Myanmar and Asia united, Australia left behind long ago

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Abstract

It is well known that western Myanmar is underlain by a continental fragment, the West Burma Block, but there are arguments about its origin and the time of its arrival in SE Asia. This study presents the first petrological, XRD diffraction, heavy mineral and detrital zircon U-Pb age data from turbidite sandstones in the Chin Hills that were deposited on West Burma crust in the Triassic. These sandstones contain detritus derived from areas surrounding West Burma and thus help resolve arguments about its location in the Palaeozoic and Mesozoic. West Burma, Sibumasu and Western Australia have similar populations of Archean zircons derived from Western Australian cratons. Until the Devonian all formed part of the Gondwana supercontinent. The abundance of Archean zircons decreases from Western Australia to West Burma and then to Sibumasu. This is consistent with their relative positions in the Gondwana margin, with Sibumasu furthest outboard from Western Australia. Differences in zircon populations indicate that Indochina was not close to West Burma or Sibumasu in Gondwana. West Burma contains abundant Permian and Triassic zircons. These are unknown in Western Australia and different from those of the Carnarvon Basin; they were probably derived from SE Asian tin belt granitoids. Cr spinel is present in most West Burma sandstones; it is common in SE Asia but rare in Western Australia. These new data show that West Burma was part of SE Asia before the Mesozoic and support suggestions that the Argo block that rifted in the Jurassic is not West Burma.

1. Introduction

SE Asia is composed of continental fragments derived ultimately from the Gondwana super-continent by rifting events during the Palaeozoic and Mesozoic (e.g. Ridd, 1971; Hamilton, 1979; Audley-Charles, 1988; Metcalfe, 1988, 1996, 2013a,b; Hutchison, 1989). Fragments that separated from Gondwana in the Devonian and were part of Asia by the Carboniferous are described as Cathaysian. Those that remained further south in the Carboniferous and were added to Asia in the Triassic are referred to as Gondwanan. The Cathaysian fragments have a distinctive low-latitude flora and fauna in contrast to Gondwanan fragments that are characterised by glacial deposits and an equally distinctive high-latitude flora. In SE Asia the principal Gondwanan fragment is known as Sibumasu. Two principal Cathaysian fragments are known as Indochina and West Sumatra. Fragments that rifted later, from what remained of Gondwana in the Jurassic, are described here for simplicity as Australian, since they are interpreted to have separated from what is now Australia's western and NW margins. The present study aims to determine how West Burma fits into this scenario.

The complex tectonic history of the region has led to controversy over when and where fragments separated from Gondwana and when and where they docked in SE Asia. Much of this controversy has been resolved and it is now accepted that Sibumasu formed part of SE Asia by the Triassic, after collision with the Sukhothai Arc and the Cathaysian Indochina-East Malaya Block (Sone and Metcalfe, 2008; Barber and Crow, 2009; Sevastjanova et al., 2011; Metcalfe, 2013a,b). However, there are still arguments about the continental basement of western Myanmar, the West Burma Block.

One view is that the West Burma Block was part of SE Asia by the Early Mesozoic (e.g. Gatinsky and Hutchison, 1986; Hutchison, 1989; Mitchell, 1992; Barber and Crow, 2005, 2009; Hall et al., 2009; Metcalfe, 2011; Hall, 2012, 2014; Morley, 2012). This implies it was part of Gondwanan Sibumasu or the Cathaysian West Sumatra Block (Barber and Crow, 2005).

An alternative view is that that West Burma separated from Western Australia in the Jurassic and was added to SE Asia in the Cretaceous (e.g. Sengör, 1987; Veevers, 1988; Metcalfe, 1990; Audley-Charles, 1991). Metcalfe (1996) positioned West Burma outboard of NW Australia, on the basis of Triassic quartz-rich turbidites above a pre-Mesozoic schist basement, and speculated that the block might have provided a source for quartz-rich sediments on Timor. This view has become widely accepted (e.g. Longley et al., 2002; Heine et al., 2004; Hoernle et al., 2011) despite Metcalfe's (1996) observation that there was “as yet no direct evidence for the origin of this [West Burma] block”.

These contrasting interpretations can be tested with provenance studies. Triassic turbiditic sandstones, exposed in the Chin Hills of Western Myanmar (Fig. 1), contain detritus derived from the landmasses surrounding their depositional sites. If West Burma separated from Australia in the Jurassic and was added to SE Asia in the Cretaceous, these sandstones will contain detritus derived from Australia. If however, West Burma was part of SE Asia before the Triassic, they will contain detritus derived from Gondwanan or Cathaysian blocks.

Detrital zircon geochronology, heavy mineral analysis and sandstone petrographical studies have proved rewarding for provenance and continental evolution studies across the world (e.g. Sircombe and Freeman, 1999; Cawood and Nemchin, 2000; van Hattum et al., 2006, 2013; Kröner, 2010; Mange et al., 2010; Gehrels et al., 2011; Rojas-Agramonte et al., 2011; Burrett et al., 2014). In Myanmar, detrital zircon age and heavy mineral studies have been used to reconstruct paleo-river drainage patterns, determine Cenozoic sediment provenance and to constrain the age of anthropoid primate fossil-bearing strata (e.g. Allen et al., 2008, Liang et al., 2008; Tang et al., 2012; Licht et al., 2013; Naing et al., 2014; Robinson et al., 2014), but have never been applied to Triassic sandstones.

This study presents the first petrographical, XRD diffraction, heavy mineral and detrital zircon U-Pb age data from the Triassic Pane Chaung turbiditic sandstones in the Chin Hills of Western Myanmar. In an attempt to resolve existing arguments about the West Burma Block, we have compared our new data to those published from Sibumasu, Indochina, the NW Shelf and Western Australia.

2. Geological setting

2.1 Regional geology of Myanmar

Myanmar can be divided into three broadly north-south trending belts (Fig. 2), the Shan Plateau, Shan Scarps and Western Myanmar, that lie on two basement blocks (United Nations, 1979; Stephenson and Marshall, 1984; Mitchell, 1993; Pivnik et al., 1998; Mitchell et al., 2012; Metcalfe, 2013a). The Shan Plateau belongs to Sibumasu, whereas the Shan Scarps and Western Myanmar lie on West Burma (Fig. 3). To the west there is the Mawgyi Nappe interpreted as an intra-oceanic arc emplaced on the SE Asian margin in the Early Cretaceous (Mitchell, 1993).

The Shan Plateau lies west of the Salween River in eastern Myanmar. The plateau is characterised by a distinctive Cambrian to Triassic succession similar to that of western Thailand (e.g. Ridd et al., 2011) and the Malay Peninsula (e.g. Hutchison and Tan, 2009). Dated rocks include Upper Cambrian siliciclastic and volcanic rocks, Ordovician to mid-Devonian carbonates and Upper Silurian-Lower Devonian black shales. These rocks are unconformably overlain by mid-Permian to mid-Triassic Plateau limestones, which in turn are overlain by deformed Upper Triassic to Lower Jurassic turbidites and mudstones, Middle Jurassic limestones and shales, and younger Mesozoic continental strata (Mitchell et al., 2012).

The Shan Scarps form a narrow zone near the Sagaing Fault. The Shan Scarps can be further subdivided into the Paunglaung-Mawchi Zone (PMZ), the Slate Belt and the Mogok Metamorphic Belt (MMB). The PMZ is a wide zone up to 3 km wide that consists of folded Upper Jurassic to Lower Cretaceous (Aptian) marine siliciclastic rocks and limestones. The Slate Belt consists of Carboniferous-Lower Permian glacial marine pebbly mudstones, similar to those in Thailand, the Malay Peninsula and Sumatra (Metcalfe, 1996; Barber and Crow, 2009; Ridd, 2009; Ridd and Watkinson, 2013). The MMB consists of high grade metamorphic rocks that are locally sapphire- and ruby-bearing. There is still much disagreement about the ages of the metamorphic rocks (e.g. Mitchell et al., 2004, 2007; Searle et al., 2007), but most authors recognise that the MMB has a complex thermal history and records Permian, Jurassic and several Cenozoic events (e.g. Searle et al., 2007).

Western Myanmar includes the Myanmar Central Basin (MCB) and the Indo-Burman Ranges (IBR) (Mitchell et al., 2010, 2012). The MCB is composed of Upper Cretaceous to Pleistocene marine and fluvial sediments overlain by Quaternary volcanoes (e.g. Pivnik et al., 1998, Mitchell et al., 2010). At Karmine (Fig. 2) there are also Permian (Murghabian) fusulinid-bearing limestones (Oo et al., 2002) interpreted to be Cathaysian (Barber and Crow, 2009). The IBR is an active fold and thrust belt composed of schists, pillow lavas, ultramafic rocks and Triassic to Eocene sedimentary rocks.

There are at least two distinct belts of ultramafic rocks in Myanmar, usually considered to be ophiolitic: (a) the Tagaung-Myitkyina Belt (TMB) in the northeast and (b) a zone along the eastern flanks of the Chin and Naga Hills (e.g. Mitchell et al., 2012). They are suggested to be parts of the same belt duplicated by dextral movements along the Sagaing Fault (Mitchell et al., 2012). The TMB ophiolites are Jurassic-Cretaceous in age (e.g. Maung Maung et al., 2008). However, other ophiolites in Myanmar are poorly dated.

2.2 The Chin Hills

The Chin Hills are situated in the eastern part of the Indo-Burman Ranges and are composed of a metamorphic basement overlain by the Triassic Pane Chaung Formation turbidites and Cretaceous shales and limestones. The metamorphic basement is composed of low-grade mica and chlorite Kanpetlet schists and higher grade amphibolite facies chlorite-epidote-garnet-bearing rocks of the Yazagyo and Hkweka Metamorphics (United Nations, 1979). The schists were originally considered to be part of pre-Mesozoic basement (e.g. Brunnschweiler, 1966) and were tentatively correlated with the Precambrian-Cambrian Chaung Magyi Metamorphic Series (Tien and Haq, 1969), but were later reinterpreted as Triassic (Maurin and Rangin, 2009; Mitchell et al., 2010). However, they remain isotopically undated and are therefore of uncertain age.

