectonically emplaced serpentinites, pillow lavas, cherts and Triassic sediments (Fig. 1c). More outcrops show the IBR is unconformably overlain by Middle/Late Cretaceous to Eocene foraminifera-bearing sediments (Acharyya 1998, 2015; Bannert et al. 2011; Brunnschweiler 1966; Gramann 1974; Socquet et al. 2002). Furthermore, the Late Cretaceous sediments in western IBR (Brunnschweiler 1966) are similar to those on top of the accretionary complex in the eastern belt, indicating that these sediments were widespread across the IBR. Considering the fact that we are dealing with shallow marine sediments deposited on top of a recently formed accretionary prism, we suggest they were deposited in a near-shore trench-slope basin on top of the IBR accretionary complex—this is the Hpakan amd Hukawng Basin in Fig. 8a.

Early Cretaceous subduction system in western Myanmar

The IBR accretionary complex formed at 115–119 Ma (Liu et al. 2016), which is ca. 9 Ma older than the magmatic arc along the central axis of West Burma, which is not older than 106 Ma (Mitchell et al. 2012). This difference in age suggests they may be unrelated. However, the active continental margin arc along the western margin of the Shan-Thai block formed at 114–128 Ma (Barley et al. 2003; Liang et al. 2008; Mitchell et al. 2012), which is close to or coeval with the IBR accretionary complex. Their spatial and temporal relationships suggest that they should be genetic related. Nevertheless, the fact that the magmatic arc in West Burma is younger than 106 Ma (Metcalfe 1995, 2006, 2011; Mitchell 1981, 1993; Mitchell et al. 2015; Swe 2012) and that the youngest detrital zircons of the schist near Salingyin, to the south of Monywa are younger than 120 Ma, and that no older intervening basement has been found, indicates that the active continental margin arc along the western margin of the Shan-Thai block and the contemporaneous IBR accretionary complex were not separated by a third terrane, and belonged to each other as accretionary complex and magmatic arc, which is different from the models of Acharyya (2007) and Metcalfe (1995, 2006, 2011). Therefore, we conclude that together they constitute an Early Cretaceous (114–128 Ma) subduction system with an eastward-directed subduction (Fig. 8a) in contrast to the westward subduction polarity suggested by Mitchell (1993), Mitchell et al. (2012), and Mitchell et al. (2015).

Furthermore, the Cretaceous limestones deposited in a trench-slope basin, today exposed near Kalemyo and Gangaw (Fig. 1), contains *Globotruncana, Ammonoides* and *Acanthoceras* (Bannert et al. 2011; Gramann 1974; Swe 2012). In the Saw area limestones contain Albian-Cenomanian (~100 Ma) ammonites, corals and other fossils, while at Mindon a conglomerate contains abundant Campanian/Maastrichtian *Orbitoides* (Bannert et al. 2011); these occurrences suggest deposition in a shallow to semi-pelagic marine environment (Zhao 2001). In the Hukawng basin to the north of Kpakan there is Cretaceous amber (~99 Ma) (Poinar 2009, 2010; Poinar and Buckley 2009; Shi et al. 2012), which implies deposition in a nearshore marine environment, such as a bay or estuary (Cruickshank and Ko 2003). These relations indicate that the trench-slope basin deepened westwards (Figs. 1c, 8a). The accretionary complex on Hainggy Island in the southernmost IBR contains *Halobia*-bearing Triassic sediments and serpentinite, which to the west of Hainggy Island are in direct contact with the trench between the Indian Oceanic crust and the IBR. Trench-slope basins overlying an accretionary complex should ideally contain pelagic trench-related sediments, but, since they do not, suggests they may be unexposed and/or covered by young sediments (Fig. 8a).

