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Magmatic arcs and nappes in Myanmar and western Thailand related to Neo-Tethys closure and Indian Ocean subduction

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Abstract

Our tectonic interpretation of western Myanmar and westernmost Thailand adopts proposed restorations of ca 450 km post-Eocene dextral displacement on the Sagaing Fault and argues that in the Early Jurassic Neo-Tethys lay between convergent subducting oceanic basins, one offshore Sibumasu on the Asian plate, and one offshore a narrow continental Victoria-Katha Block. With basin closures ophiolitic nappes obducted from Neo-Tethys over-rode turbidites on the Asian and Victoria-Katha Blocks' passive margins, translating the turbidites landward as flysch (deformed or tectonised turbidite) nappes. On the Asian margin crustal thickening in the E-vergent orogen formed the Yinmabin Schist, re-thrust eastwards over the flysch before orogenic polarity reversed and the eastward-subducting Neo-Tethys generated the Early Cretaceous W-facing Mondaung Arc in Myanmar and Thailand. We suggest that on the Victoria-Katha Block's eastern margin ophiolite obduction was followed by reversal in orogenic polarity, westward subduction of Neo-Tethys and Late Cretaceous Popa-Loimye arc magmatism which ended soon after 90 Ma with Neo-Tethys closure, thrusting of the Victoria-Katha Block onto Asia and formation of a suture zone which probably continues into the Nujiang-Bangongco zone in China. Subsequent back-thrusting translated metamorphic rocks on the Asian margin westwards, over-riding the Neo-Tethys suture zone and *Orbitolina* Limestone on the Victoria-Katha Block as seen in the Shwebo Basin and north of Mogok. Following crustal shortening, partial melting and intrusion of Western Tin Belt granites at ca 70-44 Ma, orogenic polarity again reversed and eastward subduction of the proto-Indian Ocean generated Late Eocene and younger magmatic rocks of the Popa-Loimye Arc. We argue that most of the copper, gold, tin, tungsten, antimony, jadeite and gemstones in Myanmar west of the Palaeo-Tethys are related to the above orogenic events, although the formation of sapphire, ruby, Shante district gold and Monywa copper were accompanied by dextral displacement on the Sagaing Fault.

Keywords: arc reversals, convergent subduction zones, divergent flysch nappes, Mayathein back--thrust, metamorphic nappes, Neo-Tethys closure, Western Tin Belt.

1. Introduction

Most ideas on the tectonic evolution of Myanmar west of the Palaeo-Tethys and western-most Thailand infer that since the late Early Cretaceous a Zone 1, Shan Thai (Bunopas, 1981) or Sibumasu Block, part of Asia by the Late Triassic, occupied the Shan Scarps, Tanintharyi and much of the Shan Plateau (**Fig. 1**). This Block since the mid-Albian was bordered to the west by a variably-defined West Burma, West Myanmar or Victoria-Katha Block beneath which eastward subduction of a Tethyan or proto-Indian Ocean generated the Popa--Loimye or Western Myanmar (**Fig. 2**) magmatic arc (e.g. Mitchell, 1979; Deng, Wang, Li, Li, & Wang, 2014; Zhang et al., 2018; Li et al., 2020; Mitchell, Myint Thein Htay, & Kyaw Min Htun, 2021) and many of Myanmar's abundant mineral deposits (e.g. Mitchell, 1986; Gardiner, Robb, & Searle, 2014; Gardiner et al., 2016; Wang, Deng, Carranza, & Santosh, 2014). Significant

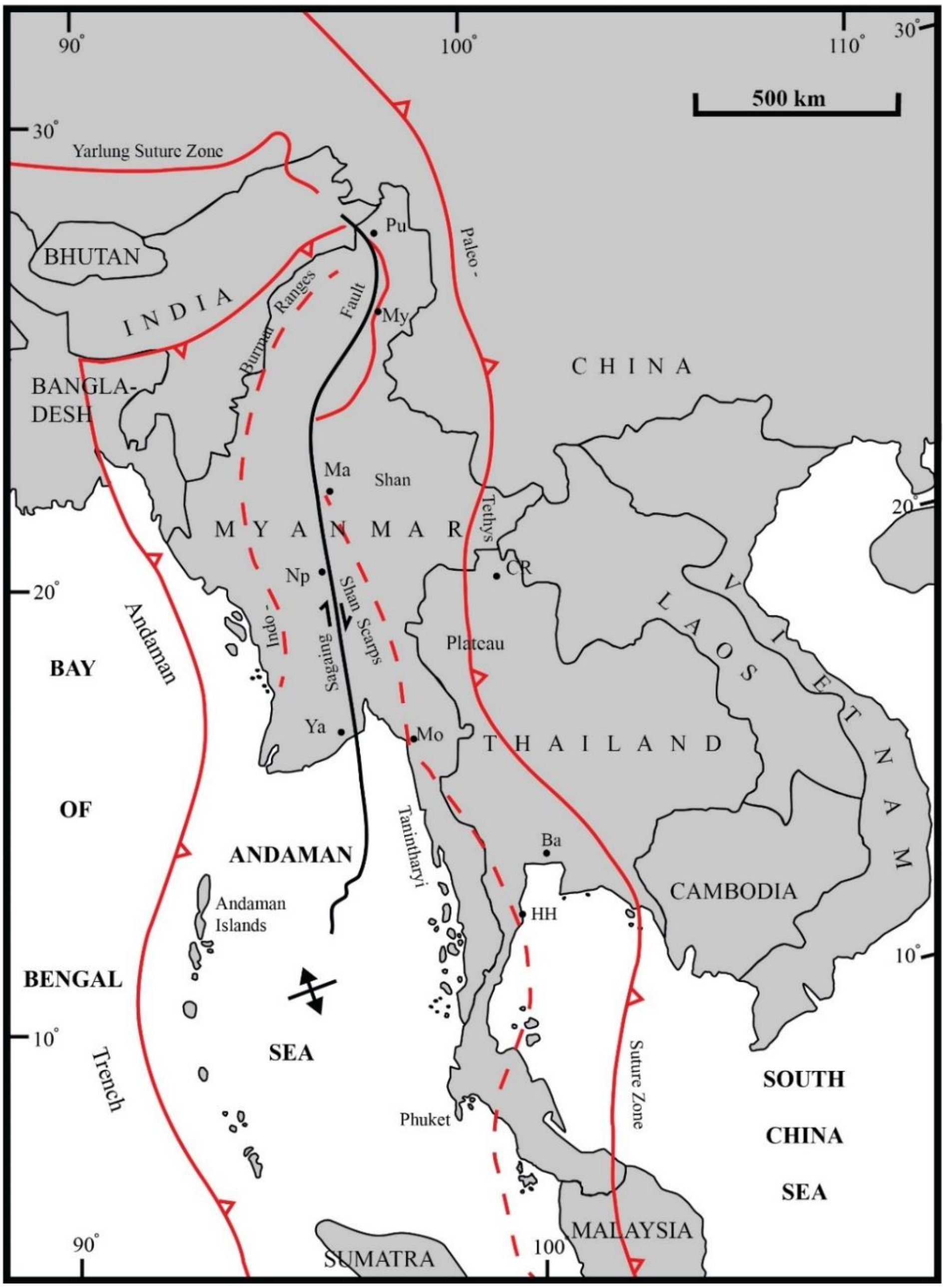


Fig. 1: Regional tectonic setting of Myanmar and western Thailand. Ba Bangkok, CR Chiang Rai, HH Hua Hin, Ma Mandalay, Mo Moulmein, My Myitkyina, Np Naypyidaw, Pu Putao, Ya Yangon.

variations of this model are those of Westerweel et al., (2019) and Morley, Chantraprasert, Kongum & Chenoll, (2021) who have proposed generation of the Popa-Loimye arc in mid--Tethys and its accretion to Asia along a Late Palaeogene dextral strike-slip fault.

For pre-Albian tectonics west of the Palaeo-Tethys there is no near-consensus comparable to that for the subsequent period. Many authors have invoked accretion to Sibumasu of a western Burma (Myanmar) block or ribbon continent. Proposed mechanisms include dextral strike-slip emplacement on a pre-Jurassic fault along (Metcalfe, 2013) or near (Barber, Khin Zaw, & Crow, 2017) the Late Cenozoic Sagaing Fault, and eastward (Mitchell, 1979; Li et al., 2018) or westward subduction (Mitchell, Tin Hlaing & Nyunt Htay, 2010; Mitchell, Chung, Thura Oo, Lin, & Hung, 2012; Mitchell, Myint Thein Htay, & Kyaw Min Htun, 2018) and closure of an ocean basin along the western margin of the Mogok Metamorphic Belt and Shan Scarp (**Fig. 3**). The Shan Scarp and Nwalabo Fault zone of Garson, Amos, & Mitchell (1976) are the proposed continuation of Jin's (1996) Nujiang Fault, the Nujiang-Luxi suture zone of Cai & Li (2001) in Yunnan. Ridd (2017a) proposed dextral strike-slip emplacement of his Irrawaddy Block along this zone in the Mesozoic and Palaeogene, and Metcalfe (2011) favoured eastward subduction beneath a coherent Greater Sibumasu which extended westwards to the Indo-Burman Ranges. Gardiner et al. (2018) illustrated collision of an amalgamated east and west Sibumasu with the small Tengchong block of Deng et al. (2014) in the Early Cretaceous, and Zhang et al. (2018) argued for post-Triassic subduction beneath Sibumasu, by then part of Asia, and accretion to its western margin of imbricated flysch units successively younger to the west. The term flysch in this paper is taken from the intensively studied Swiss Alps where it refers to turbidites deposited in a subducting ocean basin and deformed before and during ocean closure. Other previous reconstructions for Myanmar and Thailand west of the Palaeo-Tethys include proposed links between the Upper Triassic flysches of the Tethyan Himalaya, Tagaung-Myitkyina Belt and Indo-Burman Ranges (e.g. Mitchell, 1984; Cai, Ding, & Yao, 2020; Peng et al., in press).

We here adopt the restoration (**Fig**. **3**) of a long-proposed dextral displacement on the Sagaing Fault, most recently estimated at 486 Ma (Morley & Arboit, 2019) since the mid-Oligocene. In northern Myanmar where the Fault is oblique to the regional trend, restoration of ca 450 km displacement implies that Neo--Tethyan oceanic rocks in the Tagaung-Myitkyina Belt northeast of the fault continued southwestwards into the northeastern end of the Indo-Burman Ranges and Central Lowlands west of the fault, forming a single Late Triassic and Jurassic ocean (Mitchell and Garson, 1981; Mitchell et al., 2021). We also adopt earlier proposals that by the end-Triassic or Early Jurassic the Victoria-Katha block, much of which now lies west of the Sagaing Fault, was off-shore Gondwana, more specifically Australia (Cai et al., 2020), and separated from the continent by an incipient proto-Indian Ocean and from Sibumasu by Neo-Tethys. We argue that oceanic basins on the Victoria-Katha and Sibumasu plates subducted on convergent zones beneath Neo-Tethys, from which ophiolite nappes were obducted on to the Victoria-Katha and Sibumasu Block margins. Subsequent reversals in orogenic polarity and closure of Neo-Tethys were followed by latest Cretaceous back-thrusting and generation of the Western Tin Belt in Myanmar and southwestern Thailand. The main structural belts in Myanmar and westernmost Thailand are shown in **Fig. 2.**

2 The Victoria-Katha Block west and east of the Sagaing Fault

The Victoria-Katha Block (Mitchell et al., 2021) includes the Kanpetlet Schist and Naga Metamorphics in the Indo-Burman Ranges, the anticlinal core of the Jade Mines Uplift east of the southern Naga Hills, the basement of the Myanmar Central Depression between the Indo--Burman Ranges and Sagaing Fault, the Katha--Gangaw Range and Tagaung Myitkyina Belt, and possibly part of the Kumon Range (**Fig. 2).**

2.1 Indo-Burman Ranges:

We describe first the Chin Hills and Rakhine Yoma in the south of the Ranges (**Fig. 4a)**, based largely on the mapping by United Nations (1979a, b, c), and then describe the Naga Hills (**Fig**. **4b**) of Aitchison et al. (2019) in northwestern Myanmar and adjacent India.

