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Post-collision reactivation of the Bentong-Raub Suture Zone and regional tectonic implications

Choong Chee-Meng[1,2,*], Benjamin Sautter[3], Askury Abd Kadir[4], Atilia Bashardin[5]

[1] Digital Geoscience Global Sdn Bhd, 13-9, Binjai 8, Lorong Binjai, 50400 Kuala Lumpur, Malaysia
[2] Geosciences Department, Faculty of Sciences and Information Technology, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[3] Geo-Ocean, Univ Bretagne Sud, Univ Brest, CNRS, Ifremer, UMR6538, Université de Bretagne Sud, Vannes, France
[4] GEO MAG Engineering Sdn Bhd, 31B, Jalan Pelabur B 23/B, Seksyen 23, 40300 Shah Alam, Selangor, Malaysia
[5] Jabatan Mineral dan Geosains Kedah/ Perlis/ Pulau Pinang, Jalan Perak Off Jalan Putra, 05150 Alor Setar, Kedah, Malaysia
*Corresponding author email address: cheemeng.choong@gmail.com

Abstract: The Bentong-Raub Suture Zone (BRSZ) is one of the few remnants of the Paleo-Tethys Ocean, which completely closed in the late Triassic period. The main structural features of the BRSZ are expected to correspond to a compressional event during the Indosinian Orogeny. However, several studies in Peninsular Malaysia have suggested the reactivation of structures inherited from previous tectonic events during the late Mesozoic to Cenozoic times. In the present study, we conduct a regional structural analysis to investigate the deformation events affecting the BRSZ and report two new K-Ar ages of deformed igneous and metamorphic rocks. Three structural events have been identified along two transects (Lojing and Pos Betau) across the BRSZ: an initial ~E-W shortening (D1), followed by dextral shear in an N-S trend (D2), and a subsequent ~NW-SE extension (D3). Schistose granite and andesitic rock affected by the D2 event have been dated using the K-Ar method, yielding mid-Cretaceous ages. The D2 structures are commonly found on the steeply dipping bedding or foliation planes of the suture rocks, suggesting a structural reactivation of former orogenic D1 structures. Cross-cutting relationships and K-Ar ages suggest a D1 event corresponding to the Indosinian Orogeny's compressional event, followed by a reactivation of its structures in the late Cretaceous as regional C-S fabric, where N-S dextral faults (D2) act as C-planes and NW-SE sinistral faults represent S-planes. Finally, a post-D2 relaxation period (D3) in a predominantly NW-SE extension direction is observed through the ubiquitous occurrence of normal movements, most likely linked to exhumation of adjacent granitic batholith, regional basin development and changes in the boundary conditions of the Sunda Plate during the Cenozoic.

Keywords: Bentong-Raub Suture Zone, reactivation, brittle, ductile shear, dextral faults, K-Ar, structural inheritance

INTRODUCTION

The Bentong-Raub Suture Zone (BRSZ) in Peninsular Malaysia is one of the remnant structures of the Paleo-Tethys Ocean, which completely closed in the late Triassic. The accretionary wedge comprises of sedimentary rocks and ophiolite units originating from the Paleo-Tethys Ocean and the conjugate continental margins of the Sibumasu and Indochina blocks. During the closure and collision, the units in the suture zone underwent varying degrees of deformation (Tjia, 1984; Tjia & Almashoor, 1996; Shuib, 2000; Pour *et al*., 2016). After the closure of the Paleo-Tethys Ocean and the collisional event between the Sibumasu and Indochina blocks, a late Cretaceous to early Paleogene transpressional event affected the Malay Peninsula (Tjia, 1996; Morley, 2012; Sautter *et al*., 2019; Sautter & Pubellier, 2022), evidenced by the occurrence of strike-slip shear zones. It has been suggested that the BRSZ was reactivated during this event, although there is no concrete evidence to support this claim. To date, the results of past structural studies in the BRSZ (Tjia, 1984; Tjia & Almashoor, 1996; Setiawan & Abdullah, 2003) are rather localized, and evidences constraining the timing of deformation is limited. This study investigates the key structural events along two selected transects across the BRSZ (Figure 1), their relative timing based on newly acquired K-Ar ages of deformed rocks and their implications for the tectonic history of Western Sundaland.

BENTONG-RAUB SUTURE ZONE (BRSZ)

Geological setting and lithologies

The BRSZ cuts across the entire Peninsular Malaysia and is defined as a N-S trending belt of metamorphosed oceanic-related successions that represent the remnant of one of the branches of the main Paleo-Tethys Ocean

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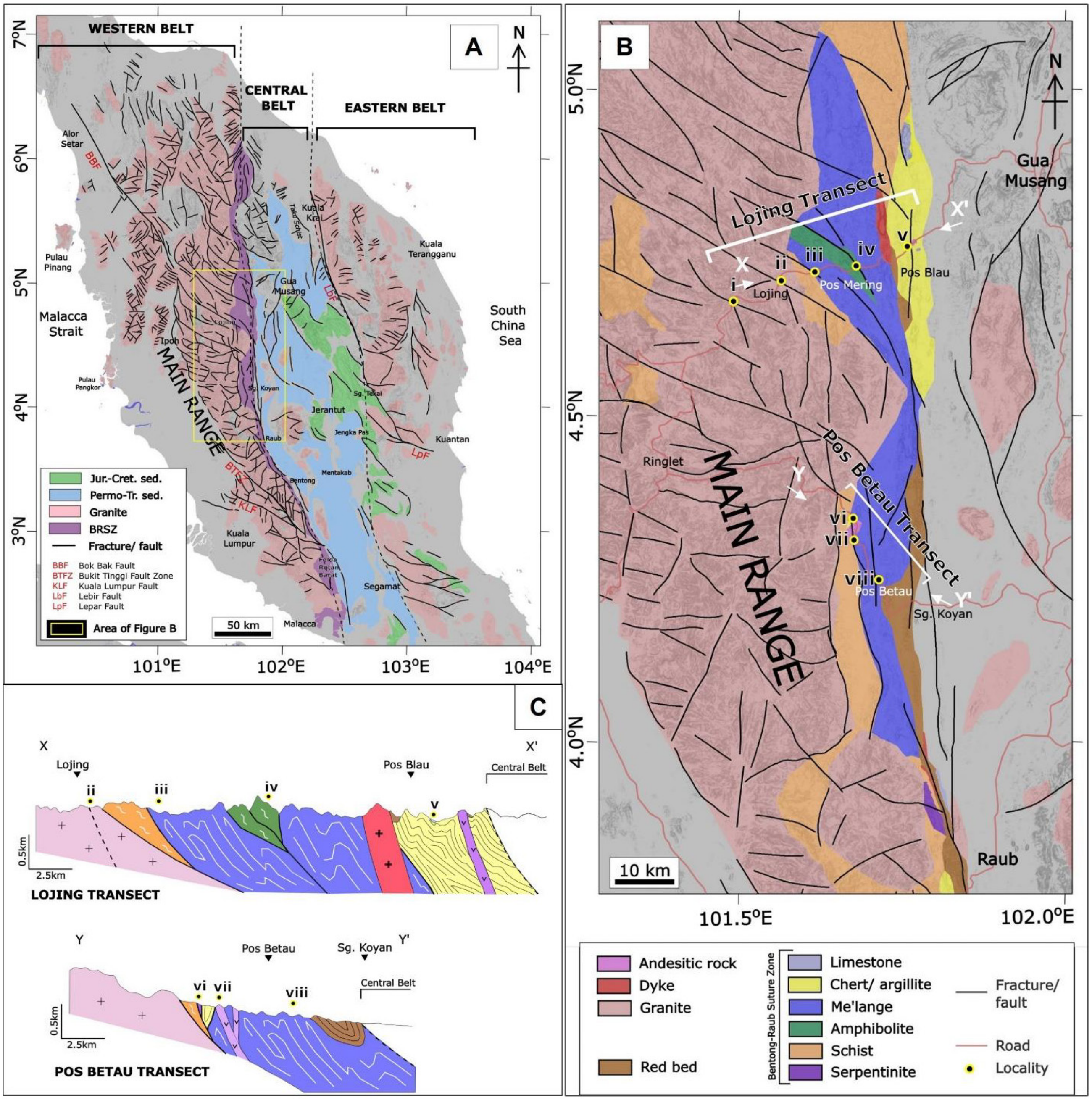

Figure 1: Extent of the Bentong-Raub Suture Zone (BRSZ), granitoids, Permo-Triassic and Jurassic- Cretaceous sedimentary rocks, and major faults in Peninsular Malaysia. The box indicates the location of the study area shown in Figure [B]. [B] Structural map of the BRSZ (Lojing to Raub area) and Main Range with the locations of studied outcrops. [C] Schematic cross-sections of the Lojing Transect (X-X') and Pos Betau Transect (Y-Y') constructed based on the structural map and field data. Legends refer to Figure [B]. The locations of field photos are also provided to illustrate the geological features observed on-site, Locality i: Figure 2A-2D; ii: Figure 2E-2H; iii: Figure 3; iv: Figure 4; v: Figure 5; vi: Figure 6; vii: Figure 7A-7D and viii: Figure 7E-7H.