The Pane Chaung Formation is widely exposed along the eastern flank of the southern Chin Hills and the Arakan Yoma (Fig. 1) and is composed of indurated turbiditic sandstones and shales. The sandstones are predominantly quartz wackes, locally calcareous quartz wackes, with rare thin limestones and rare interbedded ribbon-bedded cherts (Mitchell et al., 2010). The sandstones and shales contain rare *Halobia* fossils, indicating a Triassic depositional age (Bannert et al., 2011). The formation is strongly faulted and deformed, and the beds are steeply dipping and commonly overturned. There are common sole marks, load casts and intrabasinal mud clasts in the upper parts of sandstone beds, and fining-upwards sequences. Locally, the Pane Chaung Formation is overlain by pillow basalts and is cut by basalt, diabase and gabbro dykes (Mitchell et al., 2010). There are serpentinites, dunites, chromites and gabbros tectonically intercalated into the Pane Chaung Formation. Intercalated ultramafic rocks are particularly abundant in the northern Chin Hills, near Kalaymio (United Nations, 1979; Mitchell, 2010) (Fig. 5e, f and g). At the eastern margin of the Chin Hills, the Pane Chaung Formation and the pillow lavas are overlain unconformably by the mid Cretaceous (Albian-Cenomanian) Paung Chaung Limestone (Mitchell et al., 2010).

West of the Kantpetlet Schist and the Pane Chaung Formation there are outcrops of interbedded mudstones, sandy turbidites, and micritic limestones with an Upper Cretaceous (Campanian-Maastrichtian) *Globotruncana* pelagic fauna. They are strongly folded, boudinaged and locally crosscut by quartz veins. They also contain exotic boulders of ophicalcites, gabbros, basalts, cherts and quartzose sandstones (Mitchell et al., 2010).

3. Materials and methods

We have examined six Pane Chaung Formation sandstone samples and one marlstone sample in thin-sections, and carried out point counting, XRD powder diffraction, heavy mineral analysis, and LA-ICPMS U-Pb dating of detrital zircons from these samples.

3.1 Samples

In the field it can be difficult to confidently differentiate between the Pane Chaung Formation and lithologically similar Upper Mesozoic and Cenozoic strata. Therefore, field sampling focused on the localities with previously reported *Halobia* fossils (A. Mitchell, pers. comm.., 2012) and at locations where it is easy to recognise the Triassic sandstones because they are in contact with the Kanpetlet

Schist or contain tectonically intercalated boulders of the ultramafic rocks (Fig. 5e, f and g) to be sure that Triassic sandstones were sampled.

We have analysed six samples from the Pane Chaung Formation (ISWB10, 13, 15, 25, 42 and 57). Of these, four (ISWB10, 13, 15 and 25) were collected from the area near Mt Victoria and two (ISWB42 and 57) were collected in the northern part of the Chin Hills, near Kalaymio. ISWB10, 13, 25, 42 and 57 are micaceous sandstones interbedded with shale (e.g. Fig. 4a, b, c, d, e and f) and ISWB13 was collected from a block of Pane Chaung Formation within the schist (Fig. 5a). ISWB15 is thickly-bedded sandstone, which appears different to other Pane Chaung Formation samples because of a more yellowish colour, coarser grain-size, lack of interbedded shales, and lack of sole marks and mud clasts (Fig. 5b).

For comparison, we have also analysed one marlstone sample (ISWB06) that is tectonically mixed in with the Pane Chaung Formation in the Mt Victoria area (Fig. 5 c and d).

3.2 Techniques

Thin-section petrographical analyses were performed and two independent techniques were used for point-counting: (i) the traditional (Indiana) and (ii) the Gazzi-Dickinson methods (e.g. Dickinson and Suczek, 1979; Dickinson et al., 1983). In the Gazzi-Dickinson method all grains larger than 0.0625 mm that occur within the rock fragments are classified as individual minerals and not as rock fragments in order to reduce grain-size effects. The method is widely used in sandstone petrography, because it is required for producing regional-scale provenance-discriminating QFL plots. However, the traditional point-counting method, which allows classification of rock fragments in detail, is more valuable for basin-scale provenance studies (e.g. Decker and Helmond, 1985). For each method, 300 counts were collected from five analysed sandstone samples, ISWB10, 13, 15, 42 and 57. Only the traditional point-counting method was applied to the marl sample, ISWB06. To determine the character of the sandstone matrix, the fine-grained component of the samples was analysed with XRD powder diffraction at Royal Holloway University of London.

Heavy minerals were separated and analysed at Royal Holloway University of London. The heavy minerals were separated in LST Fastfloat heavy liquid (2.89 g/cm^3) using the funnel technique (e.g. Mange and Maurer, 1992). The size of the heavy fraction was reduced using a quartering approach and a representative portion of heavy minerals was mounted on glass slides in Canada Balsam (R.I.=1.55). Whenever possible, at least 200 non-opaque and non-micaceous detrital heavy minerals were identified using a Nikon Eclipse petrographic microscope and counted with the line point counting method (Galehouse, 1971). Optical identifications were verified with semi-quantitative SEM-EDS analysis of grains that were hand-picked from the same samples.

The non-magnetic minerals were separated from the LST Fastfloat heavy fraction using a Frantz magnetic separator. Zircons were then separated from a non-magnetic fraction (> 1.1 A at 20° tilt angle) using diiodomethane (DIM) with a density 3.3 g/cm^3 and hand-picked, mounted in araldite resin, and polished. Zircon separation was performed at Royal Holloway University of London. CL-images of the mounted zircons were collected at the Natural History Museum, London and in the BP laboratories, Sunbury to identify cores and rims and to select the spots for analysis. U-Pb dating was carried out at the London Geochronology Centre, University College London, using a New Wave 213 aperture-imaged frequency-quintupled laser ablation system (213 nm) coupled to an Agilent 7700cs quadrupole-based ICPMS. Grains were ablated with a 40 μm laser spot. Plesovice zircon (TIMS reference age 337.13±0.37 Ma; Sláma et al., 2008) and NIST SRM 612 silicate glass (Pearce et al., 1997) standards were used for correcting mass fractionation and instrumental bias. Raw zircon U-Pb age data were processed using Glitter (Griffin et al., 2008) or Iolite software (Paton et al., 2011). Whenever possible, at least 100 grains were analysed from each sample. The calculator of Vermeesch (2004) was used to evaluate the actual size of population (f_{act}) that has not been missed at the 95% confidence level for each sample, assuming uniform distribution of ages (the worst case scenario). For simplicity, all f_{act} further in the text are given at 95% confidence level. ^{207}Pb-corrected ^{238}U/^{206}Pb ages were used for zircons younger than 1000 Ma and uncorrected ^{207}Pb/^{206}Pb ages were used for older zircons.

4. Results

4.1 Petrography

All of the analysed Pane Chaung Formation samples (ISWB6, 10, 13, 15, 25, 42 and 57) are feldspathic litharenites (Folk, 1980) that are composed predominantly of monocrystalline quartz with subordinate polycrystalline quartz, plagioclase feldspar and lithic fragments, which include phyllite, mudstone, chert, intermediate to basic volcanic rocks, and tonalite/diorite (Table 1, Fig. 6). Muscovite, biotite, chlorite and heavy minerals (zircon, tourmaline, rutile and epidote) are present in all samples (Table 1). ISWB10 contains echinoderm fragments. The matrix in all sandstone samples is dominated by clay minerals and organic matter. Authigenic cements are composed of siderite, calcite and pyrite. Locally, there are quartz and feldspar overgrowths. Authigenic clays are illitic and sericitic. XRD analyses show that the fine-grained fraction of the sandstones is composed of quartz, carbonates, illite, chlorite and plagioclase. Texturally, the sandstones are poor to moderately sorted and immature. Grain roundness ranges from angular to subrounded, but subangular grains predominate.

On QFL (quartz, feldspar, lithics) plots (Dickinson et al., 1983) the sandstones lie within the recycled orogenic provenance field (Fig. 6). The presence of sedimentary lithics in the Pane Chaung Formation confirms recycling from sedimentary rocks, but the angular to subangular grain shapes suggest a relatively short transport. Unabraded plagioclase feldspar and volcanic lithic clasts suggest first cycle contribution from contemporaneous volcanic rocks. Foliated and platy metamorphic lithics are most probably derived from chlorite schists or phyllites, such as those of the Kanpetlet Schist.

The marlstone (ISWB06) contains bioturbated clay with isolated streaks of organic matter and rare “floating” detrital grains of quartz, plagioclase, volcanic lithics and mica. Skeletal carbonate grains are composed of benthic foraminifera, locally common calcitised radiolaria, rare planktonic foraminifera and rare echinoderm debris. Authigenic cements are dominated by calcite and rare silica, and there are also rare framboidal pyrite and glauconite pellets present.

Marlstones are commonly deposited in calm-water marine environments with little siliciclastic input. Siliciclastic detrital grains in the marlstone sample (ISWB06) could either be reworked from shelf or continental areas adjacent to their depositional site, or deposited from contemporaneous volcanic ash-falls. The presence of unabraded plagioclase feldspar and small numbers of volcanic lithic fragments favours a contemporaneous volcanic provenance. ISWB06 was collected close to faulted and strongly deformed limestone that also contains volcanic clasts, the presence of which is consistent with contemporaneous volcanism (Fig. 5d). While this area is complex with several discrete lithological units of different ages tectonically mixed together, there are no known pre-Jurassic volcanic rocks reported from the Chin Hills. Most of the limestones in the area are also of Cretaceous or younger age. This, together with presence of planktonic foraminifera in the analysed marlstone, suggests that its depositional age is significantly younger than that of the Pane Chaung Formation and is closer to that of the limestone with the volcanic clasts.

4.2 Heavy mineral assemblages

Heavy minerals were analysed only in the Pane Chaung samples, five of which, ISWB13, 15, 25, 42 and 57 yielded sufficient amounts of heavy minerals to carry out a complete analysis. Only 167 grains could be counted from ISWB10. Heavy mineral assemblages of the Pane Chaung Formation are composed of zircon (40-10%), apatite (29-13%), tourmaline (25-7%), rutile (25-7%), chlorite (13-3%), and epidote (6 to less than 0.5%). The samples also contain minor (up to 3%) anatase, titanite, monazite, hematite, Cr spinel, amphibole, and pyroxene (Fig. 7). Garnet (11-5%) is present in all samples, except ISWB42. Cr spinel is present in four of six analysed samples: ISWB10, 25, 42 and 57.