2.1.1. Eastern Belt in the Chin Hills

Pre-Campanian rocks are confined to the Eastern Belt (United Nations 1979a) of the Ranges. In the southern Chin Hills the Kanpetlet Schists of Brunnschweiler (1966) were described by United Nations (1979a) as a 30 km wide belt of muscovite and biotite schist with local meta-pillowed basalts, the Hilawng Volcanics of Kyaw Win (unpub.report, 1969), and formed the core of the S-plunging Mindat Anticline (**Fig**. **4a**). The Schist is overlain to the east and west by the highly-deformed quartzose turbidites and mudstones of the flysch-like Pane Chaung Group (**Fig. 5**) which in the northern Chin Hills includes extensive broken beds. Upper Triassic *Daonella* first reported by Theobald (1871) established the age of the Group, although flysch of this age was not

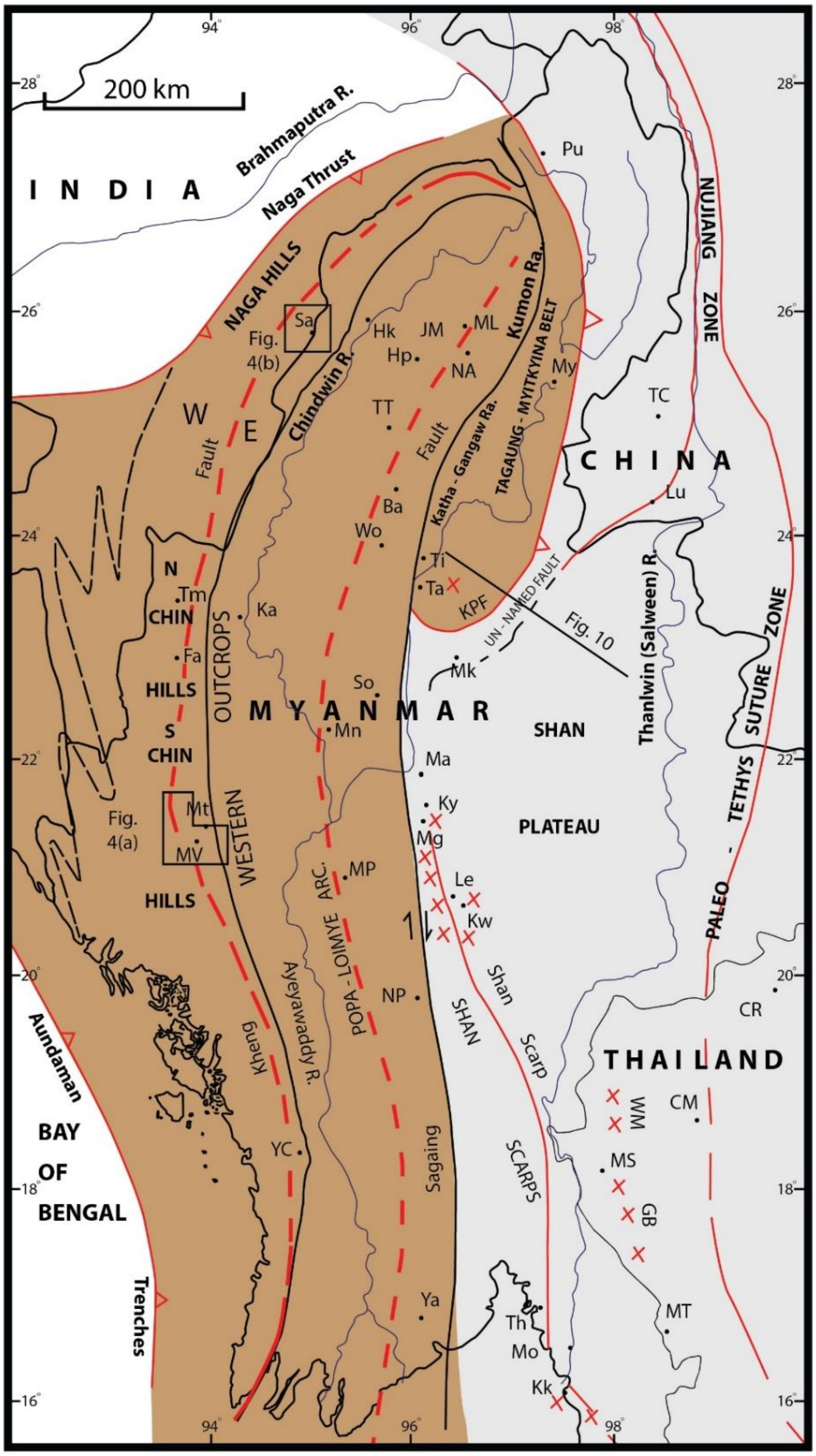


Fig. 2: Structural belts and locations in Myanmar and northwestern Thailand N of 16 deg N, partly from Myanmar Geosciences Society 2014. Ba Banmauk, CM Chiang Mai, CR Chiang Rai, E Eastern Belt Indo-Burman Ranges (IBR), Fa Falam, Hk Hkamti, Hp Hpakant, JM jade mines, Ka Kalemyo, KPF Kyaukpyu Fault, Kw Kalaw, Kk Kyaikkami, Ky Kyaukse, Le Lebyin, Lu Luxi, Ma Mandalay, Mg Mondaung, My Myitkyina, Mk Mogok, ML Mt Loimye, Mn Monywa, Mo Moulmein, MP Mt Popa, MS Mae Sariang, Mt Mindat, MT Mae Sot, MV Mt Victoria, NA Nanyaseik, NP Nay Pyi Daw, Pu Putao, Sa Mt Saramati, So Shwebo, Ta Tagaung, TC Teng Chong, Th Thaton, Ti Tigyaung. Tm Tiddim, TT Taungthonlon, Ya Yangon, YC Yethawa Chaung, W Western Belt IBR, WMGB Western Marginal Granite Belt, Wo Wuntho. Mondaung Arc shown by red crosses.

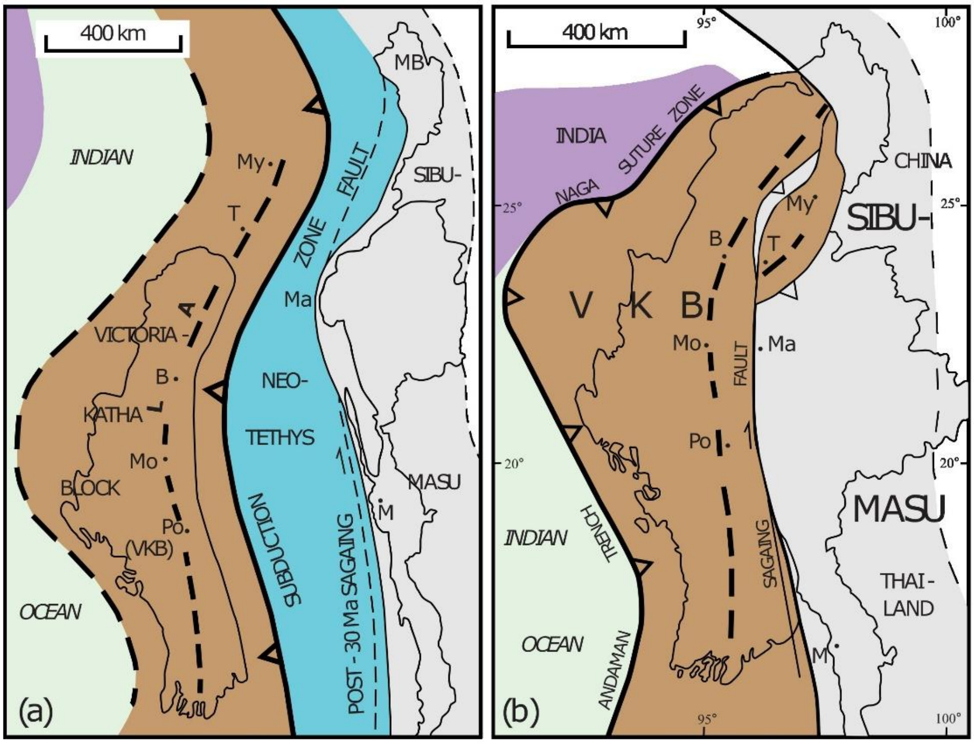


Fig. 3: Sketch maps of Myanmar and western Thailand at (a) ca 95 Ma prior to closure of Neo-Tethys and dextral displacement on the Sagaing Fault, and (b) present day. The Tagaung- Myitkyina Belt (T-My) is on the Victoria-Katha Block in (a) but east of the Sagaing Fault in (b). B Banmauk, M Moulmein, Ma Mandalay, Mo Monywa, Po Mt Popa. PLA Popa-Loimye Arc. After Mitchell et al., (2018).

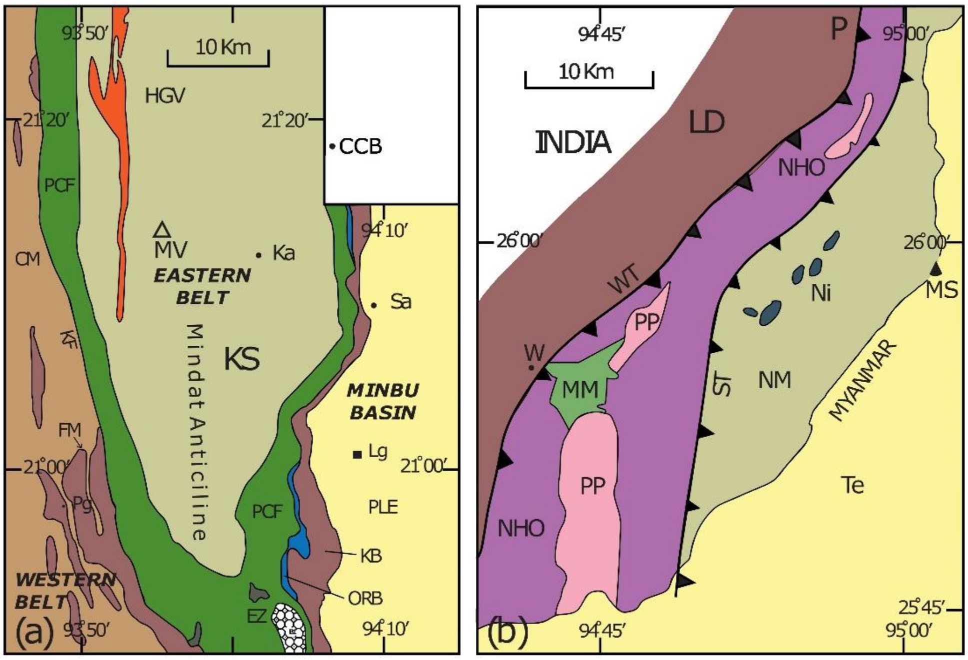


Fig. 4: Geological sketch maps, Indo-Burman Ranges. (a) Southern Chin Hills, Myanmar. CCB Che Chaung Basalts, CM Chunsung Mudstone, EZ Exotics Zone, FM Falam Fm, HGV Hilawng Volcanics, Ka Kanpetlet, KB Kabaw & Paunggyi Fms, KF Kheng Fault, KS Kanpetlet Schist, Lg Laungshe, MV Mt Victoria, ORB Orbitolina (Paung Chaung) Limestone, PCF Pane Chaung Fm or flysch, Pg Pandaung, PLE post-Lower Eocene, Sa Saw, from United Nations (1979a). (b) Part of southern Naga Hills, India and Myanmar. LD Lower Disang Fm, MM Mudstone Melange, MS Mt Saramati, NHO Naga Hills Ophiolite, Ni Nimmi Limestone, NM Naga Metamorphics, P Phokphur, PP Phokphur Fm, ST Saramati Thrust, Te Tertiary, W Waziho, WT Waziho Thrust, simplified from Aitchison et al. (2019). Locations on Fig.2.

reported by Brunnschweiler (1966). Rare chert beds occur within the Pane Chaung flysch and some other cherts contain Middle Jurassic radiolaria (Zhang et al., 2017; Zhang, Xiao, Cai, & Kyaing Sein 2020). In the northern Chin Hills the Kanpetlet Schist is not exposed and the Triassic flysch belt includes a dozen bodies of variably serpentinised ultramafic rocks. Among these United Nations (1979a,b) described the Webula Taung harzburgite-dunite body and adjacent 2 km wide amphibolite-piedmontite-quartz schist since identified as a metamorphic sole, and reported a K/Ar age of 158+- 20 Ma on low-K hornblende from a pegmatite within a serpentinite sheet in the Mindat Anticline, one of many pegmatites within serpentinites in the Chin Hills and Arakan (Rakhine) Yoma. Liu et al. (2016) obtained for plagiogranite a zircon U-Pb age of 127 Ma and for the Webula Taung amphibolitic sole, 116 Ma, the implied emplacement age of the overlying ophiolite.