(Metcalfe, 2000; Metcalfe, 2013; Choong *et al*., 2022). Its northward extension in Thailand is believed to be the Klaeng Fault Zone (Sone *et al*., 2012) and the Chiang Mai-Chiang Rai Suture Zone (Metcalfe *et al*., 2017), ending at the Himalayan Syntaxis. The accretion and collision processes have generated a large diversity of crustal materials that have been jammed along the eastern edge of the Sibumasu block. These materials include numerous low to medium grade metamorphic rocks (amphibolite, mica schist, carbonaceous schist, quartzite, and phyllite), diverse sedimentary rocks (chert, mudstone, sandstone, and minor limestone and conglomerate), volcanic rocks, mélange/olistostrome units, and minor serpentinite. The distribution and occurrence of these geological formations are supported by several published studies (Ridd, 2012; Metcalfe *et al*., 2017; Metcalfe, 2000). Previous work on radiolaria from chert in the BRSZ provides evidence of a late Devonian to early middle Permian age (e.g., Spiller & Metcalfe, 1995a; Jasin, 2013), which is inferred to represent the age of oceanic spreading. Fossils extracted from chert clasts (i.e., radiolaria) and limestone clasts (i.e., conodonts and foraminifera) within the mélange units also indicate the same age range (Igo, 1981; Spiller & Metcalfe, 1995a, b; Spiller, 1996; Metcalfe *et al*., 1999; Metcalfe, 2000).

Deformation episodes

Several tectonic episodes have affected the region since the late Paleozoic. Deciphering the structural characteristics of each overlapping event on these older rocks is a delicate task. The following section provides a summary of the past findings on the structural framework of the region and their probable relative chronology.

Deformation in BRSZ

The first evidence for deformation in the BRSZ was reported from phyllite-schist outcrops located in the Bentong area in the southern BRSZ (Figure 1A). These metamorphic rocks appeared strongly folded, with foliations commonly striking in the NW direction and dipping eastward (Alexandar, 1968; Haile *et al*., 1977). Similar nearby outcrops show additional evidence of deformation in the schist, such as SW-verging reverse faults indicated by en echelon quartz lenses and drag structures, and ~N-S dextral flexural bedding-parallel slip inferred from sigmoidal quartz flaser (Tjia, 1984). Tjia (1984) interpreted the deformation of the Bentong schist as an early E-W shortening, followed by later dextral faulting along nearly N-S trending faults. A recent structural study in the Kuala Lumpur – Bentong – Raub area interpreted similar deformation sequences, which are (1) folding and faulting in schists/phyllites and slates of the suture, (2) NE-SW shortening deformation in the Main Range granitic bodies, and (3) a NW-SE dominant strike-slip event in suture rocks and granite (Wal, 2014). A similar strike-slip event was also observed in another locality of the southern BRSZ, namely Felda Bukit Rotan Barat (location in Figure 1A), represented by N-S striking, steeply dipping, dextral shear structures in serpentinite (Setiawan & Abdullah, 2003). The area from Lojing to Gua Musang in the northern BRSZ reveals exposed NW-SE striking, moderately to vertically NE-ward dipping metamorphic and metasedimentary rocks, characterized by SW-vergence reverse faults and low-angle thrusts (Tjia & Almashoor, 1996).

Deformation in areas adjacent to the BRSZ

Triassic time

The late Triassic marked a period of major tectonic activity and magmatism in Peninsular Malaysia, defined by the collision event between the Sibumasu and Indochina blocks, also known as the Indosinian Orogeny. The late Triassic (K-Ar age: 212 ± 8 Ma) Taku Schist (Bignell & Snelling, 1977b) revealed deformation related to an overall period of E-W oriented contraction and burial metamorphism, aligning with observations of the Indosinian Orogeny (Ali *et al*., 2016). At the end of the orogeny, the stratigraphic record of Peninsular Malaysia shows a major hiatus during the latest Triassic- early Jurassic, likely related to a significant uplift event, which lasted until the late Jurassic with a resumption of continental deposition onshore Peninsular Malaysia.

Triassic or older sedimentary rocks in the Central Belt area of Peninsular Malaysia are generally strongly deformed into tight folds, likely linked to the late Triassic compressional event, while post-Triassic sedimentary rocks with gentler folds do not show such intense deformation. This can be observed in the gently folded sedimentary sequences of the late Jurassic- early Cretaceous Tembeling Group, which unconformably overlie the middle Permian highly folded limestone (Ishii, 1966) in the Jengka Pass area, Pahang (Harbury *et al*., 1990). The Triassic tuffaceous strata in the Mentakab area generally show steeply dipping or vertical spaced cleavages, striking N160°-N170°, forming upright or gently plunging folds (Shuib, 2009b), which resulted from an overall E-W compression. To the north, the Permo-Triassic strata of the Gua Musang Formation underwent early tight to isoclinal folding, followed by N-S reverse dextral faulting (Shuib, 2009b).

Post-early Cretaceous time

The timing of the following deformations is constrained by the stratigraphic age of deformed sedimentary rocks, such as the late Jurassic-early Cretaceous Tembeling Group and its equivalents, as well as the radiometric ages of deformed igneous rocks in fault zones near the BRSZ (e.g., Harun, 2002).

Sediments of the Tembeling Group have folded into large anticlinorial and synclinorial structures with a general NW-SE strike (Chung, 1977). The wavelengths of the folds range from 2 to 6 miles, with some anticlinoriums extending up to 20 miles in the Sg Tekai area (Chung, 1977). Slickensides along the Lebir Fault segments (a major fault next to the Tembeling Group, see Figure 1A) observed along roadcuts indicate sinistral movement (Tjia, 1969; Aw, 1990; Shuib, 2009a). However, Morley (2012) raised the issue that sinistral motion on the Lebir Fault could not explain the folding of the Tembeling Group, which is more compatible with a dextral sense of shear. A previous study also suggested the need for a dextral strike-slip transpressive event along the bounding faults of the Tembeling Group to fold the sediments into NNW-striking drag folds (Tjia, 1996), probably prior to the sinistral movement.

Most of the major faults in Peninsular Malaysia likely experienced a later late Cretaceous tectonic event, as evidenced by K-Ar dating and their clear geomorphic rejuvenation at a regional scale. The Kuala Lumpur Fault Zone is characterized by a main sinistral sense of shear (Stauffer, 1968; 1969), striking N100°-N120° (Gobbett, 1964). The fault zone appears as a 15 km wide valley extending for at least 80 km in length (Tjia, 1977). It is characterized by flasered, boudinaged metatuff lenses in black mylonites with an apparent sinistral motion (Tjia, 1977). However, ductile dextral movement of the Kuala Lumpur and Bukit Tinggi Fault Zones, marked by fault breccias, cataclasites, and mylonites, was also observed (Ng, 1994), differing from the commonly observed sinistral movement on the fault zones. The shear episodes of the Kuala Lumpur Fault and Bukit Tinggi Fault Zone (BTFZ) were constrained to the late Cretaceous, i.e., 83.6 Ma (Harun, 2002).

Further northwest, a fault zone in the Triassic granite of Pulau Pangkor was dated using the K-Ar method and yielded ages of 70.2 Ma and 73.2 Ma (Almashoor & Harun, 1995). The mylonite in the NW-SE trending Bok Bak Fault in NW Peninsular Malaysia was dated to the early Cretaceous ($^{40}Ar/^{39}Ar$ dating: 136.1 ± 1.4 Ma), indicating an initial ductile dextral movement of the Bok Bak Fault (Salmanfarsi, 2017), and was later reactivated as a brittle sinistral fault, probably in late Cretaceous times. Early Paleocene Segamat Basalts located east of BRSZ were cut by NW-SE sinistral faults (Abdullah *et al*., 2004), which appear to be the potential southeastward extension of the BTFZ geographically.

METHODOLOGY

Structural study

The collection of geological data involves studying various outcrops, which were selected based on accessibility and the presence of clear and significant geological structures. Detailed measurements of fractures, bedding, and other relevant features, such as cross-cutting relationships and fracture-filling materials, were recorded, along with major kinematic indicators (e.g. Tjia, 2014). The data were analyzed using the Stereonet software (version 11.4.3), in which the information was plotted on a lower hemisphere, equal-area projection. This data was used to interpret the paleo-stress field for the deformation event. Finally, all the local structural datasets were integrated into a synthesis with compiled results from the literature to reconstruct and interpret the tectonic significance of the deformation events. All observations and data were also included in a GIS database and presented in structural maps (Figure 1 and 10).