The similarities of heavy mineral assemblages in all samples suggest little or no significant geographical variations in provenance in the studied area. The high maturity of the heavy mineral assemblages (zircon, tourmaline and rutile) suggests recycling from older sandstones. Zircon is predominantly colourless, subhedral, sub-rounded, anhedral and rounded, suggesting a mixed provenance from metamorphic, sedimentary and igneous sources. Rutile is dark reddish-brown and both rounded to angular. Tourmaline is pleochroic in shades of brown, greenish brown and green. Both rounded to angular grains are common. The rounded zircon, rutile and tourmaline grains have pitted and frosted surfaces, diagnostic of sedimentary reworking. Garnet is predominantly angular. Garnet may be present in a wide variety of source rocks, but is most commonly of metamorphic provenance (e.g. Suggate and Hall, 2014). Its presence in the Pane Chaung Formation samples suggests a first cycle contribution from the metamorphic rocks. Epidote is common in metamorphic, igneous and hydrothermally altered volcanic samples (e.g. Deer et al., 1992; Mange and Maurer, 1992). In the Pane Chaung Formation epidote is present in association with chlorite, favouring a metamorphic provenance from the chlorite-epidote schists. The presence of Cr spinel, although not abundant, is significant, because it is most common in the ultramafic rocks (e.g. Mange and Maurer, 1992). Rarely, Cr spinel is also present in kimberlites and it is considered as a provenance indicator mineral of diamond (e.g. Muggeridge, 1995). To authors' best knowledge Cr spinel is very rare in Western Australia, particularly in the Pre-Triassic basement rocks. It has only been reported from layered intrusions of the Jimberlana (e.g. Roeder et al., 1985) and in diamondiferous kimberlites from Kimberley (Edwards et al., 1992). Detrital Cr spinel (chromite) has been reported from the Archean sandstones of the Pilbara Craton (Rasmussen and Buik, 1999), but it has not been found in the Phanerozoic detrital rocks of Western Australia (e.g. Cawood and Nemchin, 2000) so far.

4.3 Detrital zircon U-Pb ages

Five of six analysed Pane Chaung samples, ISWB13, 15, 25, 42 and 57 yielded over 100 concordant zircon U-Pb ages (Fig.8). The smallest zircon age population that has not been missed (f_{act}) in these samples is less than 6% (Vermeesch, 2004). ISWB10 yielded 64 concordant grains, giving f_{act} of 9%. Detrital zircon U-Pb ages in the analysed samples range in age from 3445± 52 Ma to 195±4 Ma. They contain abundant Meso-Neoproterozoic (1.4-0.7 Ga, 23-36%), abundant Neoproterozoic-Cambrian (700-480 Ma, 31-42%), and small Carboniferous (360-300 Ma, 1-5%) and Permian (300-250 Ma, 4-9%) populations. There is also a significant Triassic (250-200 Ma, 5-12 %) population present in all samples, except ISWB15; and an Archean population (>2.5 Ga, 1-8 %) is present in all samples except ISWB10. Paleo-Mesoproterozoic (2.1-1.4 Ga) and Ordovician-Devonian (410-320 Ma) zircons are present, but do not form clear-cut populations.

The marlstone (ISWB06) yielded only 39 concordant zircon ages, giving f_{act} of 13%. It is dominated by a Cretaceous (100-80 Ma, 29 out of 39 ages) population. The Cretaceous zircons are predominantly euhedral and subhedral. They show a simple oscillatory growth pattern on CL images, suggesting a contemporaneous volcanic provenance.

5. Discussion

5.1 Maximum depositional ages

The Pane Chaung Formation is known to be Triassic because of rare occurrences of *Halobia* fossils (e.g. Bannert et al., 2011), but it is difficult to be more precise about its age. The detrital zircon geochronology can improve our understanding of the stratigraphy of the Chin Hills and the West Burma Block. By definition, clastic sedimentary rocks are always younger than the detrital grains that they contain (e.g. Fedo et al., 2003). However, the measured age of the youngest zircon is often slightly younger than that of its host rock, because of lead loss, analytical uncertainties of each individual analysis or unavoidable systematic uncertainties that are introduced during the reduction of the raw data (Gehrels, 2014). A weighted average age of the three youngest zircons gives a more accurate estimate of the maximum depositional age of the host rock (e.g. Dickinson and Gehrels, 2009; Gehrels, 2014). Despite these complexities, in rocks containing zircons derived directly from contemporaneous volcanism, the maximum depositional ages determined from zircons will be close to the true depositional ages of their host rocks. The new data obtained in the present study indicate that all of the samples analysed from the Chin Hills contain a contribution from contemporaneous volcanism. It is therefore reasonable to expect that the maximum depositional age determined from zircon geochronology is close to actual depositional age of the sediments.

The detrital zircon ages collected during this study reveal new details about sandstone ages in the Chin Hills. The youngest zircon in Pane Chaung Formation sandstones is 195±4 Ma and the three youngest zircons give a weighted average age of 199±13 Ma. This confirms the Triassic age of the Pane Chaung Formation, determined based on *Halobia* occurrences, and narrows it down to the Upper

Triassic. The Triassic zircon population is present in all Pane Chaung Formation samples, except for ISWB15, in which the youngest zircon age is 251±13 Ma, the Late Permian. The weighted average age of the three youngest zircons in this sample is 255±7 Ma, also Late Permian. The lack of Triassic zircons in this sample suggests either a different provenance or a different depositional age. A different provenance is considered unlikely, because petrography, heavy mineral assemblages and the pre-Triassic zircon ages in ISWB15 closely resemble those in all other Pane Chaung Formation samples (Fig. 7 and 8). The lack of Triassic zircons in this sample may indicate that this sample was deposited during the period when there was no volcanic activity.

Marlstone collected from the Chin Hills contains only rare siliciclastic detritus (volcanic clasts, feldspar and quartz). The zircon ages form a narrow dominant Upper Cretaceous (Cenomanian-Turonian) zircon population, which we interpret as derived from volcanic ash falls contemporaneous with marlstone deposition.

5.2 Provenance of the Pane Chaung Formation

Multidisciplinary petrographical, heavy mineral and detrital zircon U-Pb age data utilised in the present study all suggest that the Pane Chaung Formation contains contributions from several sources, including reworked material, contemporaneous volcanic material and first-cycle metamorphic detritus.

Despite the well-known limitations of Gazzi-Dickinson QFL plots (e.g. Weltje, 2002, van Hattum et al., 2006; 2013), in the present study they give some useful insights into the provenance of the Pane Chaung Formation, suggesting derivation of some material from pre-existing sandstones. The reworked provenance is further supported by the presence of sedimentary lithics in thin sections and by the abundance of zircon, tourmaline and rutile in the heavy mineral assemblages, all three of which show a wide range of shapes and common surface frosting from reworking. A wide spread of zircon U-Pb ages in each sample, indicating contributions from multiple sources, is also diagnostic of mixed provenance and reworking.

However, the presence of fresh plagioclase feldspar and basic to intermediate volcanic lithics also suggests a contribution from a contemporaneous volcanic source. There is a significant proportion of euhedral and subhedral zircons in the Pane Chaung Formation samples (Fig. 7, Table 2), suggesting a direct contribution from igneous sources. In five out of the six Pane Chaung Formation samples, the age of the youngest detrital zircon and the age of the youngest zircon population is Triassic, and close to the depositional age of the samples indicated by fossils. This suggests that the volcanic activity was contemporaneous or nearly contemporaneous with turbidite deposition. Permian and Triassic zircons have a wide range of ages and this suggests that they were produced by a long-lived volcanic episode (ca. 50 Ma). The abundances of plagioclase, volcanic lithics and Triassic zircons are similar in samples collected near Mt Victoria and in those collected near Kalaymio, which at the present day are situated ~50 km apart (Fig.1, Table 1), suggesting widespread volcanic activity.

Foliated and platy metamorphic lithics and mica that are common in thin sections of the Pane Chaung Formation, as well as chlorite, fresh garnet and epidote that are common in the heavy mineral assemblages, suggest a contribution from local metamorphic basement. Metamorphic lithics are more abundant in the samples collected near Kalaymio compared to those collected near the Mt Victoria (Fig. 6). Potential metamorphic source rocks on the West Burma block are the Kanpetlet Schists and the Yazagyo and Hkweka Metamorphics.

5.3 Implications for plate tectonic models

All the tectonic models predict that the detrital zircon ages from West Burma will be similar to those of Western Australia at least up until the Middle Devonian, because all authors accept that West Burma was initially situated close to Western Australia, near to what is now the Carnarvon Basin (Fig.11). It is also well known that Sibumasu and Indochina were derived from Gondwana, but their positions within the supercontinent are less well constrained. Most authors show Sibumasu situated close to Western Australia and West Burma (e.g. Longley et al., 2002; Heine et al., 2004; Metcalfe, 2006, 2013a; Hoernle et al., 2011), although some authors position Sibumasu close to the Bird's Head of Papua New Guinea (e.g. Charlton et al., 2001). Indochina has been tentatively positioned close to

Sibumasu, either further outboard in Gondwana, close to South China, Tarim and North China (e.g. Metcalfe, 2013a), or as part of a rigid block forming the Malay Peninsula (e.g. Charlton et al., 2001). Pre-Devonian zircon ages of West Burma and Sibumasu do indeed closely resemble those from Western Australia (Fig. 9 and 10). Archean zircons derived from Western Australian cratons (Yilgarn or Pilbara) are less abundant amongst Precambrian zircons in West Burma and Sibumasu, compared to those in Western Australia (Fig. 9 and 10). This zircon age pattern is what would be expected if Sibumasu and West Burma were situated close to Western Australia, but further outboard in the Gondwanan supercontinent and not close to the Bird's Head. Pre-Devonian and particularly Pre-Cambrian zircons of Indochina are dramatically different to those from West Burma and Sibumasu, because they contain a large ca. 1.8-1.9 Ga population, almost entirely lack the ca. 1.2 Ga population and have a smaller ca. 0.6 Ga population. This suggests that in the Gondwana margin, Indochina was not close to Sibumasu or West Burma. It is possible that Indochina, but not Sibumasu, was situated close to the Bird's Head area, although this hypothesis still needs to be tested by further zircon age studies from the region.

If West Burma had remained attached to Western Australia until the Jurassic, as asserted by some tectonic models (Metcalfe, 1996; Heine et al., 2004; Gibbons et al., 2013), both of these areas would be expected to show similar Phanerozoic zircon age distributions. However, there are some significant differences. A striking feature of the West Burma sandstones is a large Permian-Triassic zircon population that is not present in Western Australia (Cawood and Nemchin, 2000; Veevers et al., 2005; Fig. 9 and 10). Some Permian-Triassic zircons have been recently discovered in the Triassic Mungaroo Formation in the Carnarvon Basin on the Australian NW Shelf (Lewis and Sircombe, 2013), but they form a very small proportion of the total number of zircons. They are also different to those from West Burma (Fig. 10). The Permian-Triassic population (Fig. 9 and 10) in the Carnarvon Basin contains a prominent ca. 220 Ma (Upper Triassic) peak and Permian zircons are not abundant, whereas in West Burma the main peaks are around ca. 240 Ma and there is a smaller peak at ca. 260 Ma (Permian). Rhyolites have been encountered in the Enderby-1 well on the NW Shelf (Veevers and Tewari, 1995), close to where the West Burma Block was initially situated. However, they are of the lowest Triassic or possibly Permian age, whereas in West Burma there are also Upper Triassic zircons common (Fig. 9 and 10). In SE Asia Permian and Triassic zircons are ubiquitous. They were sourced primarily from the Permian-Triassic granitoids of the SE Asian tin belt (e.g. Cobbing et al., 1992) and are common both in Sibumasu and in Indochina (Fig. 9 and 10) (Bodet and Schärer, 2000; Sevastjanova et al., 2011; Hall and Sevastjanova, 2012; Mitchell et al., 2012; Searle et al., 2012; Burrett et al., 2014). The presence of Cr spinel in the Pane Chaung Formation also favours deposition in SE Asia and not in Western Australia. If West Burma was part of SE Asia in the Triassic Cr spinel would have been derived from Triassic or older ophiolite belts, which are common across SE Asia (e.g. Hutchison, 1977, Metcalfe, 2000), whereas in Western Australia Cr spinel is rare.