Pillowed and massive basalts are here informally named Che Chaung (River) Basalts (Fig.5) from east of Mt Victoria **(Fig. 4a)** where they contain blocks of the underlying Pane Chaung flysch and are intruded by diabase and basalt dykes. To the south in the Maw Chaung a basalt body 2 km long and up to 40 m wide lies with a stratigraphic contact on flysch to the west and is overlain by mid-Cretaceous Paung Chaung Limestone which continues eastwards at the base of the Chindwin (forearc) basin succession. Over 250 km to the south in the Yethawa Chaung **(Fig. 2)** E-younging pillowed basalts up to 50 m thick overlie the flysch and pass upwards with increasing limestone intercalations into the Paung Chaung Limestone.

2.1.2. Western Belt in the Chin Hills

In the Western Belt of the southern Indo-Burman Ranges (**Figs. 4a, 5**) the oldest unit, the Falam Formation, consists of mudstones interbedded with Campanian and Maastrichtian *Globotruncana* -bearing pelagic limestones, and containing blocks of pillowed basalt, chert, andesite and ophicalcite, exposed in the cores of upright anticlines. Limestones within the Falam Formation, the Senonian flysch of Brunnschweiler (1966), occur as boudined and coherent beds within mudstones and only locally form the supposedly exotic blocks described by Brunnschweiler (1966) and subsequent workers. The Falam Formation is overlain by Palaeocene mudstones and turbidité sandstones beneath Eocene sand-stones and limestones preserved in syncline cores which form N-trending ridges up to 2700 m elevation. To the west the Cretaceous to Eocene succession is covered by younger sedimentary rocks. The steeply-dipping Kheng Fault juxtaposes the Eastern with the Western Belt.

2.1.3. Indo-Burman Ranges in the Naga Hills

In the southern Naga Hills four main structures have been proposed **(Fig. 4b)**. The Sarameti Thrust of Aitchison et al. (2019) carries the Naga Metamorphic Complex or Naga Metamorphics of Brunnschweiler (1966) westwards over ophiolitic rocks and the mud--matrix melange of Bannert, Albert Sang Lyen & Than Htay (2011) and Aitchison et al. (2019). These are translated westwards on the Waziho Thrust, probably equivalent to the Kheng Thrust in the Chin Hills, over Aitchison et al.'s (2019) Tertiary Indo-Burman flysch. This is the Naga flysch of Brunnschweiler (1966), and correlated by Aitchison et al. (2019) with the India-derived Disang Group of Evans (1964), but we suggest that much of the Indo-Burman flysch is instead equivalent to the Falam Formation in the Chin Hills. Evans' (1964) Naga Thrust **(Fig. 2)** carries the Disang Group westwards over younger 'molasse' sediments overlying Indian basement in the Foreland Spur and is probably the continuation of the Kaladan Fault or suture zone of Yang et al. (2020) west of the Kheng Fault in the Chin Hills. Aitchison et al.'s (2019) proposed suture zone east of the Naga Metamorphics may lie within the Hpakant and Taw Maw serpentinite bodies which flank the metamorphic core in the Jade Mines area.

Aitchison et al. (2019) have shown that the Naga Metamorphics are probably post-Cambrian and that radiolarian cherts to the west have Middle and latest Jurassic and middle Early Cretaceous ages. Triassic flysch is not reported in the Naga Hills but we suspect its presence beneath the Sarameti Thrust in the melange which might include broken beds.

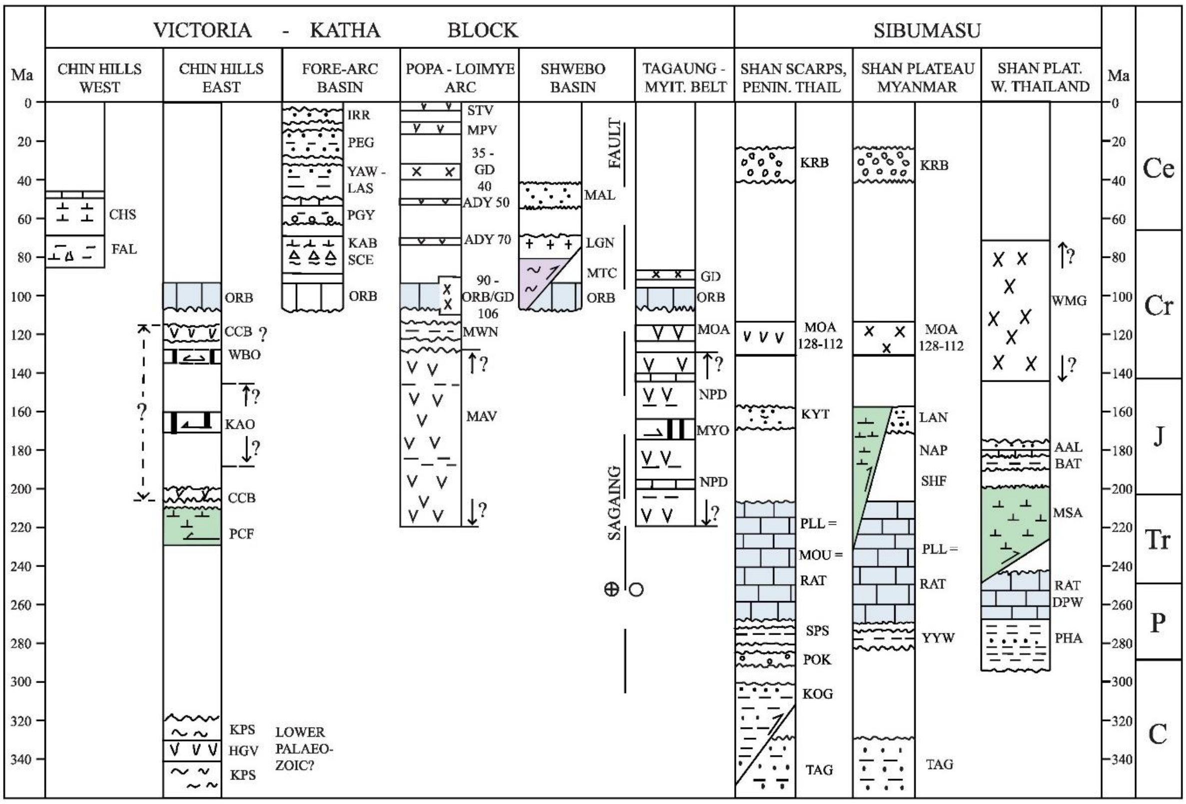


Fig. 5: Post-Devonian stratigraphic columns for structural belts in Myanmar and Thailand west of Palaeo-Tethys. AAL Aalian, ADY andesitic dyke, BAT Bathonian, CCB Che Chaung Basalts, CHS Chunsung Fm, DPW Doi Phawar Fm, FAL Falam Fm, GD granodiorite, HGV Hilawng Volcanics, IRR Irrawaddy Fm, KAB Kabaw Fm, KAO Kalemyo ophiolite, KOG Kogwe Mudstone, KPS Kanpetlet Schist, KRB Kalaw Red Beds, KYT Kyaukhsu Taung Fm, LAN Loi An Fm, LAS Laungshe Shales, LGN leucogranite, MAL Male Fm, MAV Mawgyi Volcanics, MOA Mondaung Arc, MOU Moulmein Limestone, MPV Mt Popa Volcanics, MSA Mae Sariang Fm, MTC Mayathein Complex, MWN Mawlin Fm, MYO Myitkyina ophiolite, NAP Napeng Fm, NPD Ngapyawdawchaung Fm, ORB Orbitolina Limestone, PCF Pane Chaung Flysch, PEG Pegu Gp, PGY Paunggyi Fm, PHA Pharaka Fm, PLL Plateau Limestone, POK Poklokkale Fm, RAT Ratburi Limestone, SCE Sin Chaung Exotics, SHF Shweminbon Fm, SPS Spinomartinia prolifica Shale, STV stratovolcanoes, TAG Taungnyo Gp, WBO Webula ophiolite, WMG Western Marginal Granite Belt, YAW Yaw Fm, YYW Yin Yaw Fm.

2.1.4. Structure of the Indo-Burman Ranges

United Nations (1979a) inferred that ophiolite was thrust westwards over the Pane Chaung flysch, although in the eastern limb of the Mindat Anticline they show flat-lying inverted flysch beds with W-vergent folds forming the lower limb of a regional eastward-overturned anticline with Kanpetlet Schist in the core. The E-vergent structure has not been confirmed by subsequent workers and we follow Zhang et al. (2017) who reported W--vergent folds in right-way-up beds, and Cai et al. (2020) who related 290-200 Ma detrital zircons from the Pane Chaung flysch to deposition in a submarine fan along the northern margin of Australia (**Fig. 6a)** in an analogous setting to the Tethyan Himalayan flysch. We suggest that a Victoria-Katha Block with the Pane Chaung flysch on its eastern margin then rifted from Australia, possibly in front of a back-arc basin **(Figs. 6b, 7a)** and that as proposed by Mitchell (1986) the Pane Chaung flysch was translated westwards (in present orientation) beneath an obducted ophiolite nappe (**Fig. 7b).** An Early to mid-Jurassic age for this ophiolite**,** and for many of the ultramafic bodies within the flysch belt in the northern Chin Hills, is inferred from the presence of mid-Jurassic cherts in the Ranges. Obduction of a second ophiolite **(Fig. 7 d, e**) can explain the Webula Taung ultramafic body ca 116 Ma (Liu et al., 2016). Following erosion, we speculate that the Pane Chaung flysch was covered by Che Chaung Basalts before deposition of *Orbitolina* Limestone **(Fig. 7f, g**).

2.2 Central Lowlands:

The Myanmar Central Lowlands (Central Basin or Depression) are divided by the Popa--Loimye Arc into the fore-arc basin in the west (**Fig. 2**) and the narrower back-arc or Shwebo basin in the east.

2.2.1. Fore-arc (Salin-Chindwin and Minbu) basin and the Sin Chaung Exotics Zone

The fore-arc basin, situated between the Indo-Burman Ranges and the Popa-Loimye Arc, contains up to 17 km of sedimentary fill (Pivnic et al.,1998). The Upper Albian--Cenomanian Paung Chaung (*Orbitolina*) Limestone of the Chin and Rakhine foothills re-appears in the western flank of the Popa--Loimye Arc (**Fig. 5)** and has been intercepted in an oil exploration borehole in the Chindwin Basin. Although said to be unconformable on the Late Triassic flysch (Gramman, 1974), the Limestone commonly overlies the Che Chaung Basalts (**Fig. 5**) with an inter-layered basalt--limestone transitional zone (United Nations, 1979a).