K-Ar dating

Biotite minerals from a fine-grained schistose granite and a whole rock sample of an andesitic rock have been dated using the K-Ar method by Actlab, Canada. For the K-Ar dating, aliquots of the samples were loaded into a container and degassed at approximately 100°C for two days to remove surface gases. Argon was then extracted from the samples in a double vacuum furnace at 1700°C. The radiogenic argon content was determined twice using an MI-1201 IG mass spectrometer by the isotope dilution method, with 38Ar used as a spike, which was introduced to the sample system prior to each extraction. The extracted gases were purified in a two-step purification system, and pure Ar was introduced into a custom-built magnetic sector mass spectrometer (Reynolds type). Each sample was tested twice to ensure consistency of results. The 38Ar spike calibration was carried out using two globally accepted standards (P-207 Muscovite and 1/65 "Asia" rhyolite matrix). For age calculations, the international values of constants were used, specifically λ_K=0.581*$10^{-10}y^{-1}$, λ_β-=4.962*$10^{-10}y^{-1}$, ^{40}K=0.01167 (at.%).

RESULTS AND DISCUSSION

Deformation along Lojing and Pos Betau transects

The Lojing and Pos Betau transects follow the roads across the BRSZ, where various suture units are exposed (Figure 1B and 1C). The Lojing Transect pertains to Federal Route 185, stretching from Lojing to the foothills of the Main Range, approximately 20 km west of Gua Musang (Locality i to v shown in Figure 1B and 1C). The roadcuts along the Lojing transect reveal a diverse array of geological units, including (from west to east) granite, mica schist, mélange, amphibolite, quartz ridge, conglomerate, bedded chert, and limestone. The Pos Betau Transect follows part of Route 102, stretching from 30 km east of Ringlet to Sg Koyan (Locality vi to viii shown in Figure 1B and 1C). Along the roadcuts of this transect, various rock units are exposed, including granite, mica schists, serpentinite, cherts, andesitic rocks, mélange, and conglomerate.

Lojing Transect

Granites

The Main Range is characterized by late Triassic porphyritic granites. Along roadcuts, the observed granite often appears fractured. At Locality i (coordinate: 4.677838, 101.493697), the fractures predominantly exhibit steep dips, but locally they show gentle dips, that could suggest exfoliation planes (Figure 2A). Some of the steeply dipping fractures have a N-S strike and show striations with horizontal pitch (Figure 2B). The risers transverse to fault striations on this slickensided surface, i.e. pluck steps (Tjia, 2014) provide clear evidence of dextral motion. A steeply dipping fracture forms an extensive cliff face (Figure 2C), which features an elongated step riser, also known as a bruised step (Tjia, 2014). The riser contains fine to coarse grained shavings derived from the host granite by faulting (Figure 2D). The sense of normal fault motion is interpreted based on the morphology of the bruised step. This fault appears to cross-cut other geological structures in the area.

At Sg Ber Hot Spring (Locality ii; coordinate: 4.709939, 101.568181), near the granite-suture contact in the Lojing-

Pos Blau area, a weakly foliated/ schistose, fine- to medium-grained granite with penetrative C-S fabric was observed. The C-planes of the fabric strike approximately N-S, while the S-planes are oriented NW-SE (Figure 2E and 2F). Both the C- and S-planes are nearly vertical dipping. Hand specimens of the schistose granite also exhibit centimeter-scale C-S fabric in the same orientation (Figure 2G and 2H). The schistose granite has been sampled for K-Ar

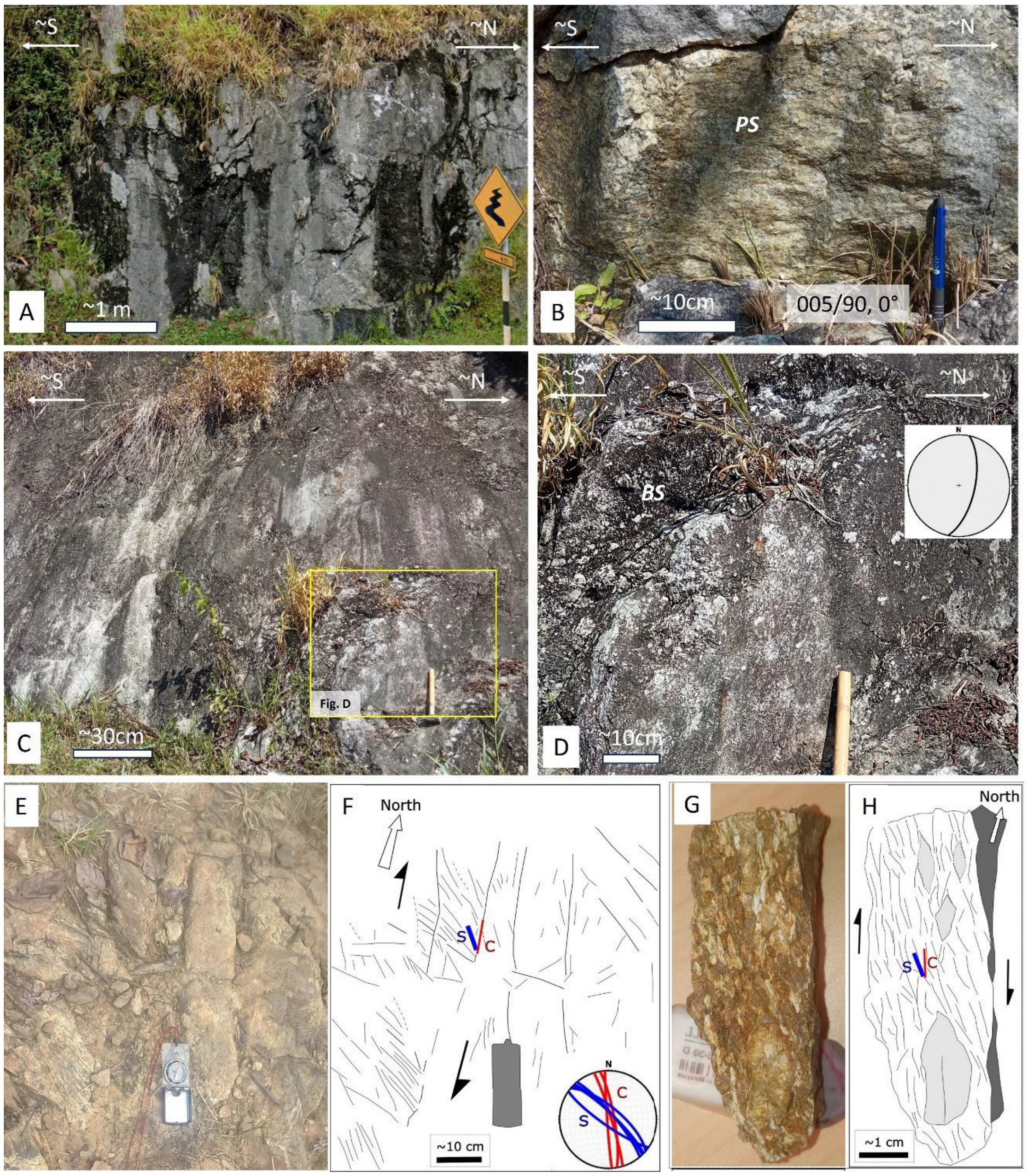

Figure 2: [A] Granites exposed at the roadcut of the Lojing transect at Locality i. The cliff faces are predominantly controlled by steeply dipping fractures. Sub-horizontal dipping fractures can also be observed at this locality. Photo source: Google Maps - Street View. [B] The pluck steps (*PS*) on a fault plane (005/90, 0°) with whitish slickenfibres, when analyzed using the smoothness criterion, it indicates a dextral strike-slip motion. [C] The cliff face is defined by a steeply dipping fracture. The yellow box marks an elongated step riser, with a zoomed-in view provided in figure [D]. [D] Faulting resulted in fine to coarse grained shavings (left side of the figure), which recrystallized to form an elongated step riser also known as a bruised step (BS). The sense of fault motion is indicated by the facing direction of the riser, showing normal fault motion in this case (orientation of plane: 012/64, as shown on stereonet). [E] Top view of granite at the Sg. Ber Hot Spring area (Locality ii). The western area (left side of the figure) shows more intense schistosity compared to the rest of the area, forming a possible C-S fabric. [F] Sketch of figure [E], marking the C-plane (red line) and S-plane (blue line), indicating a dextral motion. Stereonet shows the orientation of the C-planes and S-planes of this outcrop. [G] Top view of hand specimen of schistose granite with the C-S fabric. [H] Sketch of figure [G], marking the C-plane and S-plane. The coarse-grained minerals e.g. feldspar and quartz (light grey polygons) are deformed into sigmoidal shapes.

biotite dating and yielded an age of 100 Ma (sample 540, See Table 1).