Implications for the Early Cretaceous framework of Neotethys

The Early Cretaceous subduction system in Myanmar (Fig. 8) comprises the IBR accretionary complex and active continental margin arc along the western margin of the Shan-Thai block, which is part of the Sibumasu (Fig. 1b) (Metcalfe 1995, 2006, 2011) or Cimmerian continental sliver (Şengör 1984). Moreover, the Triassic strata in the IBR, which occur in the Early Cretaceous accretionary complex, have comparable equivalents, e.g. the Langjiexue Group to the south of the Yarlung-Tsangpo ophiolitic belt in southern Tibet (Cai et al. 2016a; Wang et al. 2016). Hao et al. (1995) suggested that the Langjiexue Group may be a component of an accretionary complex. The Gangdese arc, situated to the north of the Langjiexue Group, has been active since the Jurassic (Huang et al. 2015). Therefore, in southern Tibet there may be an Early Cretaceous subduction–accretion system including the Gangdese arc and an accretionary complex containing the Yarlung-Tsangpo ophiolites and sediments of the Langjiexue Group (Cai et al. 2016a; Hao et al. 1995; Liu et al. 2016; Wang et al. 2016; Wu et al. 2014). This northward-directed subduction zone clearly extends from Tibet in SW China, around the eastern Himalayan syntaxis, to the east belt of IBR in Myanmar. It continues farther southward in a dismembered state to the archipelago in Indonesia (Hamilton 1988; Hennig et al. 2016). The extension of this Early Cretaceous subduction system (Hall 2002; Scotese and Sager 1988) consists with many occurrences of *Orbitolina*, a large dermarsal foraminifera, which lives in a very shallow, warm marine setting in the tropical zone (Wan et al. 2003).

The subduction–accretion of the Neotethys Ocean generates an Early Cretaceous subduction system in Myanmar (Liu et al. 2016). Its active continental margin arc is situated at the western margin of the Shan-Thai block, which is part of the Sibumasu (Metcalfe 1995, 2006, 2011) or Cimmerian continental sliver (Şengör 1984). This continental sliver was separated from the Gondwana supercontinent (Acharyya 1998; Metcalfe 1995, 2006, 2011; Şengör 1984) and was situated on the southern or western margin of the Paleotethys ocean (such as in western Yunnan province, China), which closed along the Changning-Menglian - Chiang Mai - Bentong-Raub suture zone from Yunnan in SW China (Pan et al. 1997; Zhong 1998) to Thailand (website: http://www.dmr.go.th/main.php?filename=GeoThai_En) and Malaysia (Spiller and Metcalfe 1995).

Conclusions

Our new field, structural and geochronological data from the IBR, integrated with published data from the western Shan-Thai block, leads to the following conclusions:

1. The IBR comprises serpentinite, greenschist facies basalt and chert, blueschist and eclogite, sericite schist and unmetamorphosed Triassic sandstone, mudstone and siltstone intercalated with chert, which together with their stratigraphic and structural relationships, constitutes an accretionary complex. These components are structurally repeated by multiple imbricated thrust slices. From the central core of the accretionary complex, there is a symmetrically opposite decrease in metamorphic grade eastwards and westwards from greenschist to sericite schist/slate to unmetamorphosed sediments in the Mindat and Magwe sections. These structural–metamorphic relationships demonstrate the presence of east-dipping antiformal exhumation isoclines. The bottom boundary of the isoclines is a thrust that has transported the metamorphic rocks over unmetamorphosed Triassic sediments to the west, and the top boundary is an extensional fault, which is responsible for bringing down unmetamorphosed Triassic sediments to the east. Taken together, these relations meet the requirements of major wedge extrusion of the accretionary complex of the IBR to the west, and this polarity confirms that the original subduction polarity was to the east.
2. In the Natchaung area the presence of Triassic sandstone and mudstone (unmetamorphosed), quartzite and sericite schist (whose protoliths were chert and pelagic mudstone), actinolite schist and amphibolite (derived from MORB-type basaltic rocks and metamorphosed at ca. 600–700 °C), indicates an increase in metamorphic grade from west to east. The amphibolite is directly overlain by peridotite, whose olivines have undulatory extinction suggesting low-temperature deformation at about 700 °C. Similar metamorphic and deformation temperatures of such rocks in contact suggest that the amphibolite belongs to a metamorphic sole formed during emplacement of the peridotite.
3. The metamorphic sole has a U-Pb zircon age of 115–119Ma close to that of the active continental margin arc (to the east) along the western margin of the Shan-Thai block, which is significantly older than the magmatic arc (U-Pb zircon ages <106 Ma) along the central axis of West Burma. The genetic temporal connection between the IBR accretionary complex and the active continental margin arc along the western margin of Shan-Thai block suggests they constitute an Early Cretaceous subduction system, which continues into Tibet and farther westward to the Iranian-Turkish plateau, and southwards to the coeval subduction systems in Indonesia.

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