Serpentinite sheets or sills from a few metres to a few hundred metres thick are most abundant near the eastern margin of the flysch where as noted by Chhibber (1927, *in* Chhibber, 1934) they commonly occur within *Orbitolina* Limestone and like the larger ultramafic bodies include hornblende pegmatite veins. Hydrothermal ophicalcite (listwaenite), the silicic rock of Chhibber (1934), occurs at the limestone-serpentinite contact.

Outcrops of *Orbitolina* Limestone in the southern Chin foothills are overlain in the Western Outcrops (**Fig**. **2**) by the E-dipping Kabaw Formation **(Fig. 5)** of Aung Khin & Kyaw Win (1968) and Win Swe, Thacpaw, & Nay Thaung Thaung (2010), a mudstone--turbidite-limestone association partly arc--derived (Yang et al., 2012) and equivalent to the Falam Formation west of the Mindat Anticline (**Fig. 5).** At the southern end of the Anticline, United Nations (1979a), Mitchell (1984), and Mitchell (2017, fig. 11.5) described E-dipping *Orbitolina* limestone overlain by a 2 km-wide zone of varie-coloured mudstones with rafts of Senonian micritic limestones and blocks of chert, diabase, gabbro, gabbro-clast conglomerate, basalt, ophicalcite, marble and scarce rounded cobbles of Triassic sandstone. This succession, the Sin Chaung Exotics Zone (United Nations (1979a), is over-ridden on the Kabaw Thrust (**Fig**. **7h**) by an easterly-dipping upward sequence of Triassic flysch, *Orbitolina* Limestone and Kabaw turbidites beneath conglomerates of the unconformable mid--Palaeocene to Lower Eocene Paunggyi Formation. We infer deposition of the *Orbitolina* Limestone on and east of the Che Chaung Basalts on the Victoria-Katha Block margin, followed in the Campanian and Early Maastrichtian by deposition of the Falam and Kabaw Formations on and east of the Limestone.

The fore-arc basin succession above the Kabaw Formation (**Fig. 5)** is predominatly clastic and well-exposed in the Western Outcrops **(Fig. 2).** Major unconformities occur at the bases of the Paunggyi Formation, the Oligocene Lower Pegu Group, the Lower and Middle Miocene Upper Pegu Group and the Upper Miocene to Pliocene Irrawaddy Formation (Tainsh, 1950; Ridd 2017b). The basin succession forms a synclinorium with E-vergent thrusts east of the Bago Yoma medial uplift and W-vergent to the west (Myanmar Geosciences Society, 2014).

2.2.2 Mawgyi Volcanic Group and the Popa-Loimye Arc

The Mawgyi Volcanic Group (**Figs**. **5, 7f, g)** best seen together with the younger Popa--Loimye Arc in the Wuntho-Banmauk and Monywa-Salingyi uplifts, is also known as Mawgyi Andesites, Mawgyi Basalts, or Mawgyi Volcanics. The Group consists of a thick succession of largely basaltic pillow lava and lava breccias with pervasive chlorite-epidote propylitic alteration. These are inter-bedded with volcanogenic sedimentary layers and pass up into the entirely volcaniclastic Mawlin Formation (**Fig. 5)** which is overlain by *Orbitolina* Limestone (Mitchell, 2017).

Numerous andesitic dykes, largely porphyritic hornblende-bearing and unaltered, intrude the Mawgyi Volcanic Group. Isotopic ages on the dykes are confined to K/Ar determinations of 70 and 50 Ma near Shangalon (United Nations, 1978a). Small bodies of rhyodacite intrude the Mawgyi Group, which may correlate with either the Che Chaung Basalts (**Fig. 5)** or pre-mid Cretaceous supra-subduction zone oceanic arcs inferred to have overlain the obducted upper mantle bodies in the Chin Hills (**Fig. 7d).**

In the Popa-Loimye Arc, also known as the Western Burma or Popa-Wuntho magmatic arc (Mitchell, 2017; Li et al., 2020), the older arc rocks are intrusions within the Mawgyi Volcanic Group and Mawlin Formation, all of which form inliers within Tertiary sediments (**Fig. 5**). These intrusions include mid-and early Late Cretaceous (ca. 107 to 90 Ma) I-type biotite and biotite-hornblende granites and smaller diorites of the Kanzachaung batholith. Two-mica and foliated garnet-bearing granites form the Pinhinga Plutonic Complex north of the batholith. Younger Arc magmatic rocks are described in Section 3.7.

The arc basement (United Nations, 1979d ; Mitchell, 2017), includes amphibolites and migmatitic gneisses in the Banmauk (**Fig**. **2**) region, garnet and sillimanite schists and pegmatites at Shinmataung south of Monywa, blocks of garnet-amphibolite rock in Late Cenozoic basaltic lavas at Monywa and gneiss xenoliths at Mt Popa. Sericite and chlorite schists north of Banmauk may correlate with phyllites and argillites in the same area and with phyllite pebbles in Eocene conglomerates at Shangalon. Chlorite-albite schists northeast of Wuntho underlie the Mawgyi Volcanics and may be equivalent to those in the Tagaung--Myitkyina Belt and to the Hilawang Volcanics of the Chin Hills.

Although widely interpreted as a W-facing arc throughout its life (e.g. Mitchell, 1986; Gardiner et al., 2014, 2016; Li et al., 2020, 2018), speculative westward subduction beneath an E-facing arc (**Figs. 7f, 8a**) from ca 107 to ca 90 Ma (Mitchell et al., 2010, 2018,) allows for a Late Cretaceous closure of Neo--Tethys and either an interruption or dramatic decrease in arc magmatism until westward subduction began in the Eocene (Section 3.7).

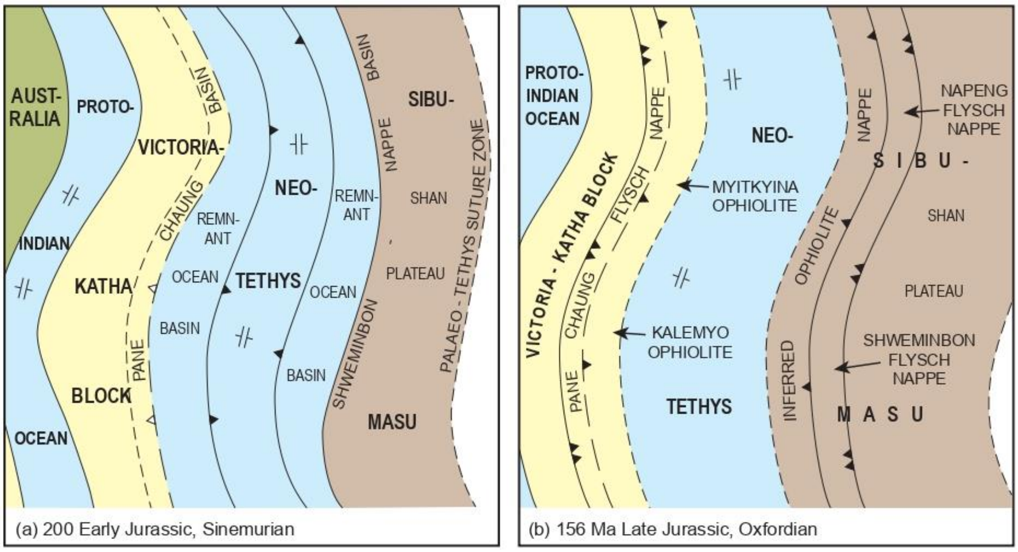


Fig. 6: Schematic sketch maps showing blocks and oceans in Myanmar and western Thailand at (a) 200 Ma Early Jurassic, Sinemurian and (b) 156 Ma Late Jurassic, Oxfordian.

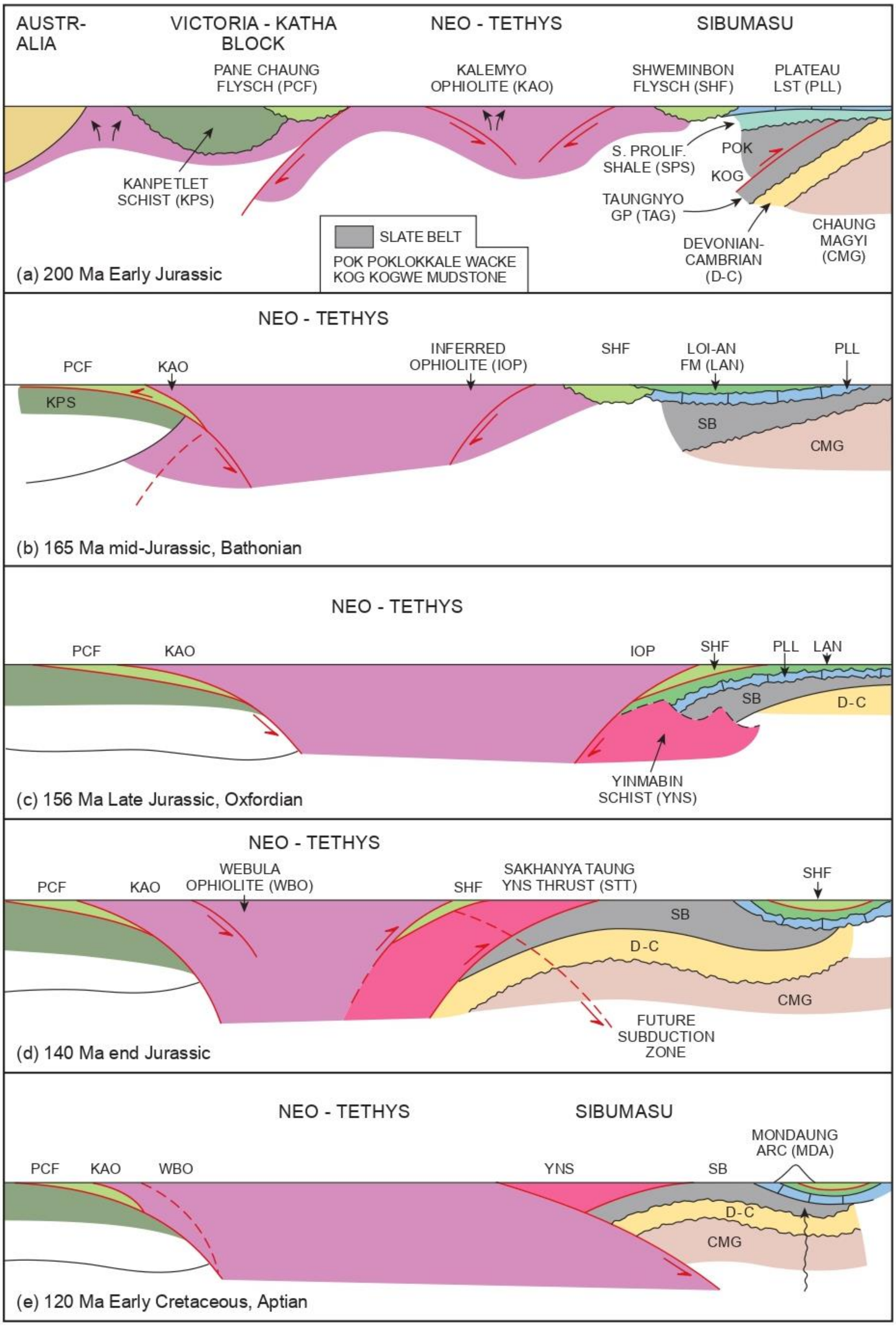


Fig. 7: Schematic E-W sequential cross-sections through north-central Myanmar and northwestern Thailand illustrating structural evolution, ocean basins and some rock units not to scale. Yinmabin Schist in (c) is metamorphosed overlying stratigraphic sequence.