Mélange

The mélange of the Pos Mering area (Locality iii; coordinate: 4.722772, 101.620440) consists of tuffaceous sandy clasts embedded in a carbonaceous silty to muddy matrix (Figure 3A). The muddy matrix of the mélange exhibits partial foliation with steep dips. The foliations, striking approximately N-S, are parallel to the long axes of clasts, which often appear sigmoidal in shape (Figure 3B and 3C). This ductile deformation is characterized by C-S bands, where the longer edges of sigmoidal clasts represent the C-planes (parallel to foliations), and the S-planes are defined by the shorter edges of the clasts oriented in the NW-SE direction. Based on the orientations observed in this outcrop, the C-planes (150/80) and S-planes (300/80) indicate a dextral shear. Additionally, there is a suspicion that the shearing may include a dip-slip (reverse fault motion) component, suggesting an oblique (dextral reverse) shear event.

Amphibolites

A few hundred meters of fresh amphibolites along the Lojing Transect are exposed at Locality iv

Table 1: K-Ar ages of the rocks near to or within BRSZ.

Sample (dated materials)	Locality & Lithology	Coordinates	K, % ±σ	^{40}Ar rad, (ng/g)	%^{40}Ar air	Age, Ma	Error 2σ
540 (biotite)	Locality ii: Schistose granite, Sg. Ber Hot Spring	4.709939, 101.568181	1.07±0.02	7.61±0.04	22.9	100	4.0
526 (whole rock)	Locality vii: Andesitic rock, NW Pos Betau	4.311536, 101.674736	1.52±0.02	9.87±0.11	40.9	91	3.0

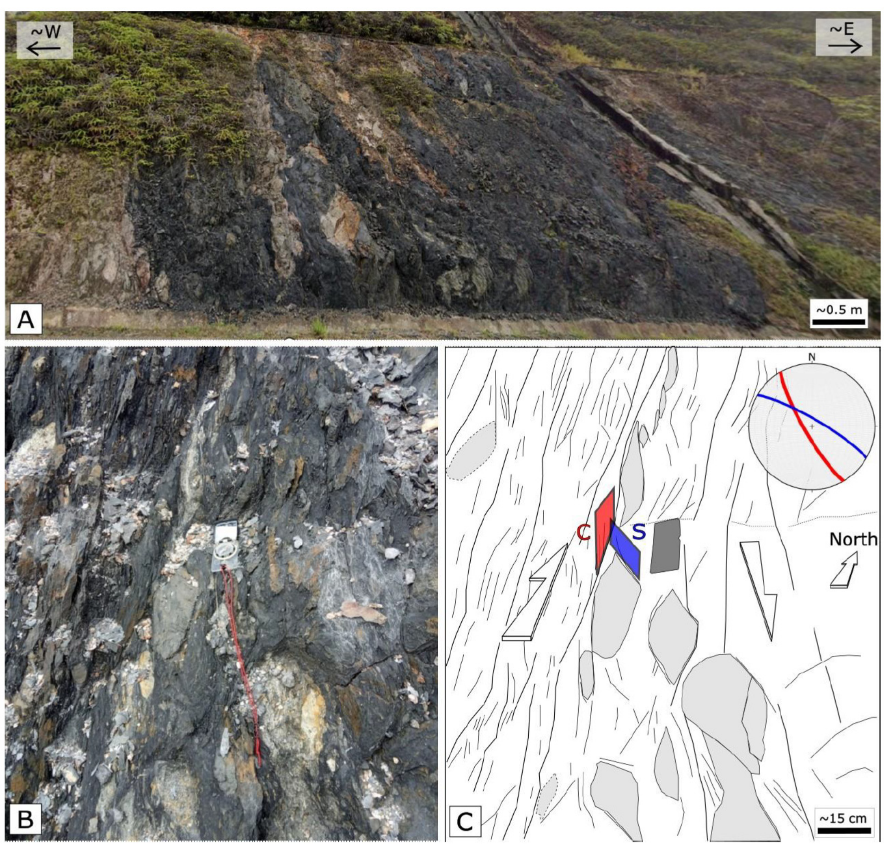

Figure 3: [A] The mélange exposed at a cliff face in the Pos Mering area of the Lojing transect consists of dark grey foliated muddy matrix enclosing light grey tuffaceous sandy clasts. Photo source: Google Maps - Street View. [B] The sandy clasts commonly exhibit deformation into sigmoidal shapes. [C] Sketch of figure [B]. The long edges (red plane) and short edges (blue plane) of the clasts (grey polygons) represent C-planes and S-planes of C-S fabrics, interpreted as resulting from a dextral deformation.

(coordinate: 4.723787, 101.679586). These rocks exhibit steep to vertical foliations predominantly striking in a N-S direction. The amphibolites are highly fractured and show local folding. A N-S tight fold is suspected to have been crosscut by a NE-SW fault with dextral motion (Figure 4A). Striations and slickenfibres on the foliation planes indicate that significant shearing has occurred. Slickensides along the foliation planes of the amphibolite show a N-S dextral strike-slip shearing movement, indicative of clear brittle shear (Figure 4B and 4C). Additionally, a set of NW-SE faults (orientations: 310/65 and 290/70) (Figure 4D and 4E) crosscut the entire outcrop, displaying a sinistral to normal motion as evidenced by oblique striations (pitch: 45° west) on the slickensides (Figure 4E).

Limestone

Localized limestone outcrops at Locality v (coordinate: 4.757390, 101.759622) within the Lojing Transect in the BRSZ exhibit clear brittle deformation features. The grey-coloured limestones are highly fractured and lack clear bedding. Numerous fair to well-preserved slickensides are observed in the fractured limestone. The most prominent fracture sets are N-S oriented dextral strike-slip faults based on fault morphologies such as fault *roche moutonnee* (Tjia, 2014) (Figure 5A), similar to those observed in the amphibolite outcrops described earlier. Some of these faults display oblique striations, indicating shear movement such as dextral-normal slickensides (Figure 5B). A local oblique dextral slickenfibre appears to overprint the pure dextral strike-slip fault plane (Figure 5A), suggesting dextral normal