The Late Triassic turbidite depositional environment of the West Burma Block sandstones are quite different from those of Western Australia and the NW Shelf, which were dominated by fluvial and deltaic deposition and carbonate shelf sedimentation (e.g. Bradshaw, 1998, Longley et al., 2002). Triassic turbiditic sandstones are widespread both in Sibumasu and in Indochina (e.g. Barber et al., 2005; Barber and Crow, 2009). Triassic paleogeographic reconstructions of SE Asia suggest that deposition of turbidites, similar to those of West Burma, would have been widespread in SE Asia (e.g. Barber and Crow, 2009; Hutchison and Tan, 2009).

Most models that argue for a Jurassic separation of West Burma from Australia also assume that West Burma collided with SE Asia in the Cretaceous (e.g. Mitchell, 1993; Robinson et al., 2014). This interpretation is based on a tentative suggestion that ophiolite belts in Myanmar, which up to now remain poorly dated, represent a continuation of the Indus-Yarlung Suture Zone in Tibet (e.g. Mitchell, 1993). Several authors have used this model to explain the Cretaceous granitoids that are common in Myanmar (e.g. Mitchell et al., 2012; Searle et al., 2012) as subduction-related (e.g. Robinson et al., 2014), despite the fact that there are almost no Cretaceous volcaniclastic sediments in Myanmar. It is also difficult to reconcile a major Cretaceous collision with the geological evidence from the Chin Hills. Mitchell et al. (2010) argued that the basal unconformity recorded by the Paung Chaung Limestone shows that this area was above sea-level in the early Albian. However, the new data presented in this study show that by the Cenomanian-Turonian, West Burma included areas of calm-water environments with marl deposition. Rare detrital volcanic lithic clasts, plagioclase and quartz that are present in the marl may indicate a contribution from contemporaneous volcanics, plausibly ash-falls, and there is no indication of a major Cretaceous continental collision. While Cretaceous magmatism was abundant along the western margin of SE Asia and Cretaceous zircons-bearing rocks are found in Sumatra, the Andaman Islands, the Malay Peninsula and Indochina (e.g. Hall, 2009, Hall and Sevastjanova, 2012), not all Cretaceous granitoids are subduction-related. In Western Myanmar, some Cretaceous magmatism may have been associated with docking of the Woyla-Mawgyi island arc (e.g. Barber, 2000; Barber and Crow, 2009).

A more convincing candidate for a block that separated from area adjacent to the Carnarvon Basin in the Jurassic is the East Java Block (e.g. Smyth et al., 2007, Hall et al., 2009; Hall, 2012). Ages of Pre-Jurassic zircons from East Java are almost identical to those from Western Australia. Both areas contain a significant Archean (>2.5 Ga), abundant Mesoproterozoic (ca. 1.2 Ga) and Neoproterozoic (ca. 0.9 and 0.6 Ga) populations and almost entirely lack Permian and Triassic zircons.

6. Conclusions

1. West Burma and Sibumasu sandstones contain an Archean zircon population (>2.5 Ga) interpreted to be derived from the Western Australian Yilgarn and/or Pilbara cratons. We propose that until the Devonian West Burma and Sibumasu were situated close to each other and close to Western Australia within the Gondwana supercontinent.
2. The abundance of Archean zircons decreases from Western Australia to West Burma and then to Sibumasu. This is consistent with their relative positions in the Gondwana margin, with Sibumasu furthest outboard from Western Australia.
3. The differences in zircon populations suggest that Indochina was not close to West Burma or Sibumasu within Gondwana, before the separation of Indochina from Gondwana in the Devonian.
4. The abundance of Permian and Triassic zircons, occurrences of Cr spinel, and turbiditic character of the Myanmar Upper Triassic sandstones suggest that West Burma was part of SE Asia before the Mesozoic. Permian and Triassic zircons are different from those in the Carnarvon Basin and are Cr spinel is rare in Western Australia.

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Figure captions

Fig. 1. Principal geographical features of Myanmar.

Fig. 2. The main structural belts of Myanmar (after Mitchell et al., 2012). Grey dashed lines show locations of ophiolitic belts. TMB: Tagaung-Myitkyina Belt. Grey dashed-dotted lines show international borders. White dots show sample locations. For simplicity, the prefix "ISWB" is omitted from all sample labels on the map.

Fig. 3. Principal basement blocks of SE Asia. Modified from Hall (2014) after Metcalfe (1996, 2013a,b), Barber et al. (2005), and Hall and Sevastjanova (2012).

Fig. 4. Field photographs of outcrops sampled in the present study. (a) Mud clasts at the base of a sandstone, (b, c) sole marks at the base of beds, and (d) overturned sandstones with (e, f) loads seen on bed surfaces.

Fig. 5. Field photographs of outcrops sampled in the present study. (a) Block of the Pane Chaung Fm within the Kanpetlet Schist. (b) Thick-bedded sandstone with a more yellowish colour and coarser grain-size compared to other Pane Chaung Formation samples. There were no interbedded shales, no sole marks and no mud clasts in this sandstone. (c, d) Outcrops of strongly deformed calcareous rocks, locally (d) with volcanic (?) clasts. (e, f, g) Pane Chaung Formation outcrops that are in sharp contact with serpentinised peridotites. Note blocks of sandstone and shale in the serpentinite.

Fig. 6. QFL plots showing (a) sandstone classification (Folk, 1980) and (b) Gazzi-Dickinson's (Dickinson et al., 1983) provenance fields for the Pane Chaung Formation. Q- total quartz, F – total feldspar and L – total lithics. All samples can be broadly divided into two groups, Gp1 includes samples collected near Mt Victoria and Gp2 includes samples collected near Kalaymio. Note that lithics are more abundant in Gp2 samples. The lithics are predominantly metamorphic.

Fig. 7. Bar charts (top) and boxplot (middle), showing compositions of heavy mineral assemblages and abundances of different zircon types in the Pane Chaung Formation samples. Zir: zircon, Tur: tourmaline, Rt: rutile, Gr: garnet, Ap: apatite, Ep: epidote, Sp: Cr spinel, Chl: chlorite,

Euh: euhedral, Sbh: subhedral, Sbrd: subrounded, Rd: rounded, Anh: anhedral, Oth: other. Other heavy minerals include anatase, amphibole, pyroxene, titanite and hematite. All zircon types mentioned above are colourless. Other zircon types include brown, purple, zoned, metamict and surrounded by matrix. For simplicity, the prefix “ISWB” is omitted from all sample labels on the bar charts. At the bottom: selected images of detrital Cr spinel from the Pane Chaung Formation, collected using a scanning electron microscope (SEM).

Fig. 8. Histograms and probability density plots showing detrital zircon U-Pb ages from the Pane Chaung Formation and from the marlstone sample collected in the Chin Hills. Plots on the left show 0-500 Ma ages; histogram bin widths are 10 Ma. Plots on the right show 500-4000 Ma ages; histogram bin widths are 50 Ma.

Fig. 9. Comparison of detrital zircon ages from the Pane Chaung Formation in West Burma (present study), with those from East Java (Smyth et al., 2007), Indochina-East Malaya (Bodet and Schärer, 2000), Sibumasu (Hall and Sevastjanova, 2012), Western Australia (Sircombe and Freeman, 1999; Cawood and Nemchin, 2000; Veevers et al., 2005) and the Carnarvon Basin (Lewis and Sircombe, 2013). Plots on the left show 0-500 Ma ages and the bin widths are 10 Ma. Plots on the right show 500-4000 Ma ages and the bin widths are 50 Ma.

Fig. 10. Comparison of detrital zircon ages from the Pane Chaung Formation in Indochina-East Malaya (Bodet and Schärer, 2000), Sibumasu (Hall and Sevastjanova, 2012), West Burma (present study), East Java (Smyth et al., 2007), Carnarvon Basin (Lewis and Sircombe, 2013) and Western Australia (Sircombe and Freeman, 1999; Cawood and Nemchin, 2000; Veevers et al., 2005). Bin widths are 50 Ma.

Fig. 11. Early Jurassic (190 Ma) reconstruction based on Hall (2012) showing postulated position of West Burma at that time. Our data favour the SE Asia position. West Sumatra after Barber et al. (2005) and Sibumasu and Indochina after Metcalfe (2013a).

Fig. 1 (Colour for web only)

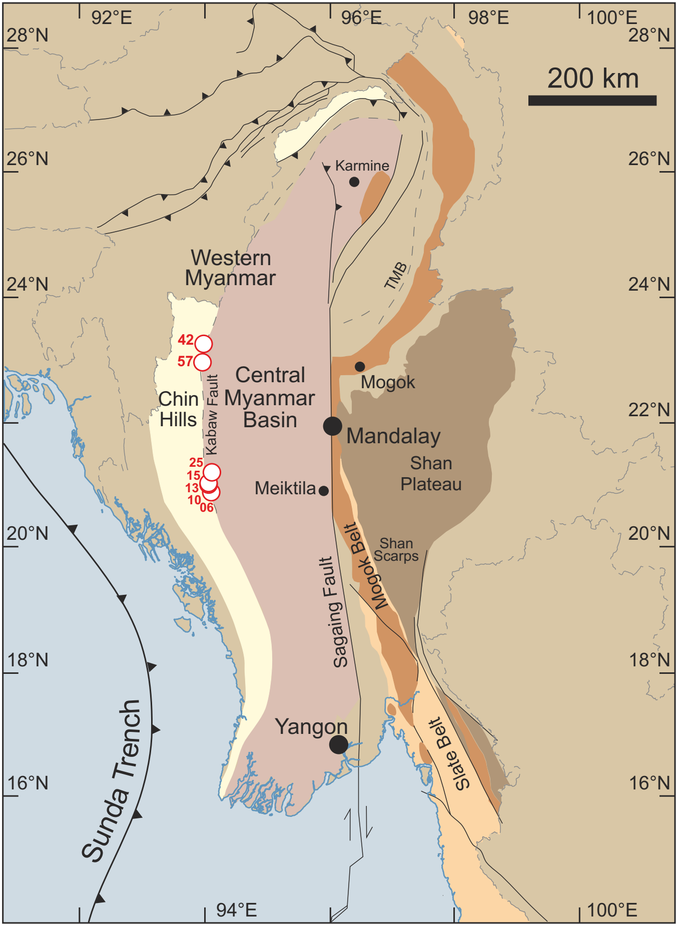


Fig. 2. Colour for web only.