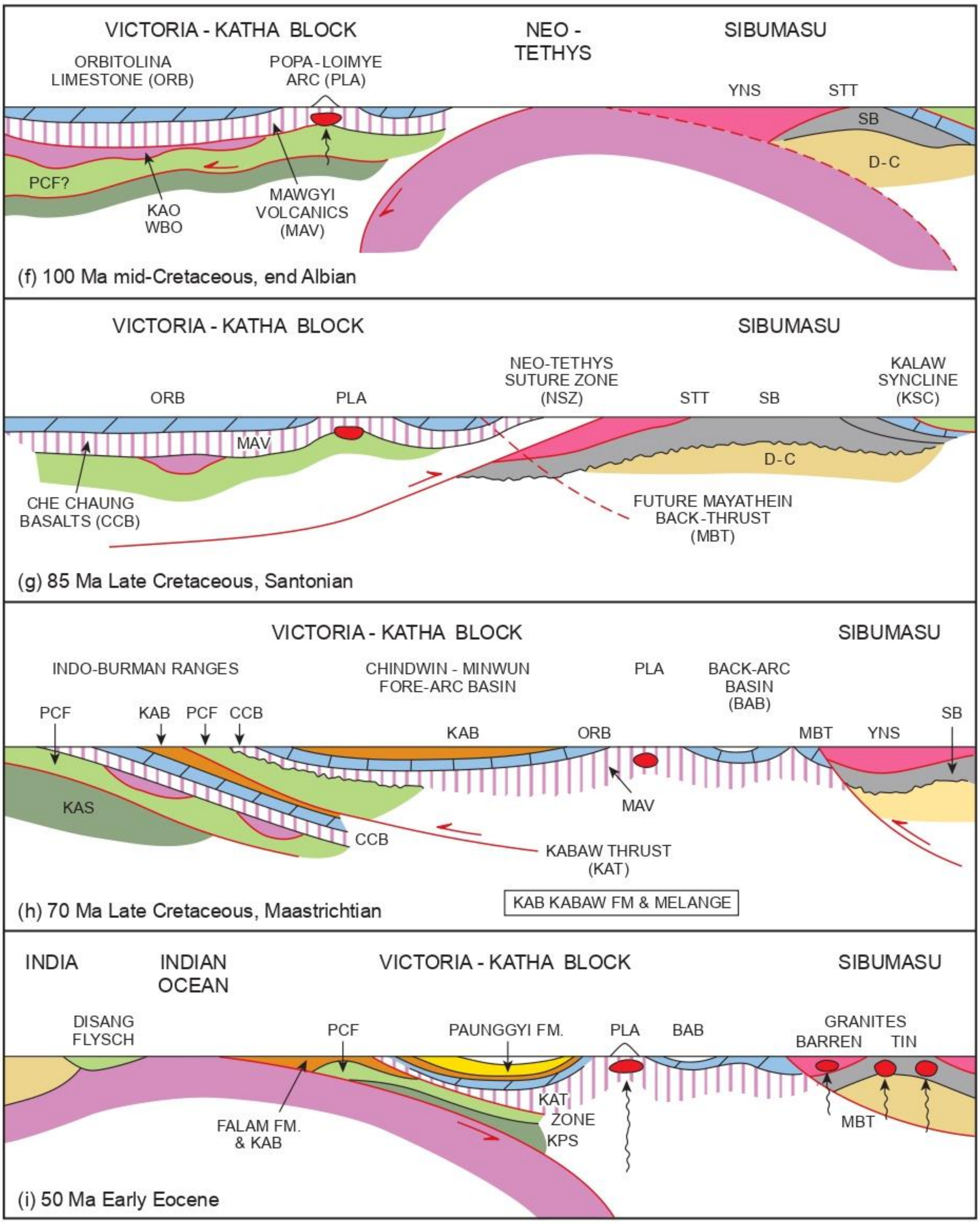


Fig. 7: Schematic E-W sequential cross-sections through north-central Myanmar and northwestern Thailand illustrating structural evolution, ocean basins and some rock units not to scale. (contd.)

2.2.3 Back-arc or Shwebo Basin

This basin attains its greatest width around latitude 22 deg 30 min N but narrows northwards to 24 deg N where granodiorite of the Popa-Loimye Arc is only 20 km west of the Sagaing Fault.

The basin is occupied largely by a succession (**Fig. 5**) of sandstones and shales with open upright folds, the Male Formation, with the Lower Eocene Tongyauk Conglo-merate at the base (Myint Thein & Maung Thein, 2014). South of Kyaukse, Neogene sedimentary rocks exten to east of the Sagaing Fault.

In the Shwebo Basin west of Tigyaing **(Fig. 2)** and a kilometre west of the Sagaing Fault a narrow inlier of diopside-phlogopite marble, skarn, amphibolite and migmatitic gneiss intruded by leucogranite forms the N-trending Mayathein Complex of United Nations (1979b, c). This is juxtaposed with the *Orbitolina*--bearing (Myint Thein, 2015) Kywethe Limestone to the west (**Fig. 5**). A few kilometres further west the Ubye serpentinite trends NNE for 15 km and is bordered on the west by basalts, phyllites, volcanogenic sediments and minor limestones forming the Ngypaw-dawchaung Formation of United Nations (1979b), correlated with the Mawgyi Volcanics in **Fig. 7f.** At the serpentinite-basalt contact pyritic quartz-haematite rock, probably listwaenite, replaces limestone.

2.3. Tagaung-Myitkyina Belt and Katha-Gangaw Range:

These features lie east of the Sagaing Fault (**Figs. 2, 3)** but their geology resembles that to the west (**Fig. 5).** The historically rather inaccessible Tagaung-Myitkyina Belt in Myanmar's Northern Shan and Kachin States consists of actinolite-epidote-albite and chlorite schists, and basaltic rocks (Than Tun & Khin Myint, unpub report, 2002) in a stratigraphic succession correlated with the Ngapyawdaw Chaung Formation (Section 2.2) west of the Sagaing Fault. The succession, well exposed in the Nan Sen Chaung east of Paladokhta and southeast of Tagaung **(Fig. 2**), comprises a thick sequence of pillowed and massive basalt lavas, pillow breccias, volcanogenic sediments, cherty mudstones and andesites, with minor coralline Triassic limestones (Dr. Thura Oo, written comm., 2005), intruded by locally sheeted basalt dykes. A similar assemblage intruded by hornblende diorites and serpentinites was described by Clegg (1941) from the Ayeyawady River south of Myitkyina. Near Myitkyina basalt, leuco-gabbro, plagiogranite and pyroxenite yield zircon U-Pb ages of 166 to 177 Ma (Yang et al., 2012), and diorites resembling plagiogranites and gabbros ages of ca 173 Ma (Liu et al., 2016). Upper Triassic flysch occurs in the west of the belt.

At Tagaung Taung (**Fig. 2)** southwest of Tigyaing United Nations (1979c) described harzurburgite and dunite with chromitites overlying a metamorphic sole of chlorite schist and quartzite thrust over cherts in which Teza Kyaw, Suzuki, & Maung Maung (2020) reported uppermost Jurassic, Hauterivian and Aptian radiolaria. At Myitsone north of Myitkyina uppermost Jurassic cherts overlie red mudstones (Maung Maung, Aung Naing Thu, & Suzuki, 2014). Throughout the Tagaung-Myitkyina Belt the mid-Cretaceous *Orbitolina* Limestone occupies synclines, is unconformable on the basalts and chert, and in the two Ayeyawady defiles northeast of Tagaung (**Fig**. **2**) shows W-dipping axial planes (Clegg, 1941; Thura Oo, oral comm., 2004).

The Katha-Gangaw Range (**Figs. 8a, 9),** part of the Victoria-Katha Block, is a sinuous ridge about 170 km long underlain by the Katha Schist, comprising garnet-mica schist and micaceous quartzites beneath talc schists, with phyllite and marble to the east. Detrital zircons from the Schist include 418 Ma (Silurian) zircon U-Pb ages and a frequency peak at 500 Ma (Zhang et al., 2018). Rocks older than the Ngapyawdaw Chaung Formation occur northwest of the Ayeyawady's second defile where serpentinite is thrust over meta-turbidites and talc schists, probably part of the Katha Schist.

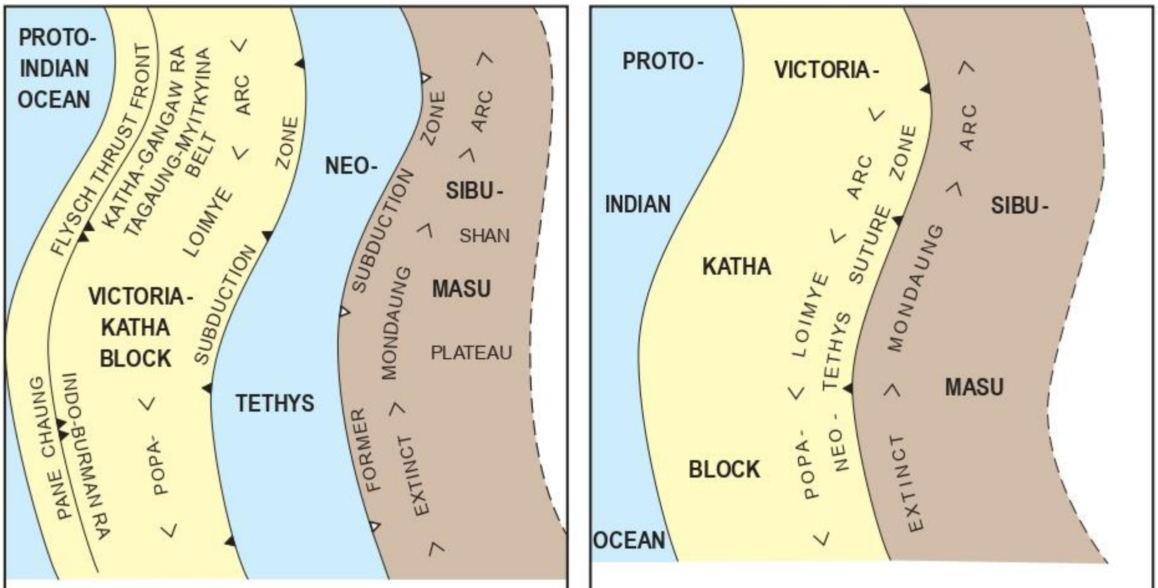
3. Shan Plateau, Shan Scarps and Mon-daung magmatic arc

The Plateau, Scarps and Mondaung Arc all lie east of the Sagaing Fault.

3.1. Shan Plateau succession:

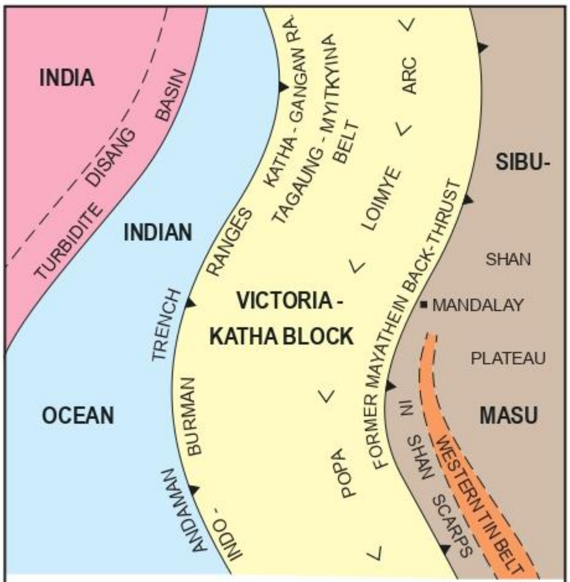
The Shan Plateau occupies eastern Myanmar and western Thailand and continues northwards as the Baoshan Block (e.g. Jin, 1996) in Yunnan. Our description of the Plateau refers to its western part.