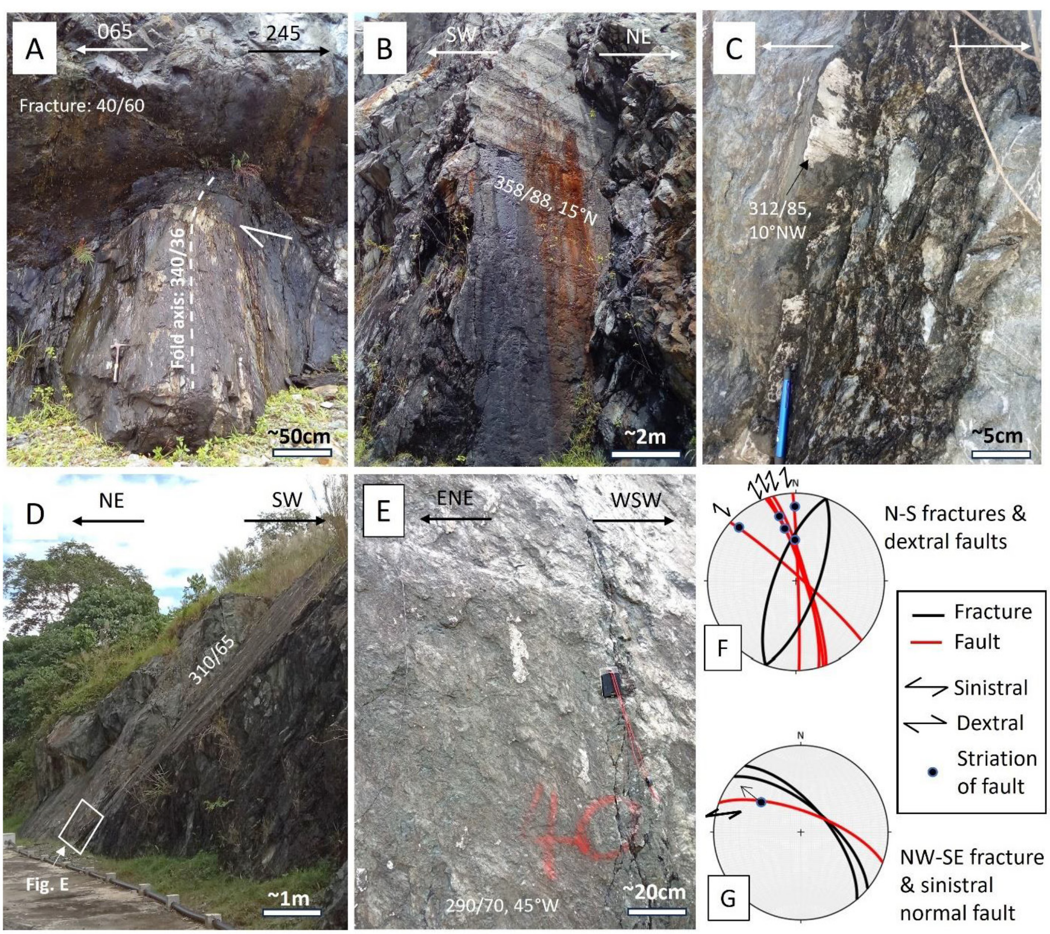

Figure 4: Structures of amphibolite outcrop at the Lojing Transect. [A] A tight fold with a well-preserved hinge (fold axis: 340/36) cut by a NE-SW fracture (040/60). A drag structure is evident at the fold contacts with the NE-SW fracture, interpreted to result from a dextral motion. [B] The top part of a cliff face or vertical fracture showing a horizontal groove and ridge structures, likely representing a strike-slip fault plane with dextral motion. [C] A schistose zone (dark grey colored area) bounded by light-grey massive amphibolite bodies. The boundary of the schistose zone exhibits slickenfibres, indicating a dextral strike-slip fault. [D] A steeply dipping fracture (310/65) that crosscuts the entire outcrop. The white box indicates a zoomed-in view provided in figure [E]. [E] A slickenside (290/70, 45°W) displaying oblique fault movement. [F] Stereonet showing readings of N-S fractures and dextral faults, including those shown in [B] and [C]. [G] Stereonet showing readings of NW-SE fractures and sinistral normal faults, as seen in [E]; a dot marks the striation (lineation: 316/50), and an arrow points to the extension direction.

faulting occurred subsequent to the initial dextral strike-slip faulting. Several oblique reverse faults with sinistral motion are also evident in this limestone (Figure 5C). However, the stress field inferred from these faults contrasts with that of the dextral faults described earlier, indicating a distinct structural event. There are no clear cross-cutting relationships observed between the dextral and sinistral faults.

Pos Betau Transect

Serpentinite

The serpentinite outcrop at Locality vi (coordinate: 4.344870, 101.671243) is exposed along the roadside in the east Ringlet area. Depending on exposure, they range from fresh to highly weathered, often turning into reddish soil. The rocks appear as a ~100m stretch of dark green-colored (fresh serpentinite) and highly deformed material. Part of the serpentinites is highly schistose (Figure 6A) and exhibits clear C-S fabrics of ductile deformation (Figure 6B). Both C-planes and S-planes are striking approximately N-S and are steeply dipping. It is notable that S-planes generally exhibit steeper dips compared to C-planes. The deformation of serpentinite at the current locality is expected to have occurred at medium temperature and medium to high pressure conditions, referred to the examples from the Voltri massif, Italy (300°C–640°C, 0.6–2.2 GPa) (Hermann *et al*., 2000; Auzende *et al*., 2015) and the Zermatt-Saas zone, Western Alps (550°C ± 50°C, 2 ± 0.5 GPa) (Wassmann *et al*., 2011). One of the C-planes within the C-S fabric appears as slickensides, showing evidence of brittle deformation i.e. striations with reverse fault motion (Figure 6C and 6D). The coexistence of both brittle and ductile deformation in serpentinite is not uncommon, and has been observed in both experimentally and naturally deformed serpentinites (e.g. Auzende *et al*., 2015). Overall, the presence of both C-S fabric (strike: ~NNE-SSW direction) and striation (335/62) supports a top-to-~southeast (~SE) reverse fault motion in this serpentinite outcrop.

Andesitic rock

The fractured andesitic rocks crop out at the northwest part of the Pos Betau Transect (Locality vii; coordinate: 4.311710, 101.674530). The rocks display a clear set of conjugate fractures and faults (Figure 7A), some of which possess strike-slip slickensides. The ~E-W fractures exhibit sinistral shear motion (Figure 7B), while the ~N-S fractures show dextral shear motion (Figure 7C), as deduced from the

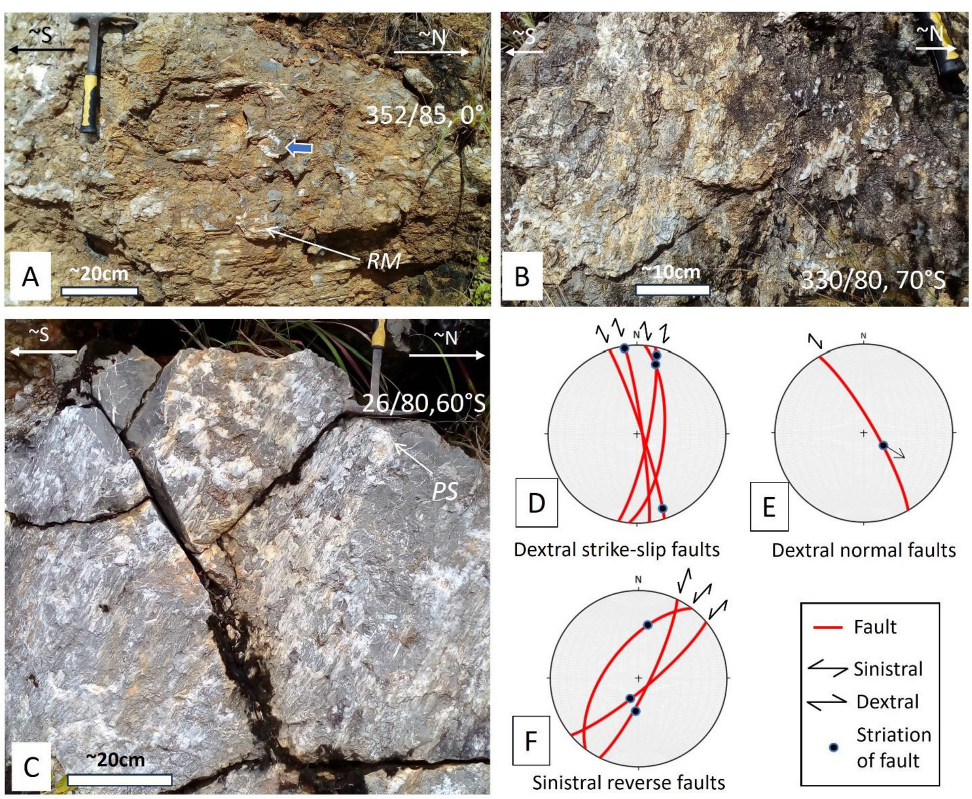

Figure 5: [A] Dextral strike-slip fault plane (352/85, 0°) with fault *roche moutonnee* (*RM*) observed in limestone at Pos Blau. A local slickenfibre with a pitch of 45° south (indicated by the blue arrow) appears to overlay the major pure strike-slip slickenside. [B] Oblique/ dextral normal fault plane (330/80, 70°S) observed in the limestone. [C] Oblique/ sinistral reverse fault (026/80, 60°S) with well-preserved whitish-coloured slickenfibres and pluck step (*PS*). [D] Stereonet showed the readings of ~N-S dextral strike-slip faults. [E] Stereonet showed the readings of ~N-S dextral normal faults, dot marked the striation (lineation: 125/68), arrow points to the extension direction. [F] Stereonet showed the readings of ~NE-SW sinistral reverse faults.