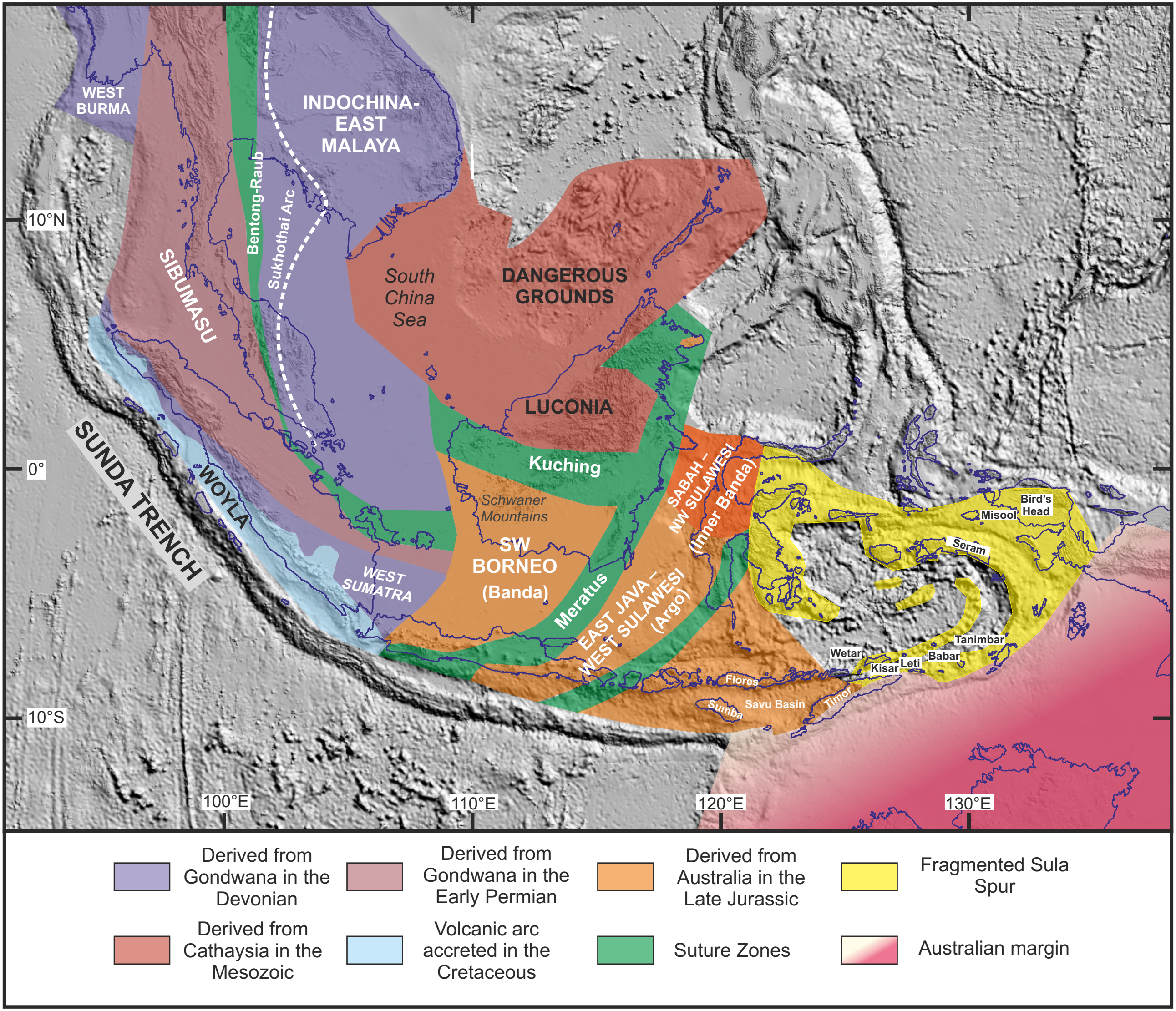

WEST BURMA
INDOCHINA-EAST MALAYA
Bentong-Raub
Sukhothai Arc
SIBUMASU
South China Sea
DANGEROUS GROUNDS
LUCONIA
Kuching
Schwaner Mountains
SW BORNEO (Banda)
Meratus
EAST JAVA – WEST SULAWESI (Argo)
SABAH – NW SULAWESI (Inner Banda)
SUNDA TRENCH
WOYLA
WEST SUMATRA
Bird's Head
Misool
Seram
Tanimbar
Babar
Leti
Kisar
Wetar
Flores
Sumba
Savu Basin
Timor
10°N
0°
10°S
100°E
110°E
120°E
130°E
Derived from Gondwana in the Devonian
Derived from Gondwana in the Early Permian
Derived from Australia in the Late Jurassic
Fragmented Sula Spur
Derived from Cathaysia in the Mesozoic
Volcanic arc accreted in the Cretaceous
Suture Zones
Australian margin