Northeast of Mandalay the Mong Long Mica Schist and Mogok Metamorphics are overlain on an un-named fault by a southeasterly-dipping monoclinal succession with the Late Proterozoic to Early Cambrian Chaung Magyi Group at the base (**Fig. 5).** The Group, several kilometres thick, consists of slates, slatey to phyllitic sandstone turbidites and mudstones, and semi-schist or coarse-grained meta-wacke.



(a) 100 Ma mid-Cretaceous, Albian
(b) 85 Ma Late Cretaceous, Santonian

Fig. 8: Schematic sketch maps showing blocks and oceans in Myanmar and western Myanmar at (a) 100 Ma mid-Cretaceous, Albian and (b) 85 Ma Late Cretaceous, Santonian



50 Ma Early Eocene

Fig. 9: Schematic sketch map showing blocks and Indian ocean at 50 Ma Early Eocene

At its southeastern margin the Chaung Magyi is overlain probably conformably by rhyolitic pyroclastics of the Bawdwin Volcanics; both are overlain unconformably by Upper Cambrian cross-bedded quartzitic sandstones, shales and dolomitic limestones with a basal conglomerate. As recently summarised (Aye Ko Aung, 2020) the Upper Cambrian is overlain by a sequence comprising Ordovician argillaceous carbonates and shales, Silurian graptolitic shales and quartzose sandstones, and Devonian shales, dolomitic limestones and oolitic ironstones. The overlying Plateau Limestone here consists of the uppermost Permian to Triassic Nwabangyi Dolomite and Triassic Natteik Limestone. The Napeng Formation, an Upper Triassic flysch, overlies the Plateau Limestone and is said to be overlain unconformably (Brunnschweiler, 1970) by the mid-Jurassic Tati Limestone beneath the unfossiliferous Kalaw Red Beds. East of the Shan Scarps, on the western margin of the Plateau, Plateau Limestone with the Middle and Upper Permian Thitsipin Limestone at its base continues into the mid to Late Triassic. On **Fig**. **5** we show the Plateau Limestone overlain by the Bathonian to Oxfordian Loi-an Formation and the Loi-an overthrust by the complexly-folded turbidites and local limestone of the upper Triassic and lower Jurassic Shweminbon Formation, although the relationhip of the Shweminbon to the Loi-an Formation is disputed. The Shweminbon is correlated with the Napeng Formation to the north and overlain unconformably by Telu Limestone beneath Kalaw Red Beds.

3.2 The Slate Belt in the Shan Scarps, Tanintharyi and southwestern Thailand:

The Shan Scarps (**Figs. 1, 9**) were defined in the 1930s as the southward-widening belt between the Shan Plateau and Central Plain or Lowlands, extending from Mondaung south of Kyaukse to near Moulmein and bounded by the Shan Scarp in the east and alluvium east of the Sagaing Fault in the west (Myanmar Geosciences Society, 2014). The Scarps consist largely of the Slate Belt, a siliciclastic succes-sion at least partly Late Palaeozoic in age, together with the Yinmabin Schist. The Slate Belt, absent in the Mandalay-Mogok region, re-appears in the Tengchong block (**Fig**. **2**) in Yunnan and continues in Kachin State as a N--trending strip bordering China. South of the Scarps the Belt occupies most of Tanintharyi and southwestern Thailand including Phuket Island.

The lowest unit in the Slate Belt succession (**Fig. 7a)** is probably the Taungnyo Group, the Taungnyo Series of Leicester (1930), first defined in the Moulmein-Kyaikkami region (**Fig. 2**) and Late Tournaisian and Early Visean in age (Dr. Thura Oo, unpub. thesis, 2002). The Group also occurs at scattered localities along the western margin of the Shan Plateau, including Loikaw (Kyi Pyar Aung, Owens, & Metcalfe, 2014; Metcalfe & Kyi Pyar Aung, 2014) where it overlies mid-Palaeozoic strata and consists of marine sandstones, shales and minor limestones.

The Kogwe Mudstone (**Figs. 7a, 5**), the lower Formation of the Mergui Group in the Shan Scarps east of Yamethin (Mitchell et al., 2004), is probably older than and thrust over the Taungnyo Group, since the Upper Carboniferous in Sibumasu is missing (Wang et al., 2021). The Kogwe Mudstone, consisting of argillites and quartzites, is at least 2 km thick and unfossiliferous with 516 Ma detrital zircons (Kyaw Linn Zaw, Ohn Thwin, Travnor, & Thet Paing Kyaw Win, 2020) suggesting a possible source in the Bawdwin Volcanics. The Poklokkale Pebbly Wacke, the upper Formation of the Mergui Group, overlies the Kogwe Mudstone and includes thick beds of diamictite or pebbly wacke which occur through peninsular Thailand and Sumatra to Bangka Island in eastern Indonesia, and northwards through northeastern-most Myanmar into Central Lhasa and the South Qiangtang Block (**Fig. 1**) in Tibet. In South Quiangtang and south of Myanmar the distinctive pebbly wackes contain Asselian fossil assemblages (Wang et al., 2021) and in Myanmar, detrital zircons of Carboniferous, Ordovician and Precambrian age (Aung Zaw Myint et al., 2017).

The Poklokkale Wacke is overlain stratigraphically by the Sakmarian *Spino-martinia prolifica* Shale (**Fig. 5)** well exposed around Kyaukse, near Moulmein in the Zinyeik and Taungnyo Ranges and Hpa-an to the east, and east of Lebyin. South of Kyaukse the Magiye Conglomerate with clasts of Devonian to Ordovician age (refs *in* Mitchell, 2017) overlies Devonian beds and passes up into *S. prolifica* Shale beneath mid-Permian to Triassic Plateau Limestone (Thura Oo, Tin Hlaing, & Nyunt Htay (2002). On the Shan Plateau east of Nay Pyi Daw the *S. prolifica* Shale and equivalent Yin Yaw Formation of Hobson (1941) are overlain by the Plateau Limestone. In Thailand the Pharaka Formation southeast of Mae Sot and southwest of Mae Sariang **(Figs. 2, 5)** includes Sakmarian shale and is overlain by Middle Permian Limestone (Sukto, Suteethorn, Boripatgosol, Meesok &

Sareerat, 1984; Ueno & Charoentitirat, 2011). The Khao Phra Formation of Raksaskulong & Wongwanich (1993) west of Hua Hin (**Fig. 1)** includes Asselian diamictites and is therefore older than the *S. prolifica* Shale.

In northern Tanintharyi a 15 km wide belt of slates and quartzites resembling the Kogwe Mudstone is overlain by pebbly wackes dipping west beneath granite gneiss (Saw Naung et al., unpub., 1981). A similar pebbly wacke-gneiss relationship is seen at Kyaikkami near Moulmein (Nyunt Htay, Ko Ko & Ba Than, unpub. reprt, 1982). The Moulmein Limestone in Tanintharyi and the equivalent Ratburi Limestone in western and peninsular Thailand correlate with the Plateau Limestone and overlie the Slate Belt and the roughly equivalent Kaeng Krachan Group in Thailand. In the Phuket region Mitchell, Young, & Jantaranipa (1970) divided their Phuket Group, the Kaeng Krachang Formation of Javanaphet (1969) and Raksaskulong & Wongwanich (1993), into a Lower Formation with pebbly mudstones or diamictites, and a bryozoa-rich Upper Formation at least partly of Early Permian age and here correlated with the *S. prolifica* Shale, overlain by the Ratburi Limestone.

The Shan Scarps have been variously interpreted as either part of Sibumasu (e.g. Metcalfe, 1984), formerly Shan-Thai (Bunopas,1981), or a separate unit (e.g. Bender, 1983; Ridd, 2017a) or terrane with its eastern boundary in Myanmar at the W-facing Shan Scarp (**Fig. 2**). The Scarp in most places consists of Plateau Limestone and southwards from Kyaukse the westernmost outcrops of pre- Carboniferous rocks lie up to 30 km to the east. Nevertheless the *S. prolifica* Shale-Plateau Limestone succession overlies both the Asselian diamictite-bearing strata in the Slate Belt of Myanmar and western Thailand, and Devonian strata on the Shan Plateau (**Fig. 5).** This suggests that, despite a contrary view (Jin, 1996) for these belts in Yunnan, the Plateau and Shan Scarps were on the same plate through the Permian-Triassic and were not separated by an ocean basin.

The mid-Jurassic (170-172 Ma) granitic rocks intruding spinel and ruby-bearing marble at Mandalay Hill and diopside marble at Kyanikan 30 km to the north (Barley, Pickard, Khin Zaw, Rak, & Doyle, 2003), and also ca 20 Ma hornblende-biotite bearing dykes near Payangazu, lack obvious explanations.

3.3 The Shweminbon, Napeng and Mae Sariang flysch nappes:

The Upper Triassic to Lower Jurassic Shweminbon and Napeng Formations have been interpreted as passive continental margin deposits **(Figs. 6a, 7a, b)** thrust eastwards onto the Shan Plateau as an orogenic flysch **(Figs. 6a, b, 7c)** beneath an inferred and now-eroded obducted ophiolite (Mitchell et al., 2004). Cai et al. (2017) reported a 1.8 Ma peak and Permian to Triassic U-Pb ages on Shweminbon detrital zircons implying derivation from easternmost Myanmar. As noted above, the Bathonian to Oxfordian Loi-an and equivalent Kyaukhsu Taung Formations of shallow marine sediments and coals were probably deposited unconformably on Triassic Plateau Limestone and Slate Belt clastics (**Fig. 5)**, before being overthrust by the Shweminbon Formation **(Fig. 7 b, c).**

To the southeast of the Scarps in northwestern-most Thailand, Chonglokmani (2011) described the Middle and Upper Triassic Mae Sariang Formation **(Figs. 2, 5)** of cherts and pelagic limestones overlain by flysch with E-vergent folds; we correlate this with the Shweminbon Formation in Myanmar. The Mae Sariang Formation overlies siliciclastics which are underlain by the Middle and Upper Permian Doi Phawar Formation (Ueno & Charoentitirat, 2011) equivalent to the Plateau Limestone and Moulmein Limestones in Myanmar (Ridd, 2016). Curiously, ophiolitic melange thrust sheets in the Palaeo-Tethyan Changning-Menglian suture zone in Yunnan are also E-vergent (Zhong & Zhao, 2000); the exact location of the suture zone's continuation through Myanmar into northwestern Thailand **(Fig. 1**) is uncertain.

In our interpretation Jurassic emplacement of the flysch onto the Plateau was followed by generation and emplacement of the Yinmabin Schist described below.

3.4 The Yinmabin Schist in the Shan Scarps and Tanintharyi:

At its western margin the Slate Belt is overlain structurally on the Sakhanya Taung Thrust by metamorphic rocks assigned by Mitchell (2017) to the Mogok Metamorphic Group. Here we revert to the name Yinmabin Schist (Maung Thein et al., 1972, unpub.) for the metamorphics west of Yinmabin and elsewhere in the Scarps south of Mandalay. The Schist includes sillimanite schist, diopside-phlogopite marble, and migmatites, the mixed gneisses of Dutt (1942), with extensive areas of augen gneiss. It is intruded by latest Cretaceous and Palaeocene granites including the 72 Ma Nattaung Granite and a 59 Ma dyke in Bilin Quarry near Kyaukse (**Fig. 2)** town (Mitchell, Chung, Thura Oo, Lin, & Hung, 2012) which cut the main metamorphic fabric. The Schist attains a maximum width of 30 km east of Nay Pyi Taw and the Sagaing Fault (Bateson, Mitchell, & Clarke, 1972).