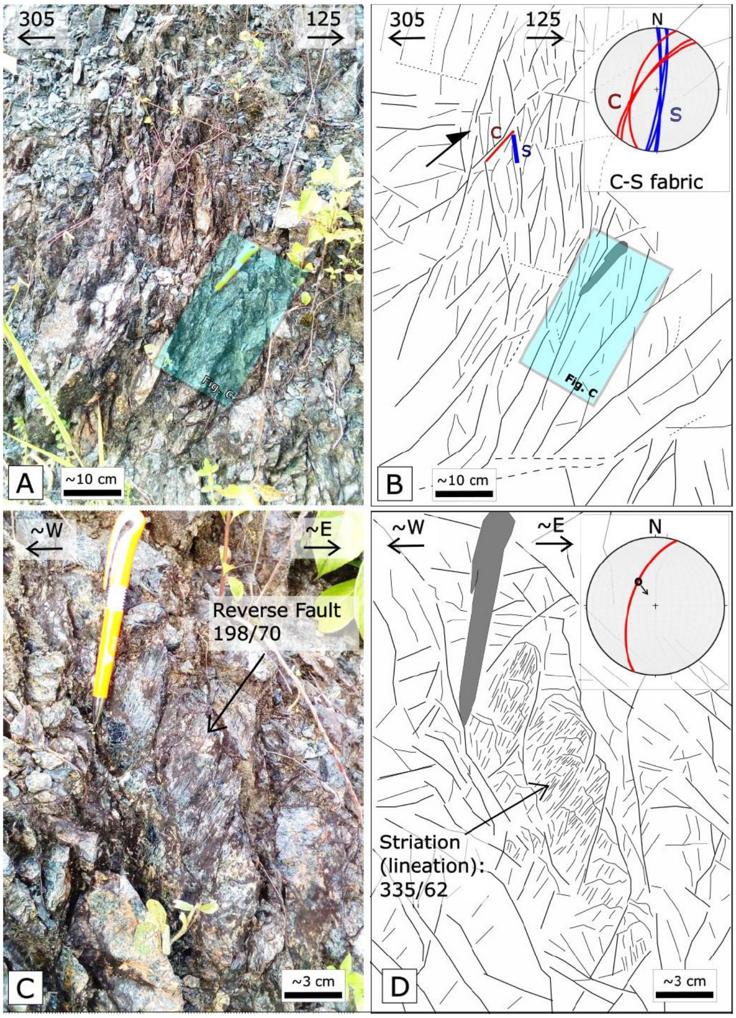

Figure 6: [A] Highly schistose serpentinite of the east Ringlet area. The blue box marks the location of a zoomed-in view provided in figure [C]. [B] A sketch of the structures observed in [A] shows an overall C-S fabric and is interpreted to indicate a top-to-SE reverse fault movement. C: C-plane; S: S-plane. The stereonet shows the collected readings of C-planes and S-planes. [C] Striations formed on a part of a C-plane (198/70, 70° N) with their orientation sub-parallel to the dip direction of the plane, indicate reverse fault movement based on surface morphology. [D] A sketch of the structures observed in [C]. Striations (orientation: 335/62) are abundant on the plane at the center of the figure. The stereonet shows the orientation of the reverse fault plane and small circle with small arrow marks the striation (lineation).

fault plane markings such as pluck steps (Tjia, 2014). These features form a conjugate fault set suggesting a ~NE-SW compression direction. An andesitic rock sample from this locality (sample 526) has been collected for K-Ar whole rock dating and yielded an age of 91 Ma (see Table 1), which represented its crystallization age.

Mélange

The mélange of the Pos Betau Transect (Locality viii; coordinate: 4.245965, 101.718620) consists of a dark grey muddy matrix (locally foliated/phyllitic) and light-yellowish colored sandstone to quartzitic clasts ranging from centimeter- to decimeter-scale, similar in composition to the mélange observed at the Lojing Transect. The phyllitic texture of the muddy matrix may indicate a greenschist facies. The foliation in the muddy matrix commonly strikes N-S and dips steeply, characterized by a C-S fabric (Figure 7E and 7F), alongside sigmoidal-shaped sandstone clasts (Figure 7G and 7H). The major N-S striking foliations of the mélange could be interpreted as possible C-planes of the penetrative C-S fabric, while the ~NW-SE striking discontinuities separating the sandstone clasts are interpreted as S-planes, indicating a N-S dextral shearing event (Figure 7G and 7H).

K-Ar age dating of selected rocks

Two rock units near or within the BRSZ exhibiting dextral shear movement were dated using the K-Ar method: a schistose granite in the Lojing area yielded an age of 100 Ma (biotite), while an andesitic rock in NW Pos Betau yielded an age of 91 Ma (whole rock). Details of the age dating are provided in Table 1. The finer grain sizes of the weakly foliated, schistose granite sample are assumed to have experienced recrystallization during deformation. The recrystallization temperatures for quartz and biotite are approximately 300°C to 400°C (Voll, 1976; Stipp *et al*., 2002). The weakly deformed, sigmoidal-shaped feldspar grains of the granite (Figure 2G) evidence the transition between brittle and plastic deformation, which occurs within the temperature range of 300-450°C (Tullis & Yund, 1977). The above-mentioned temperature ranges, derived from the observed deformation, fall within the closure temperature of biotite, which is approximately 325°C (e.g. Harrison *et al*., 1985; McDougall & Harrison, 1999). This temperature range is thus sufficient to reset the Ar system in the biotite mineral and represents the cooling age (100Ma in this case), which may be associated with shearing in the granite.

The Cretaceous age (91Ma) of the andesitic rock suggests that its origin is not associated with the Raub Group adjacent to the suture zone (Alexandar, 1968) nor Pahang Volcanic Series (Willbourn, 1917). Additionally, the Upper Cretaceous period (~107 Ma to ~87 Ma) was marked by a significant period of thermal perturbation in Peninsular Malaysia, as indicated by $^{40}Ar/^{39}Ar$ analyses (Cottam *et al*., 2013; Ghani *et al*., 2013). This period is characterized by numerous isolated intrusions of dykes and/or plutons (Cottam *et al*., 2013). The implications of these K-Ar ages are discussed in the subsequent section.

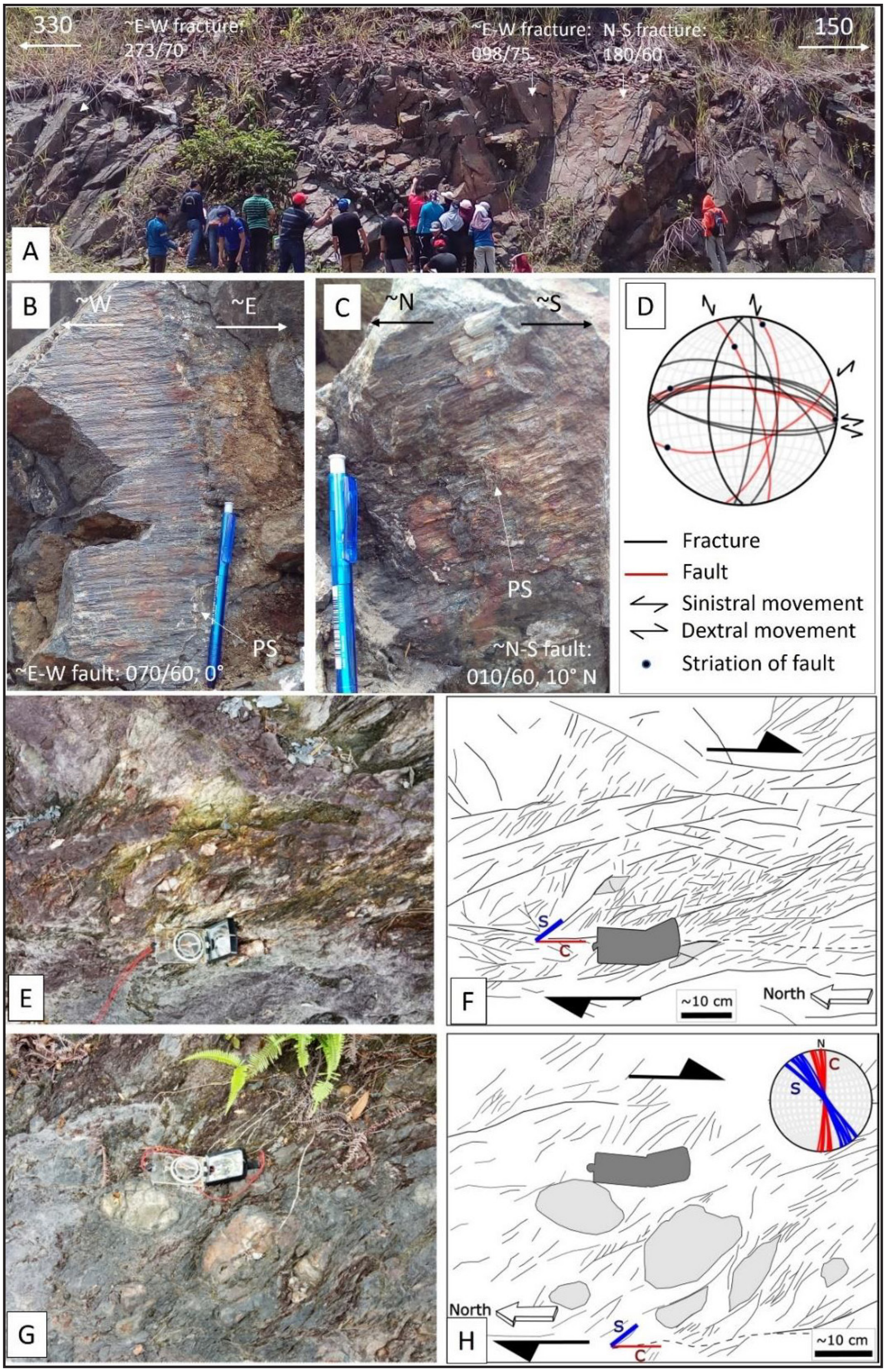

Figure 7: [A] Andesitic rocks occur in the Pos Betau transect (Locality vii). Highly fractured rocks show a conjugate fracture set (~E-W fracture: 098/75 and ~N-S fracture: 180/60) appearing at the center of the photo. [B] Well-developed striations are observed in this outcrop. The pluck step (PS) at the lower part of slickenside suggests an E-W sinistral strike-slip motion (orientation: 070/60, 0°). [C] One of the dextral strike-slip fault planes striking ~N-S (010/60, 10°N) with pluck step (PS) is observed in this outcrop. [D] The stereonet shows the overall data of faults and fractures measured in the andesitic rock, including the fault planes from [B] and [C]. [E] Top views of mélange exposed at the road cut of the NW Pos Betau area (Locality viii) showing a highly schistose zone within the muddy matrix. [F] The sketch of figure [E] illustrates the presence of C-S fabric within the schistosity. The light grey-coloured bodies are sandstone clasts. The C-S fabric suggests a dextral strike-slip movement. [G] Sandstone clasts within the mélange have been deformed into sigmoidal shapes, and the muddy matrix also shows partial schistosity. [H] The sketch of figure [G] highlights the C-S fabric within the schistosity. The light grey-coloured bodies are sandstone clasts. The C-S fabric suggests a dextral strike-slip movement.