Fig. 3

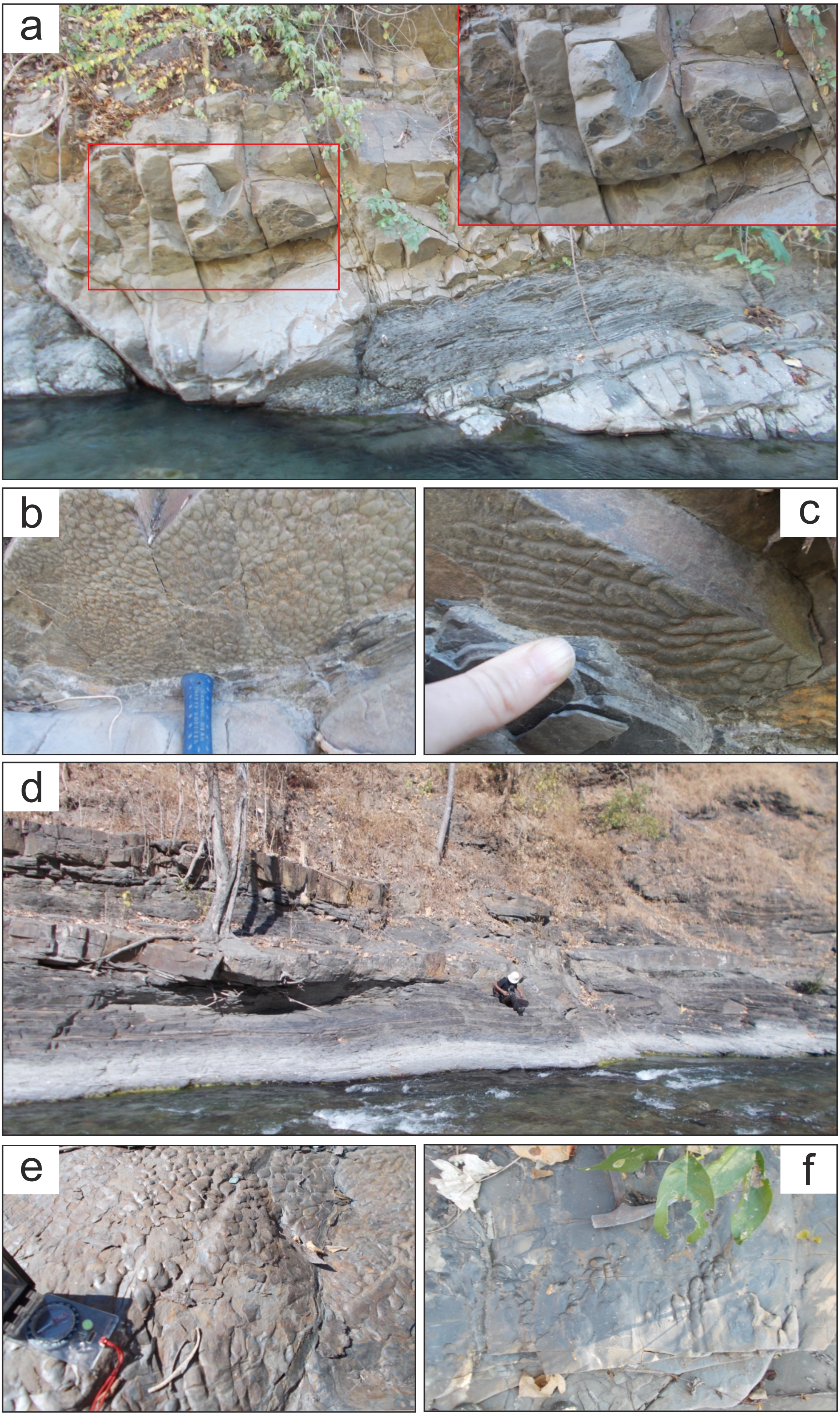


Fig. 4

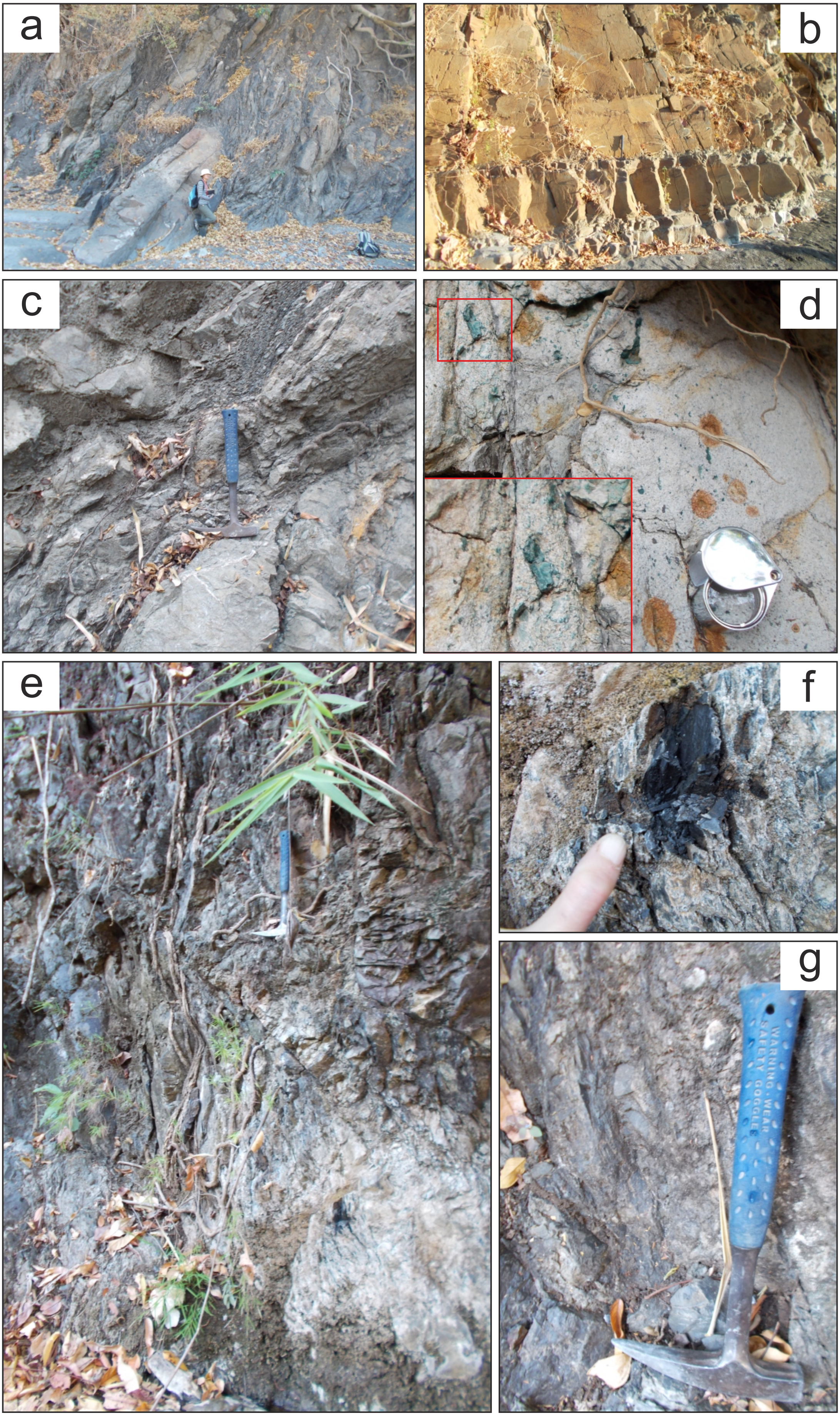


Fig. 5

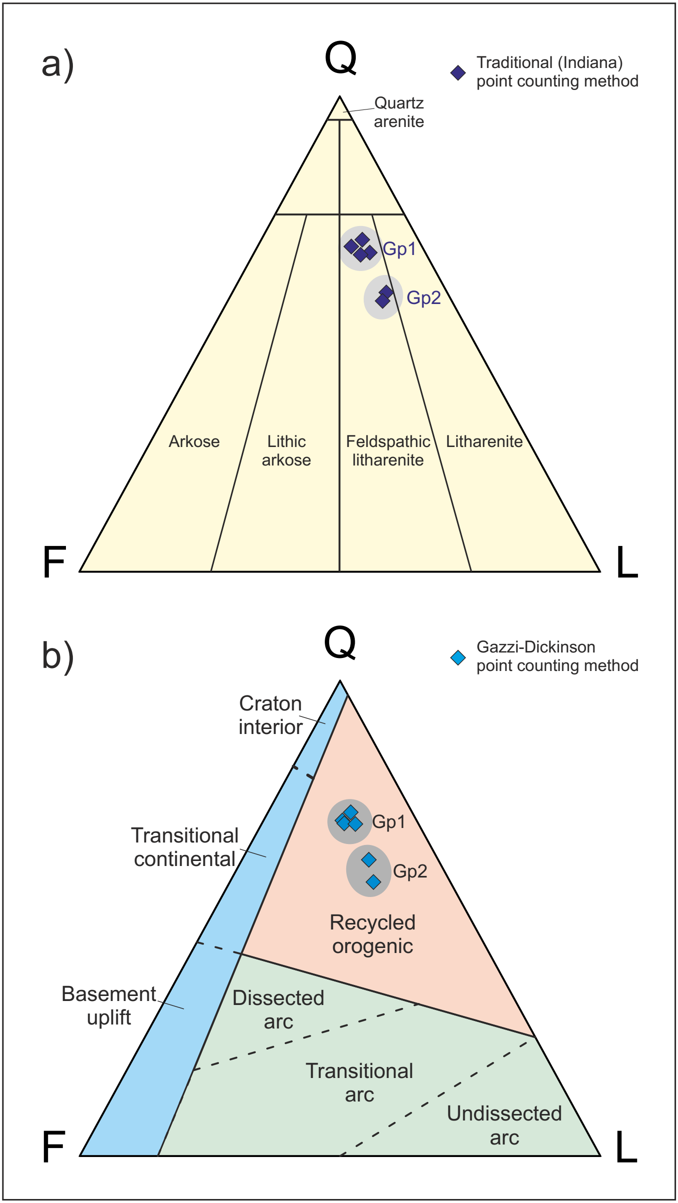
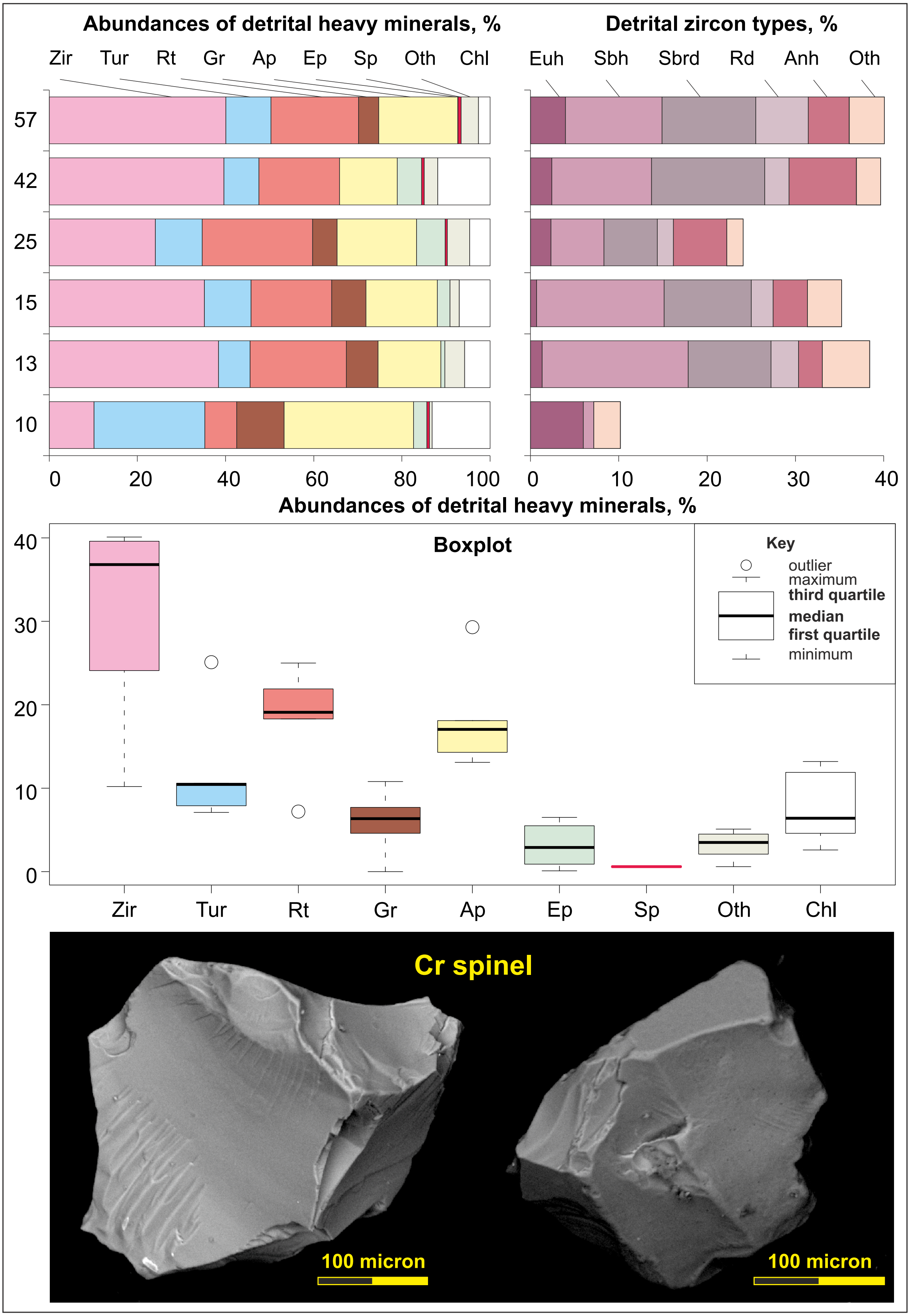
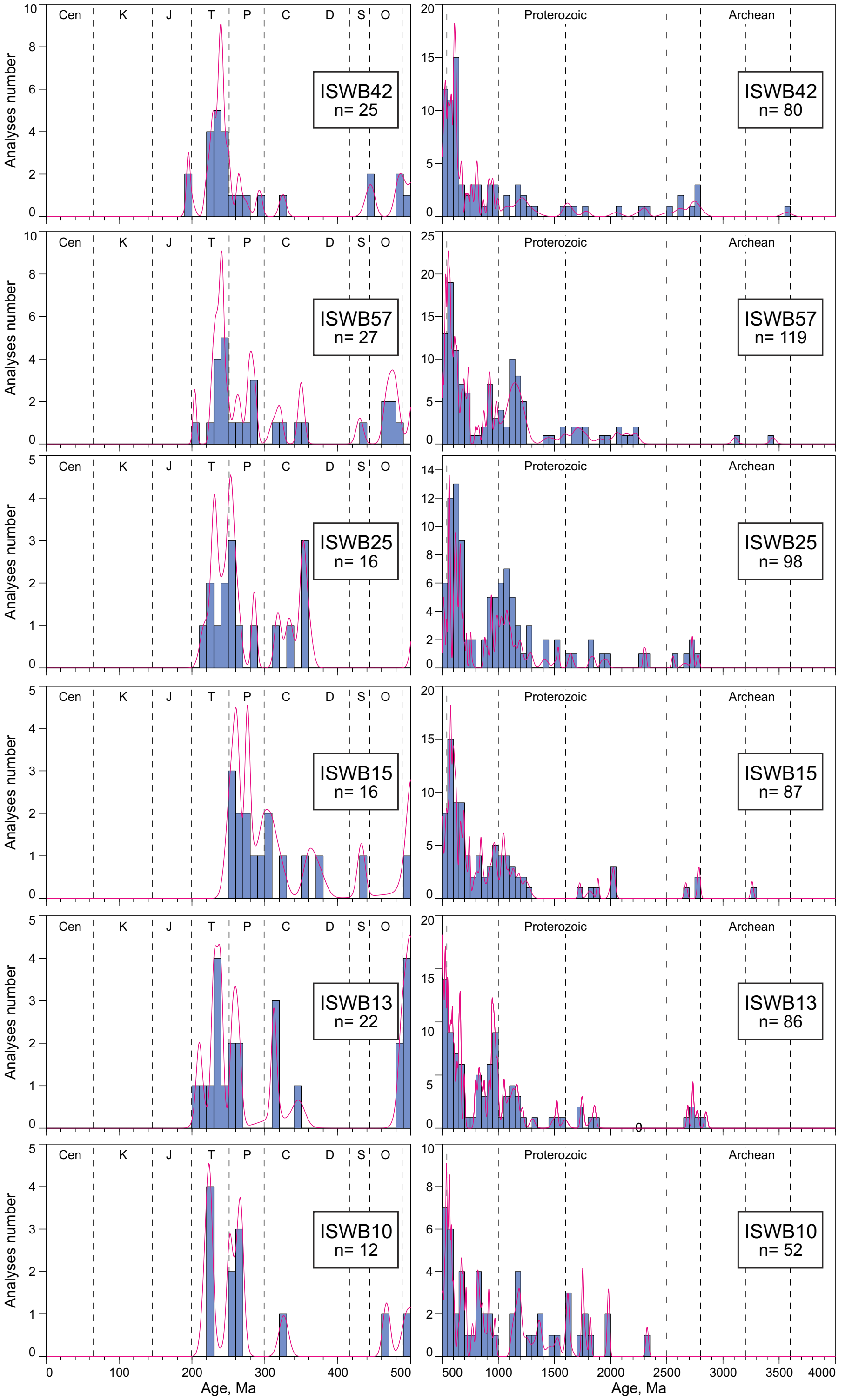