The locally abundant marble and calc-silicate within the Schist suggest an origin by tectonic burial of the Shan Plateau succession with its high content of Ordovician to Devonian and Permian carbonates. We infer that during and following emplacement of the Neo-Tethys-rooted Shweminbon flysch and inferred overlying ophiolite, the underlying Shan Plateau crust was shortened, metamorphosed to form the Yinmabin Schist and translated eastwards over the ophiolite, flysch and Slate Belt on the Sakhanya Taung Thrust **(Figs. 7c, d, 8a).** The Schist therefore now is structurally above the flysch, which is no longer on the western margin of Sibumasu (**Fig. 7e**) but probably correlates with Triassic flysch in the southwestern segment of the Luxi-Nujiang-Bangongco suture zone of Mo, Lu, & Shen (1993) and Chu et al. (2009) in Yunnan.

At the eastern margin of the Slate Belt south of Lebyin a narrow strip of schist, gneiss and diopside-phlogopite marble known informally as the Bon Schist can be interpreted as part of the Yinmabin Schist nappe translated eastwards on the Sakhanya Taung Thrust in the latest Jurassic or earliest Cretaceous. Uplift to the west and truncation in the east by an E-dipping extensional fault (Mitchell et al., 2021) resulted in preservation of the Schist as a klippen.

3.5 Early Cretaceous Mondaung Arc in the Shan Scarps and Plateau margin:

Rhyodacitic sills or dykes, diorites and granodiorites occur west and immediately east of the Shan Scarp in Myanmar, and comprise the Mondaung Arc of Lin, Mitchell, & Chung (2019) and Mitchell, Kyaw Min Htun, & Myint Thein Htay (2020). The Arc **(Fig. 2)** includes the Lawa or Law Chaung diorites intruding Shweminbon flysch east of Lebyin, rhyodacite dykes west of the diorites and at numerous localities between Lebyin and Mondaung, and the Yebokson Granodiorite and Yinmabin West diorite in the Slate Belt and schist near the Meiktila-Kalaw motor road. Lin et al. (2019) established that zircon U-Pb ages of these intrusions are within the 128 to 113 Ma range; the 113 Ma sample is a pebble within the Pyinyaung Formation which includes the Patchaung Volcanics of United Nations (1979c,e). Some of the intrusions form the continental margin arc of Zhang et al. (2018) who related it to eastward subduction within the Indo-Burman Ranges. We follow a proposal that subduction of Neo-Tethys (**Fig. 8a**) generated the arc after E-vergent orogeny and reversal in orogenic polarity (Mitchell et al., 2020, 2021).

Dacitic and andesitic undated dykes in the Mergui Group south of Lebyin and in the Loi-an Formation east of Kalaw, and the 121 Ma Mawpalaw Taung granite of Mi Paik & Khin Zaw (2014) southeast of Moulmein (**Fig. 2)** are probably part of the Mondaung Arc, as are Cretaceous hornblende-bearing granitic rocks to the north in Cobbing's (2011) Western Marginal Granite Belt in Thailand, I-type granites in western Tanintharyi (Cobbing, Pitfield, Derbyshire & Mallick, 1992) and rhyolites in the Mergui Archipelago. At Kyaikkami (**Fig. 2)** south of Moulmein Thet Paung Kyaw Win, Hla Kyi, & Kyaw Lin Zaw (2020) reported a zircon U-Pb age of 121 Ma on migmatite intruded by granodiorite and biotite granite. We speculate that the granite is part of the arc and that its emplacement reset the migmatite age to 121 Ma. Mondaung Arc magmatism evidently ceased long before intrusion of the 90 Ma Mokpalin diorite (Mitchell et al., 2012) northwest of Moulmein.

3.6. Late Cretaceous closure of Neo-Tethys:

The interruption to magmatic activity in the E-facing Popa-Loimye Arc beginning ca 90 Ma (Section 2.2.2.) can conveniently be attributed to closure of Neo-Tethys and end-Cenomanian (ca 90 Ma) collision of the Victoria-Katha Block or island arc with Sibumasu on the subducting Asian plate **(Figs. 7f, g, 8a, b).** Collision-related shortening in the Sibumasu crust accompanied by regional metamorphism can explain the transformation of some Cretacous granites to augen gneiss, for example the augen-gneiss near Kyaukse town with a 114 Ma zircon U-Pb magmatic age recording its intrusion into the Yinmabin Schist. Eastward-overturned folds in *Orbitolina* Limestone northeast of Tagaung may also have resulted from the collision.

3.7 Back-thrusting and crustal granites in the Western Tin Belt:

Granites of the Western Tin Belt of Myanmar and Thailand (Mitchell, 1977) intrude the Slate Belt between Mondaung **(Fig. 2)** and Phuket Island in Thailand. These are S-type or evolved ilmenite series peraluminous and reduced fractionated granites and almost all are in the 72 to 44 Ma age range. The granites are commonly explained by either the India-Asia collision (Wang et al., 2014) or the ca 70 Ma roll-back of the supposed low-angle E-dipping subduction zone related to the Popa-Loimye Arc system (Jiang, Li, Jiang, Wang, & Wei, 2017; Sanematsu, Manaka, & Khin Zaw, 2014; Li et al., 2018, 2019). We suggest instead that following Late Cretaceous closure of Neo-Tethys and thrusting of the Victoria-Katha Block on to Sibumasu **(Fig. 7g)**, orogenic polarity reversed. A related W-directed back-thrust carried Sibumasu over the Victoria-Katha Block, resulting in crustal shortening followed by partial melting and granite generation in tectonically thickened crust of the underthrust Block (**Figs. 7h, i, 9).** The back-thrust is perhaps analogous to that proposed by Oliver, Zaw, Hotson, Meffre, & Manaka (2014) for the generation of tin granites following closure of Palaeo-Tethys and orogenic polarity reversal in the Main Range Malaysia.

We infer that in the Indo-Burman Ranges west of the main back-thrust, related W-directed thrusts translated the Falam-Kabaw Formations to their present position in the Chin Hills and generated over-pressure beneath mudstone seals within the Formations. Resulting fluidisation and disruption of the interbedded limestones and underlying sediments formed melanges or oliststromes in the Sin Chaung Exotics Zone (**Fig. 4a)** and rafts of volcanic rock in the Manipur River (United Nations, 1979a) in the northern Chin Hills. Thrusting may also have mobilised previously obducted serpentinite, allowing its ascent as sheets in the *Orbitolina* Limestone. The proposed Sin Chaung Fault (Mitchell et al., 2021) lies to the north of the Exotics Zone.

We suggest that the back-thrust is exposed in the Shwebo Basin as the N-trending fault west of the Sagaing Fault, between the Mayathein Complex and the *Orbitolina* Limestone and nearby Ubye Serpentinite (Section 2.2.3). We regard the Mayathein Complex as part of the Yinmabin Schist east of the Sagaing Fault, thrust westwards in the early Palaeocene over the Kywethe (*Orbitolina*) Limestone **(Fig. 7h, i)**. Although forming the boundary between the Victoria-Katha Block and Sibumasu, the back-thrust in most places buries the Late Cretaceous collisional suture zone. Before Oligocene and Late Cenozoic dextral dislacement on the Sagaing Fault (**Fig**. **3 a**,**b**) the Mayathein Complex, the back-thrust and the underlying Kywethe Limestone, now situated west of Tigyaing and Tagaung (**Fig**. **2**), lay south of Nay Pyi Daw and west of the Shan Scarps.

In our interpretation by ca 55 Ma the back--thrusting had migrated to the western margin of Myanmar and initiated eastward subduction of the proto-Indian Ocean (**Fig**. **9**) with renewed magmatism in the Popa-Loimye Arc, forming Late Eocene plutons at Shangalon (e.g. United Nations, 1978 a,b; Mitchell, 2017), 14 Ma quartz andesite porphyries and rhyolites at Monywa, and ca 14 Ma rhyolites now beneath the Mt Popa (Stephenson & Marshall, 1984; Lee, Chung, & Yang, 2016,) stratovolcano **(Fig. 5)**. Many of these rocks either intrude or overlie the Cretaceous arc plutons, although Taungthonlon stratovolcano lies west of the old arc axis.

4. Mogok Metamorphic Belt

The sickle-shaped Mogok Metamorphic Belt extends northwards from Mandalay hill through Mogok to northernmost Myanmar. The Belt consists of sillimanite-bearing migmatites, calc-silicates, schists and marbles (Iyer, 1953; Searle & Ba Than Haq, 1964) in upward succession with a metamorphic grade up to granulite facies (Searle et al., 2020). The most distinctive rocks are diopside-phlogopite-graphite marbles which commonly include gem-quality spinel or locally ruby. The metamorphic rocks are intruded by Upper late Oligocene to Lower early Miocene biotite granites, and leucogranite sheets occur in the migmatites. Intrusions of nepheline syenite (e.g. Iyer, 1953) and charnockite, mostly sheet-like, are present in the Mogok gemstone district and are probably Jurassic (Searle et al., 2020) and mid-Miocene (Shi et al., 2021), both older and younger than the late Eocene-Oligocene (Lamont et al., 2021) or Oligocene-early Miocene (Myint Myat Phyo et al., 2020) high-grade metamorphism.

At Nanyaseik (**Fig. 2**) west of the main splay of the Sagaing Fault, inliers in alluvium expose a 12 km wide biotite granite in which bodies of diopside-phlogopite marble, probably roof pendants (Dr. M.J. Crow, oral comm. 2021), contain ruby and spinel and resemble marble from the Mogok Metamorphic Belt. This has arguably been translated northwards on the Sagaing Fault from an original position southwest of Mandalay.

Clegg (1941) proposed that the Mogok Metamorphic Belt is the metamorphosed equivalent of the *Orbitolina* limestone and older formations on the Shan Plateau. This equivalence, excluding the *Orbitolina* limestone, is supported by the structural position of the Mogok Metamorphics dipping southeast under the Mong Long Mica Schist and Chaung Magyi Group (**Fig. 10**). We suggest that the Mogok Belt and Yinmabin Schist both formed by metamorphism of a Shan Plateau succession protolith and had a similar early tectonic and metamorphic history, but that the Mogok Belt underwent longer-lasting uplift than the Schist. The north-eastward continuation of the Mayathein back-thrust may be the steep SE-dipping Kyaukpyu Fault between the Mogok Metamorphic Belt and Tagaung-Myitkyina Belt (**Figs. 2, 11**). Part of the Mogok Belt's uplift and exhumation may have taken place in the footwall of the un-named extensional fault (Mitchell et al., 2021), perhaps a re-activated thrust, inferred at the base of the Chaung Magyi Group. Displacement here perhaps contributed to prolonged uplift with deeper, younger and higher-grade peak metamorphism in the Mogok Metamorphics than in the Yinmabin Schist.

5. Mineral deposit and gemstone formation in western Myanmar-Thailand

Episodes of mineralisation and gemstone formation from the Jurassic to Pliocene (**Fig. 11**) are an essential part of the region's evolution. The oldest potentially economic hydrothermal deposits are the stratiform volcanogenic copper-gold occurrences situated near the top of the Mawgyi Volcanics north of Shangalon, and discovered ca 2012. The mineralisation, conformable with the Mawgyi basalt host rocks, is poorly constrained as Triassic to Early Albian.

Possibly the next oldest deposits are the orogenic quartz-gold vein systems in the Slate belt of the Shan Scarps where Modi Taung has produced an estimated ten tonnes of gold from12 km of underground workings. Veins are cut by dacitic and andesitic dykes thought to be part of the 128 to 113 Ma Mondaung Arc. The veins are no older than the maximum late Early Permian age for deformation in the Slate Belt, but we speculate that veining followed Late Jurassic emplacement of the Shweminbon flysch. Numerous similar auriferous veins are present elsewhere in the Scarps and include occurrences in the Slate Belt of Tanintharyi and near Hua Hin (**Fig. 1**) in Thailand. Orogenic quartz-gold veins in the Late Precambrian to earliest Cambrian Chaung Magyi slates (**Fig. 11**) could be co-eval with those within the Slate Belt.