Structural events in BRSZ

Both brittle and ductile deformation have been identified in the BRSZ, categorized into three main events: ~E-W shortening (D1), dextral shear in N-S trend (D2), and ~NW-SE extension (D3). The D1 event likely corresponds to the accretion and closure of the Paleo-Tethys during the Permo-Triassic period. D2 is inferred to have occurred after 91 Ma, based on the age of the youngest deformed rock, placing it in the late Cretaceous period. D3 represents an extensional event, possibly associated with the regional relaxation during the changes in the boundary conditions of the Sunda Plate in the Cenozoic. These main events are summarized in Figure 8 and discussed further below.

~E-W shortening (D1)

This event pertains to the folding and thrust faults observed within the suture units, notably in amphibolite, serpentinite, and potentially limestone. The presence of ~N-S tight folds in steeply dipping foliated amphibolite suggests E-W shortening. In the serpentinite of the Pos Betau transect, a C-S fabric within a highly schistose zone (Figure 6B) and locally well-developed slickenlines (Figure 6D) represent brittle-ductile deformation with similar kinematics i.e. ~E-W thrusting, grouped as D1 structures. The top-to-E or SE thrust of serpentinite which contradicts the common SW vergence direction (e.g. Tjia & Almashoor, 1996), can be interpreted as a local back-thrust in a major westward-directed thrust system. The steep bedding/foliation and N-S folding, along with the overall ~eastward-verging reverse faulting in the suture rocks, indicate ~E-W shortening/compression. The alignment of D1 structural trends with the general N-S strikes of the suture rocks suggests an origin linked to Indosinian Orogeny. These D1 structures, characterized by ~N-S foliation fabric, are often overprinted by D2 dextral structures.

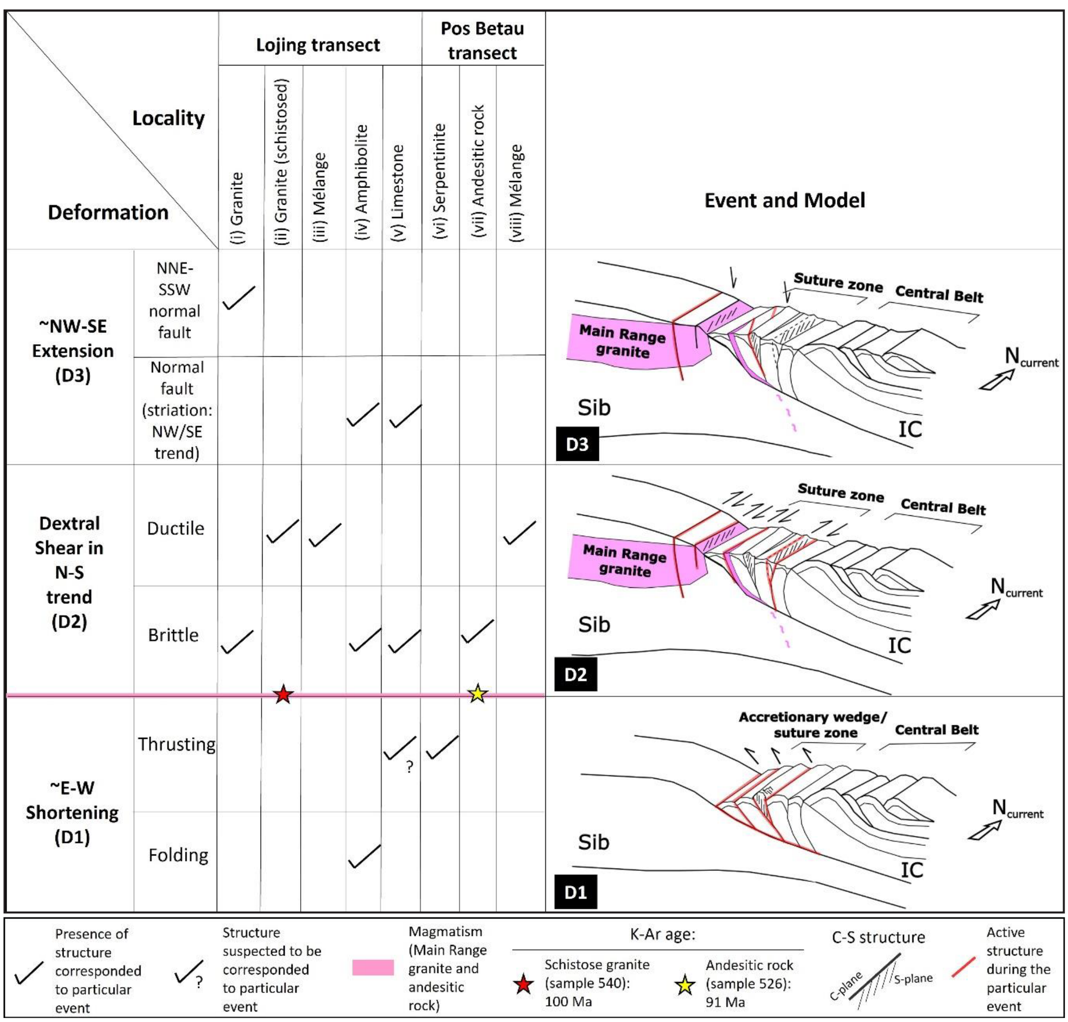

Figure 8: Summary of structural events that affected the BRSZ and Main Range area and interpreted deformations. Sib: Sibumasu block, IC: Indochina block. D1 model shows the compressional-related structures of suture units e.g. reverse faults occurred in serpentinite, and folding of amphibolite. D2 model illustrates the N-S dextral shearing along the suture zone, manifested as C-S structures in Main Range granite and mélange near Pos Betau, and as brittle faulting in amphibolite, limestone and andesitic rocks. D3 model shows the extension found in granite and amphibolite.

Dextral shear in N-S trend (D2)

The dextral strike-slip shearing in a ~N-S direction observed along the Lojing and Pos Betau transects is categorized under D2. This shearing event occur in both brittle and ductile conditions depending on the rock rheology. The brittle D2 event is accommodated along steep to vertically dipping N-S faults, where fault planes with markings, such as pluck steps and fault *roche moutonnee* (Figure 2B, 4C, 5A and 7C) are indicative of brittle dextral strike-slip faulting. These features were observed in amphibolite, limestone, and andesitic rock units.

The ductile form of the D2 event is characterized by C-S fabric, as observed in the schistose granite (Figure 2E and 2G) and mélange units (Figure 7E and 7G). The C-S fabric consists of ~N-S striking, nearly vertical dipping planes acting as C-planes, and ~NW-SE striking, nearly vertical dipping planes forming S-planes, clasts in the mélange have been deformed into sigmoidal shapes, suggesting dextral shearing along N-S planes. The N-S fold (a D1 structure) observed in amphibolite is crosscut by NE-SW dextral fault, likely represent a local second-order D2 fracture that deviates from the major N-S orientation. D2 structures commonly develop along pre-existing discontinuities, such as beddings or foliations, in the mélange and amphibolite. The current orientations of these structures (N-S striking and steeply dipping) suggest they resulted from accretion/collision, and that D2 reactivated these tilted planes.

The dextral shearing event also affected the schistose granite at Locality ii (Figure 2E and 2G) near the suture boundary, further suggesting a post-Indosinian Orogeny episode. This interpretation is supported by new K-Ar dating, which indicates ages of 100 Ma for the schistose granite and 91 Ma for the andesitic rock, suggesting that the D2 event extended until 91 Ma, possibly continuing into the late Cretaceous. This timing coincides with major NW-SE faults in Western Peninsular Malaysia, such as the Bukit Tinggi Fault Zone (Harun, 2002) (Figure 9). The similar N-S morpho-structural trends of the suture units and D2 structures, along with cross-cutting relationships and K-Ar ages, suggest a reactivation of Indosinian Orogeny structures during a younger compression event.