Fig. 6. Colour for web only.

Fig. 7. Colour for web only.



U-Pb ages of detrital zircons in the Pane Chaung Formation sandstones



U-Pb ages of detrital zircons in marlstone sample from the Chin Hills

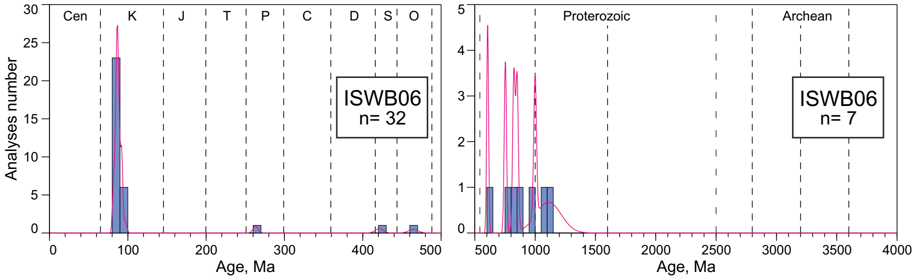
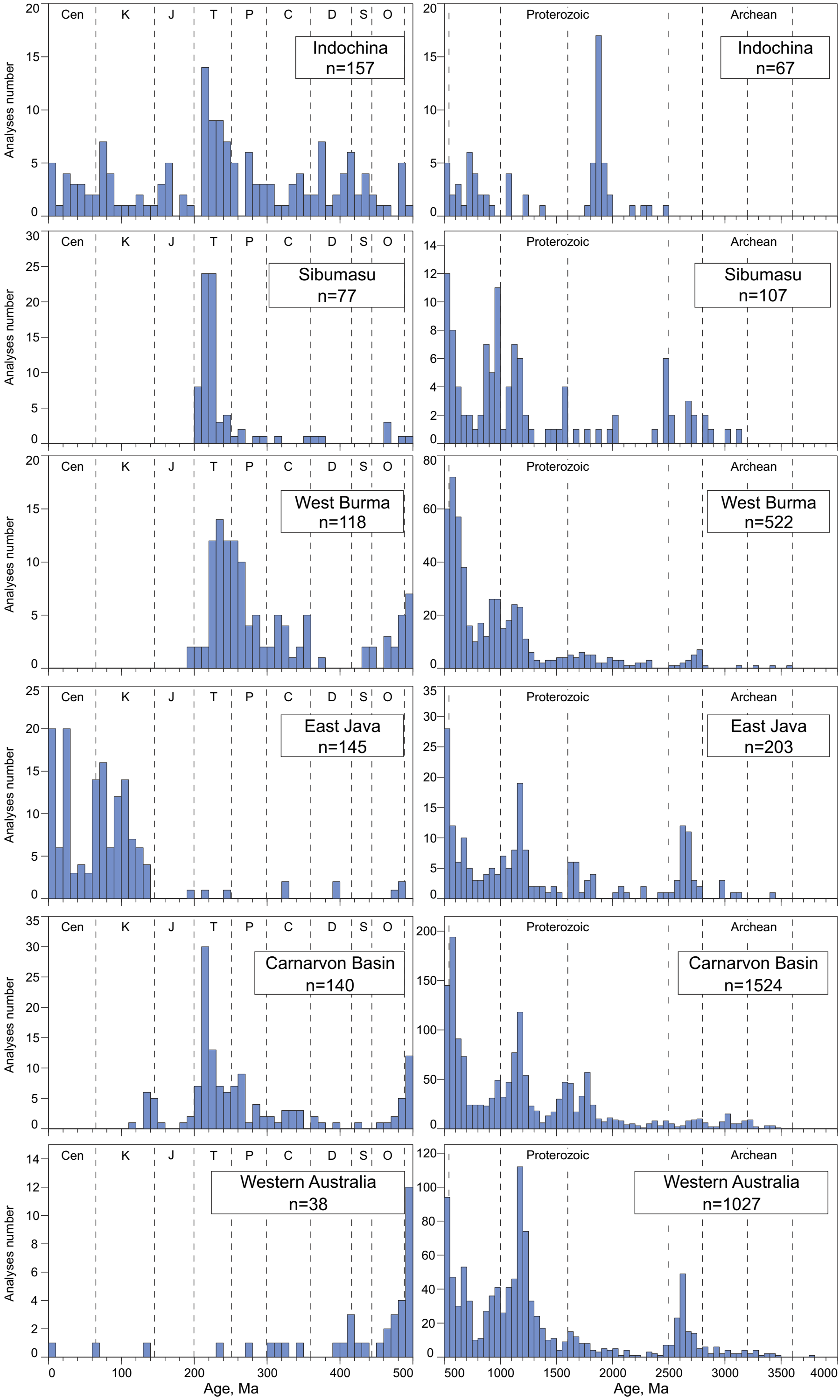


Fig. 8



Cen
K
J
T
P
C
D
S
O
Proterozoic
Archean
Indochina
n=157
Indochina
n=67
Sibumasu
n=77
Sibumasu
n=107
West Burma
n=118
West Burma
n=522
East Java
n=145
East Java
n=203
Carnarvon Basin
n=140
Carnarvon Basin
n=1524
Western Australia
n=38
Western Australia
n=1027
Analyses number
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12
14
20
40
60
80
50
100
150
200
120
0
100
200
300
400
500
Age, Ma
500
1000
1500
2000
2500
3000
3500
4000
Age, Ma

Fig. 9

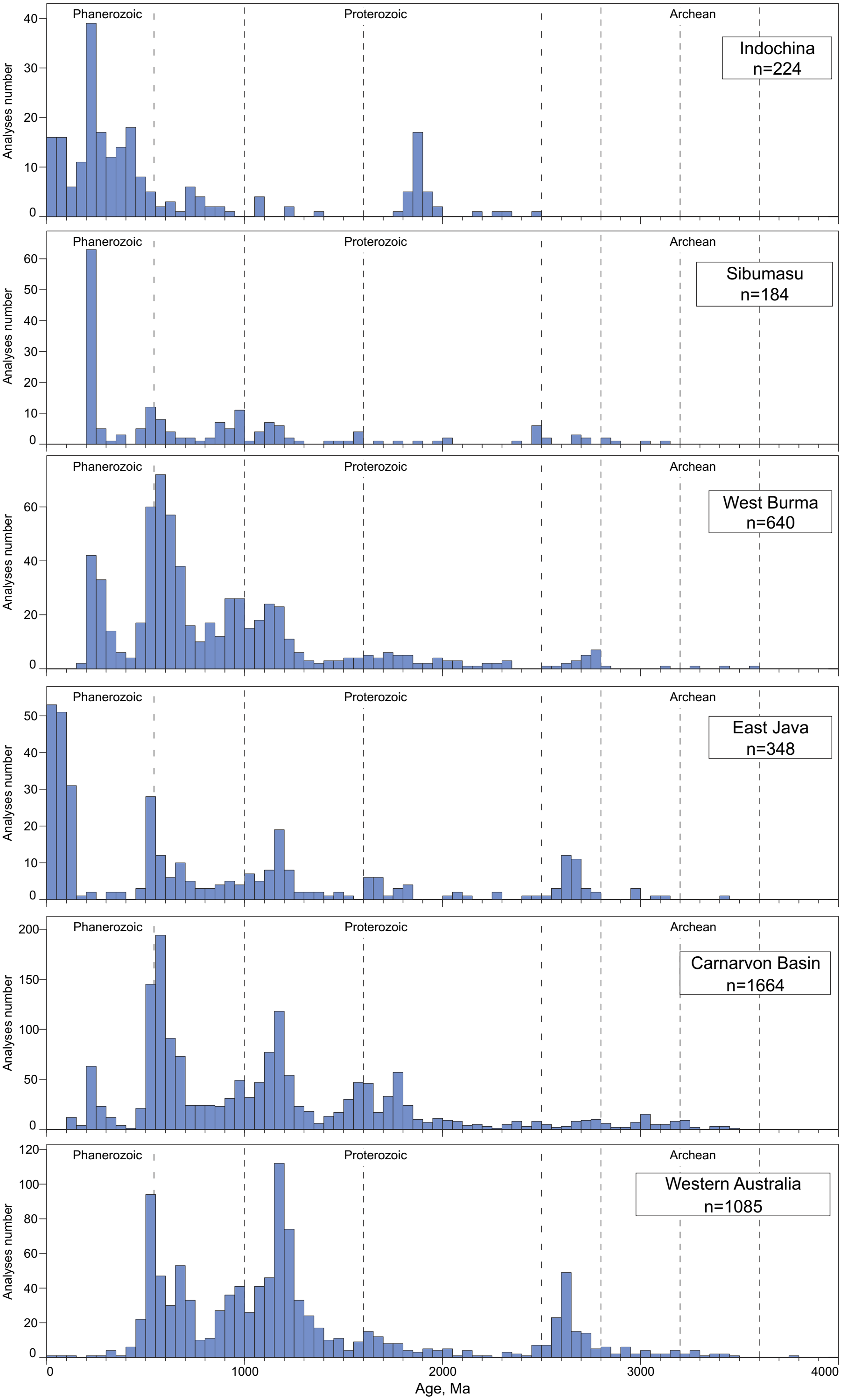

Phanerozoic
Proterozoic
Archean
Indochina
n=224
Sibumasu
n=184
West Burma
n=640
East Java
n=348
Carnarvon Basin
n=1664
Western Australia
n=1085
Analyses number
0
10
20
30
40
50
60
100
120
150
200
0
1000
2000
3000
4000
Age, Ma