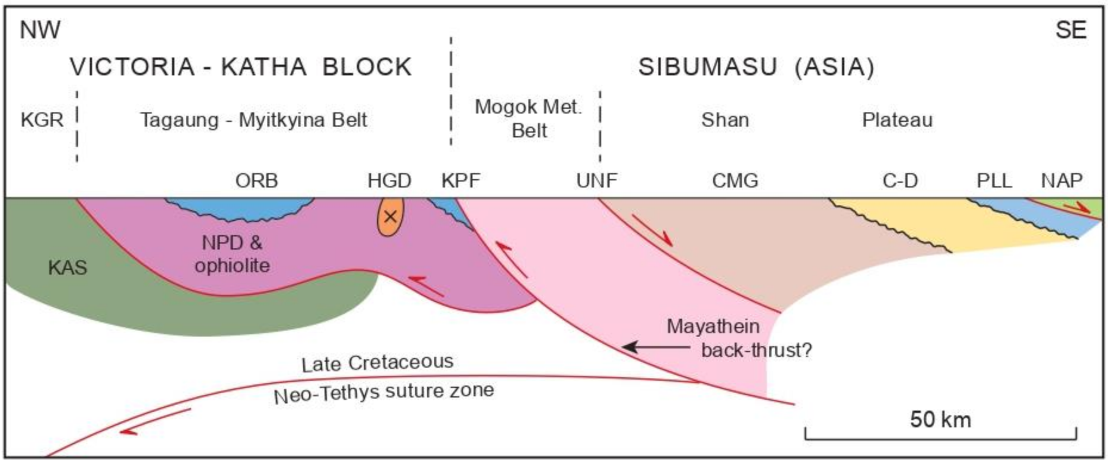


Fig. 10: Schematic NW-SE cross-section, Mogok region. CD Cambrian-Devonian, CMG Chaung Magyi Group, HGD hornblende-biotite granodiorite, KAS Kanpetlet Schist, KGR Katha-Gangaw Range, KPF Kyaukpyu Fault or thrust, NAP Napeng flysch, NPD Ngapyawdawchaung Fm., ORB Orbitolina Limestone, UNF un-named fault. Location on Fig.2.

Gold-copper skarn ores are mined from marbles and Lower Cretaceous diorite stocks and dykes of the Mondaung Arc at Shwe-minbon immediately east of Lebyin and at Paladokhta near Tagaung in the Tagaung--Myitkyina Belt. Jadeite veins in northwestern Myanmar are in serpentinites which probably ascended from deeply subducted rocks of the Victoria-Katha Block (Mitchell et al., 2021) and were exhumed by mid-Cretaceous time but most of the extraordinarily high production of gem-quality jade is from vein-derived fossil placers, probably of Late Cenozoic age at Hpakant and Palaeogene at Khamti.

In the Western Tin Belt mineralisation is associated with the reduced crustal granites (Section 7) within the Slate Belt which forms a world-class Sn-W-Ta and also an orogenic Au metallotect. Clegg (1944) described 400 Sn-W workings in the Myanmar segment where some veins yield more tungsten than tin, described with isotopic ages in many recent publications. Niobium-tantalum is recovered from concen-trates from the Thai segment. The veins and pegmatites with Sn-W-Ta occur in granite apices and host rocks which are invariably hornfelsed, but apparently identical granites in the Yinmabin Schist lack mineralisation. The tin, and also the granites, may have originated in the Victoria-Katha Block beneath the Mayathein back-thrust.

Several types of mineralisation are undoubtedly related to hydrothermal systems associated with the post-Cretaceous W-facing Popa-Loimye Arc. These include chalcopyrite-bornite veins in the 40-33 Ma granodioritic stocks and dykes at Shangalon, frequently cited as a porphyry system but with distinctive quartz stockworks and probable potassic alteration. Low sulphidation epithermal gold veins are widespread in the Mawgyi Volcanics, a gold metallotect, but are probably genetically related to unexposed deep intrusions in the Popa-Loimye Arc. Epithermal gold veins at Kyaukpahto (Ye Myint Swe, Cho Cho Aye, & Khin Zaw, 2017) are hosted by Eocene sedimentary rocks which are underlain by Mawgyi or probably equivalent Ngapyaw-dawchaung basalts. The basaltic rocks may form a structural high and suggest that the veins in the Mawgyi metallotect are also post-Eocene. Antimony deposits (e.g. Lebyin, and Thabyu near Moulmein) are associated with quartz-pyrite alteration zones implying epithermal systems, and occur in or on anticlinal uplifts within Late Palaeozoic sedimentary carbonaceous host rocks situated behind the Popa-Loimye Arc.

Porphyritic quartz andesites and adjacent sedimentary rocks host the ca 14 Ma high suphidation epithermal chalcocite-covellite copper deposits at Monywa. Pre-mining

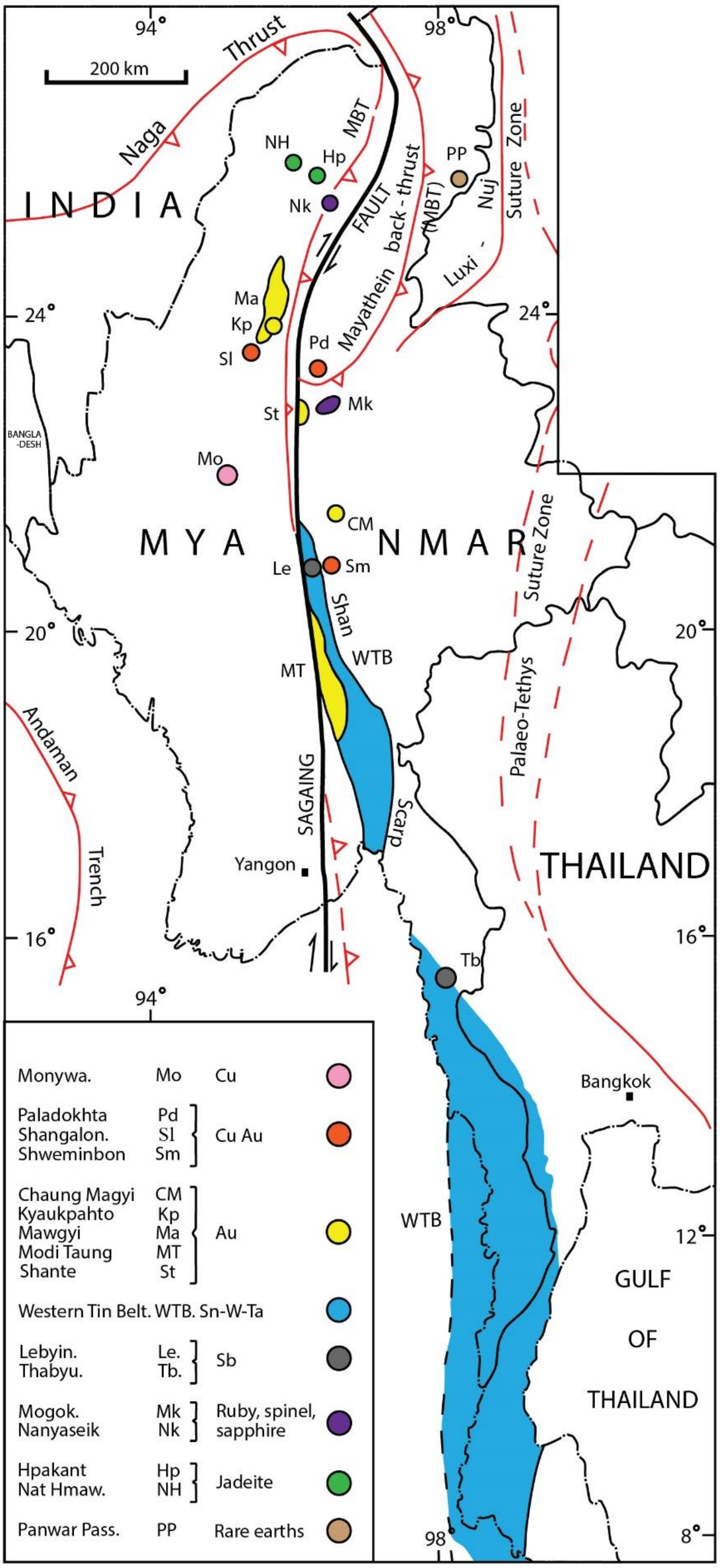


Fig. 11: Map of Myanmar and part of Thailand showing mineral deposits or metallotects and selected regional structural features described in text.

reserves of 7 mt copper are probably the largest of any producing copper mine in Southeast Asia. Minor low sulphidation quartz-gold veins at Monywa are hosted by hornfelsed mud-stones and rhyolites and no older than the copper deposits. Perhaps of similar age are advanced argillic silicic lithocaps at Mt Popa, and north of Pinlebu where they overlie copper mineralisation at depth.

The second-youngest economic minerals are the famous gem-quality ruby and spinel found mainly in the Mogok region and considered to be related to retrograde metamorphism not younger than early Miocene. Here sapphire-bearing nepheline syenite has yielded SIMS U-Pb ages ca 13.5 Ma (Shi et al., 2021). Gemstone formation was succeeded by emplacement of high-grade auriferous veins in the Shante gold district in the Mogok Metamorphic Belt southwest of Mogok, with evidence of both low sulphidation epithermal (e.g. Mitchell, 2017) and orogenic epizonal (e.g. Aung Zaw Myint, Wagner, & Khin Zaw, 2022) gold systems.

6 Conclusions

Our proposed tectonic events include obduction of Neo-Tethyan ophiolite and flysch over the Asian and Victoria-Katha Block margins, ocean closure, back-thrusting in the collision belt and reversal of the E-facing Popo-Loimye Arc. These events while in some cases speculative, provide new and reasonably satisfactory explanations for many aspects of the geology and for some of the major mineral deposits in the region considered. Late Cretaceous closure of Neo-Tethys by southward (now rotated to westward) subduction provides a possible mechanism for transporting the island arc of Westerweel et al. (2019) and Licht et al. (2020), our Popa-Loimye Arc, from mid-Tethys to the Asian margin after 95 Ma.

Our re-interpretation of the Falam Formation melanges suggests the possibility, not explored in this paper, that the Late Cretaceous Falam and Kabaw Formations and Naga flysch are an orogenic flysch deposited in a narrow ocean basin opened between the Indo-Burman Ranges and the Popa- Loimye arc. With basin closure the flysch was expelled westwards before deposition of the Paunggyi Formation began in the mid-Palaeocene.

E-vergent Triassic flysch in northwestern Thailand correlates with that to the northwest, east of the Shan Scarps in Myanmar, and implies a tectonic boundary or overlap with the established W-vergent structures in Thailand's Inthanon Zone to the east. Before its closure in the Late Cretaceous, Neo-Tethys was probably continuous with the Luxi-Nujiang-Bangongco Ocean in Yunnan and Tibet. However our proposed convergent Jurassic subduction zones beneath Neo-Tethys have not yet been reconciled with the widely accepted closure of Tibetan Neo-Tethys by divergent subduction.

Our adoption of interpretations of the Indo-Burman Ranges or Kalemyo ophiolites and radiolarian cherts as the former southwestward continuation of those in the Tagaung-Myitkyina Belt, all relicts of a single Neo-Tethys now offset by dextral displacment on the Sagaing Fault, is not in conflict with the field observations. The reports we cite of the youngest cherts (Lower Cretaceous) in the Tagaung segment of the ocean, younger than those (Upper Jurassic) in the Indo-Burman Ranges segment, neither support nor disprove our interpretation, but do reduce the credibility of the widespread opinion that the suture zone in the Indo-Burman Ranges is younger than that in the Tagaung-Myitkyina Belt.

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