Fig. 10

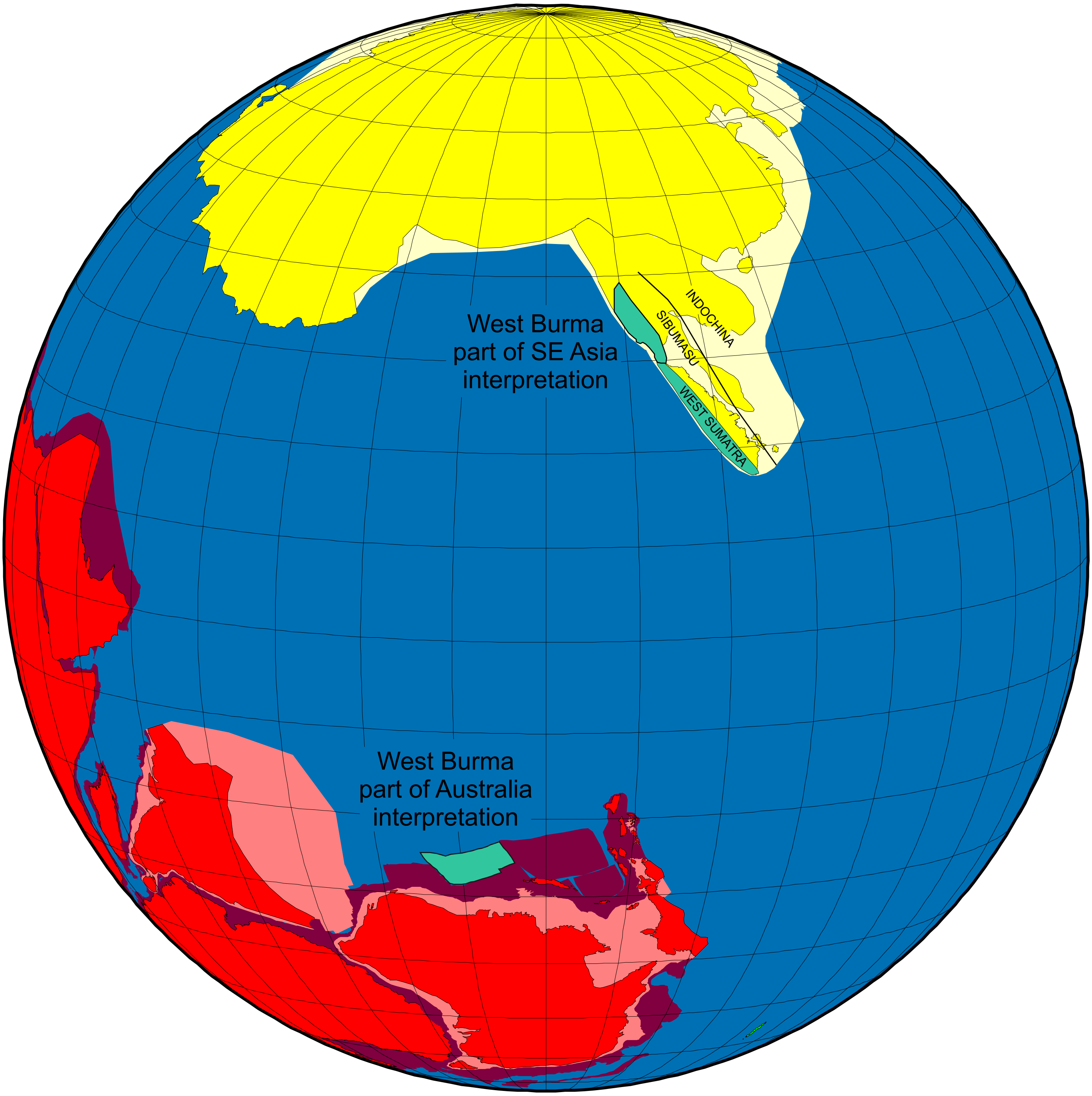

West Burma
part of SE Asia
interpretation
INDOCHINA
SIBUMASU
WEST SUMATRA
West Burma
part of Australia
interpretation

Table 1

Detrital modes of samples analysed from West Burma

		Quartz			Feldspars			Lithics/Rock Fragments									Accessory Grains and Heavy Minerals										Matrix			Authigenics							
Sample	Method	Monocrystalline Quartz	Polycrystalline Quartz	**TOTAL QUARTZ**	K-Feldspar	Plagioclase Feldspar	**TOTAL FELDSPAR**	Chert	Sedimentary Lithic	Metamorphic Lithic	Volcanic Lithic (Basic-Intermediate)	Plutonic Lithic (Plagiogranite)	Muscovite	Biotite	Chlorite	**TOTAL LITHICS/ROCK FRAGMENTS**	Phosphatic Material	Foraminifera (Benthic)	Foraminifera (Planktic)	Calcisphere/Calcitized Radiolaria	Echinoderm Debris	Zircon	Tourmaline	Rutile	Epidote	Garnet	Organics	Non-res. Detrital Clays	Micrite	Quartz Cement	Plagioclase Cement	Calcite Spar/Microspar	Siderite	Pyrite	Anatase	Illite/Sericite	Glauconite
ISWB-42	T	31.3	7.3	**38.7**		9.0	**9.0**	2.0	0.7	8.7	0.7	0.3	3.3	3.0	1.7	**20.3**						0.3	tr.		tr.		3.0	2.3		1.7		11.0	2.7	4.0		7.0	
ISWB-42	G-D	32.3	7.7	**40.0**		10.3	**10.3**	2.7		5.7			4.7	3.0	3.0	**19.0**						tr.	tr.		tr.		3.0	2.0		2.0		9.3	3.0	3.0		8.3	
ISWB-57	T	36.0	10.7	**46.7**		9.3	**9.3**	3.7	0.7	7.7	1.0	1.3	3.7	3.3	2.3	**23.7**						tr.	tr.	tr.	0.3	tr.	0.3	1.3		2.3	0.7	0.7	4.0	2.3	0.3	8.0	
ISWB-57	G-D	38.7	11.0	**49.7**		10.7	**10.7**	3.0		3.7	0.3		6.0	3.0	3.3	**19.3**						0.3	tr.	tr.	0.3	tr.	0.7	1.3		1.7	0.3	0.7	3.7	2.7	0.3	8.3	
ISWB-25	T	39.7	8.7	**48.3**		7.7	**7.7**	2.0	0.3	6.3	1.0	0.7	2.7	2.0	1.0	**16.0**						tr.	tr.	tr.	tr.		3.0	3.3		3.0	0.3	0.3	3.7	4.3		10.0	
ISWB-25	G-D	41.3	10.0	**51.3**		9.0	**9.0**	1.7		2.7	0.3		3.7	2.3	2.3	**13.0**						tr.	tr.	tr.	0.3		2.7	3.0		2.3	tr.	tr.	4.0	3.7		10.7	
ISWB-15	T	38.3	7.7	**46.0**		8.7	**8.7**	1.7	0.3	7.0	0.7	0.7	2.0	1.7	0.3	**14.3**						tr.	tr.	tr.			1.0	1.3		2.0	0.7	13.0	4.7	2.0		6.3	
ISWB-15	G-D	39.0	8.0	**47.0**		9.7	**9.7**	1.0		3.7			3.0	1.7	1.0	**10.3**						0.3	tr.	tr.			0.3	1.0		1.7	0.3	13.7	5.7	2.3		7.7	
ISWB-13	T	37.0	9.7	**46.7**		9.3	**9.3**	0.3	0.3	6.3	0.3	1.0	1.7	1.3	1.0	**12.3**						0.3		tr.	0.3		1.0	1.7		3.7	0.3	5.7	7.7	2.0		9.0	
ISWB-13	G-D	38.7	10.3	**49.0**		10.0	**10.0**	0.7	0.3	3.0			3.0	1.7	1.7	**10.3**						tr.		tr.	0.3		0.7	1.0		3.3	0.3	5.0	7.7	2.7		9.7	
ISWB-10	T	42.3	8.0	**50.3**		7.7	**7.7**	1.0	1.3	5.7	0.7	0.3	3.0	1.0	1.0	**14.0**					0.3	tr.		tr.	tr.		1.0	3.0		1.3	0.3	1.7	9.7	2.3		8.3	
ISWB-10	G-D	43.3	9.0	**52.3**		8.7	**8.7**	0.7	0.7	2.7			4.3	1.7	1.3	**11.3**					0.3	tr.		0.3	tr.		0.3	2.7		1.7	0.3	1.7	9.0	2.0		9.3	
ISWB-06	T	4.0	0.3	**4.3**		2.3	**2.3**				tr.		0.7	0.3	0.3	**1.3**	0.7	8.7	0.7	1.7	0.7						4.0	36.0	33.0	0.7		4.3		1.3			0.3

T	traditional
G-Z	Gazzi-Dickinson's
tr.	traces (<0.5 %)

Table 2

Compositions of heavy mineral assemblages in West Burma samples

Sample	Abundances of detrital heavy minerals in analysed samples, %									N	Detrital zircon types in analysed samples, %						
	Zircon	ourmalin	Rutile	Garnet	Apatite	Epidote	Cr spinel	Other*	Chlorite		Euhedral	Subhedral	Subrounded	Rounded	Anhedral	Elongate	Other**
ISWB42	39.6	7.9	18.3		13.1	5.5	0.6	3.0	11.9	328	2.4	11.3	12.8	2.7	7.6		2.7
ISWB57	40.1	10.3	19.9	4.6	17.9	tr.	0.7	4.0	2.6	302	4.0	10.9	10.6	6.0	4.6		4.0
ISWB25	24.1	10.6	25.0	5.6	18.1	6.5	0.5	5.1	4.6	216	2.3	6.0	6.0	1.9	6.0	0.9	0.9
ISWB15	35.2	10.6	18.3	7.7	16.2	2.8		2.1	7.0	284	0.7	14.4	9.9	2.5	3.9		3.9
ISWB13	38.4	7.1	21.9	7.1	14.3	0.9		4.5	5.8	224	1.3	16.5	9.4	3.1	2.7	1.3	4.0
ISWB10	10.2	25.1	7.2	10.8	29.3	3.0	0.6	0.6	13.2	167	6.0	1.2					3.0

*anatase, amphibole, pyroxene, titanite and hematite

** brown, purple, zoned, metamict and surounded by matrix

tr. traces