~ NW-SE extension (D3)

Fractures with a normal or oblique dip-slip component that cross-cut entire outcrops within the suture zone are categorized as D3. One such fault in amphibolite schist (Locality iv) exhibits clear oblique sinistral normal movement (290/70, 45°W) with a NW extension direction (striation: 316/50. Meanwhile, an oblique normal fault in limestone (Locality v) show a SE extension direction (striation: 125/68). Local slickenfibres with oblique striations (45°S) appear to overlap on the major pure strike-slip slickenside (352/85, 0°) in the limestone of the Pos Blau area, suggesting a late-stage normal dextral deformation. In the Lojing area, the granite is intersected by a steeply dipping NNE-SSW dip-slip fault. Kinematic indicators, such as bruised steps and the steep fault plane, suggest it is a normal fault with WNW-ESE extension. The orientations of D3 structures vary from locality to locality, likely due to differences in the reactivation of pre-existing fractures compared to newly formed ones, resulting in distinct fracture orientations. Therefore, these D3 fractures are interpreted as the result of a late deformation event dominated by NW-SE extension.

Post-collision structure reactivation and its regional tectonic implications

Assuming the biotite in the schistose granite at Sg Ber Hot Spring has underwent thermal resetting due to D2 dextral deformation, with no loss of argon from the biotite, it is interpreted to represent a ~N-S dextral shear event along the BRSZ at the onset of the Upper Cretaceous period (100 Ma). This D2 event likely persisted until the complete cooling of andesitic rocks that intruded the suture zone at 91 Ma.

Similarities in the geometry and timing of all these structures support a common origin of the observed deformation. We propose a conceptual model adapted from Sautter & Pubellier (2015), incorporating the concepts of Hippertt (1999). This model links the occurrence of both NW-SE and N-S discrete faults in the competent granitic and suture domains, as well as the folding of late Jurassic- early Cretaceous Tembeling Group and equivalent sedimentary strata in the Central Belt basin. In this framework, a major N-S fault (e.g., BRSZ) acts as a C-plane, while NW-SE faults (e.g., BTFZ) act as S-plane of a regional-scale pseudo-C-S band (Figure 10A & 10B). The S-C structures, where antithetic shear on the S planes (Hippertt, 1999), are responsible for the well-defined duplexes observed in the central part of Main Range granite (Figure 10A & 10B). Each of these duplexes follow the invariant function defined by Hippertt (1999), where $C_{spacing} = 2S_{spacing}$. Another diffuse C-plane is inferred along a line parallel to the BRSZ in the Kinta Valley, west of the Main Range granite. (Figure 10A & 10C). Outcrop-scale N-S dextral strike-slip faults have been reported at the flank of the Kinta Valley (Choong *et al*., 2015, Sautter *et al*., 2017) (Figure 10C, D & E). The regional-scale C-S bands have been described and thoroughly assessed for their fractal components in Brazil (e.g., Fossen *et al*., 2022) and on Mars (e.g. Hanmer, 2023). The N-S dextral and NW-SE sinistral structures observed in this study intersect at an obtuse angle (~110°), resembling the conjugate ductile shear zone described by Zheng *et al*. (2015), forming in contractional quadrants. This may indicate that the maximum principal stress direction (σ_1) is in the ~ENE-WSW direction. The major NNW-SSE fold trends of Tembeling Group and equivalent sediments, oriented perpendicularly, appear to result from the same stress field (Figure 10B). This event has been documented in several studies and may be linked to the successive diffuse compression episodes along the western

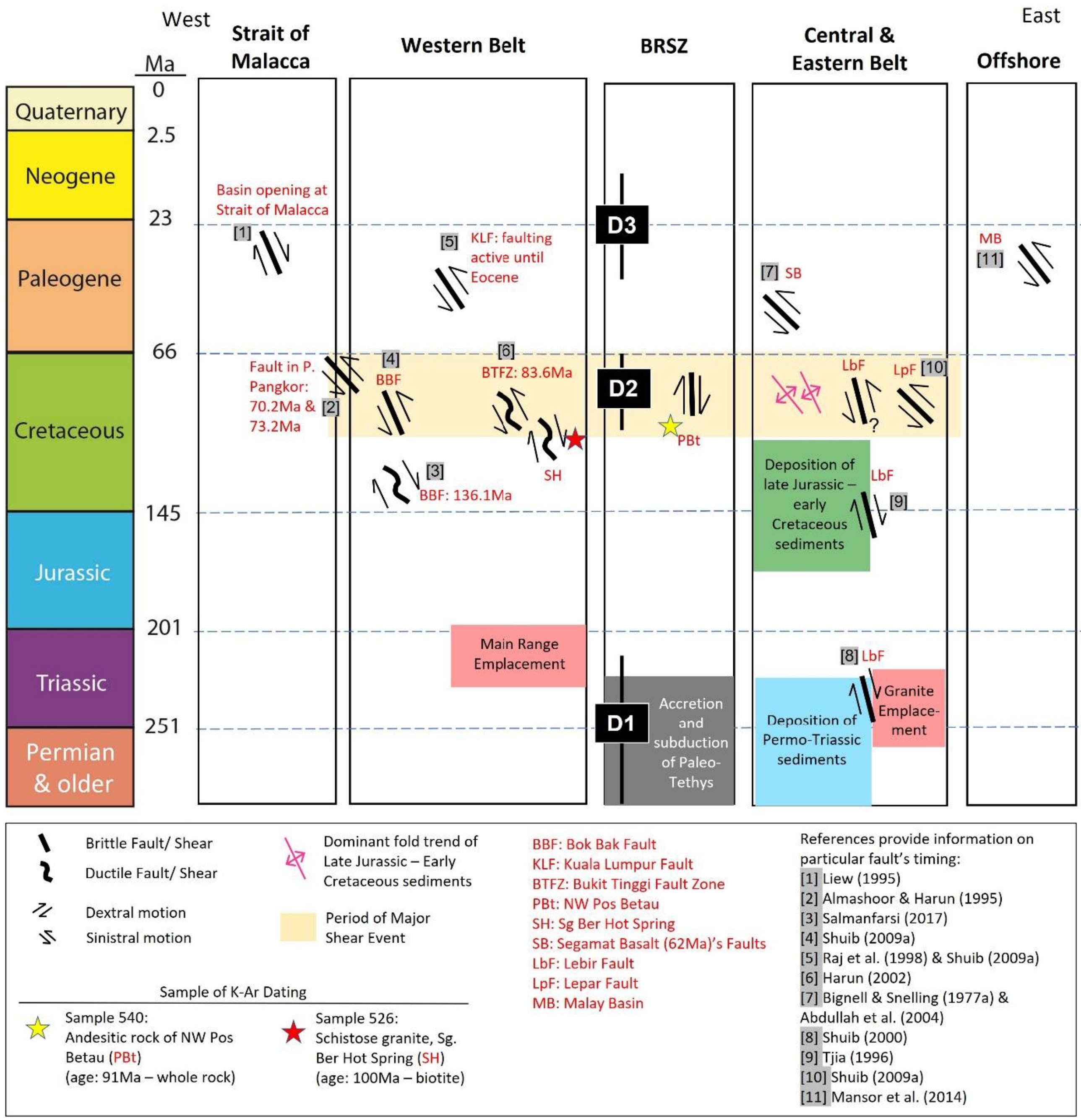

Figure 9: Major fault zones in Peninsular Malaysia and their ages, from the West (Strait of Malacca) to East (Malay Basin). The proposed timing of D1, D2 and D3 structural events are marked. The major dextral shear event (D2) is expected to occur in late Cretaceous time.

Sunda margin from the Upper Cretaceous to Cenozoic. These include the collision of the Woyla Arc at 90–100 Ma (Barber & Crow, 2009), the northward migration of the Indian plate toward the Eurasian plate (Sautter *et al*., 2019) and the subduction of the western part of the 90E ridge, which facilitated the India's rapid northwards movement (Hall *et al*., 2009; Hall, 2012). Lacking precise chronological evidence in Malaysia, we interpret these events as part of a dynamic period of continental accretion and shortening, consolidated in a single stage, D2 event, in our model.

Eventually, the Cenozoic extension of D3 occurred in the Peninsular Malaysia, reactivating some of the pre-existing structures. This event is linked to the exhumation of the adjacent Main Range Batholith. The D3 structures share similar structural orientations with nearby rifted half-grabens in the Strait of Malacca, the Malay Basin, and onshore Tertiary basins, suggesting they may have resulted from the same structural event. Cenozoic basin development and extension in this region are interpreted to be associated with changes in the boundary conditions of the Sunda Plate (Pubellier & Morley, 2014).

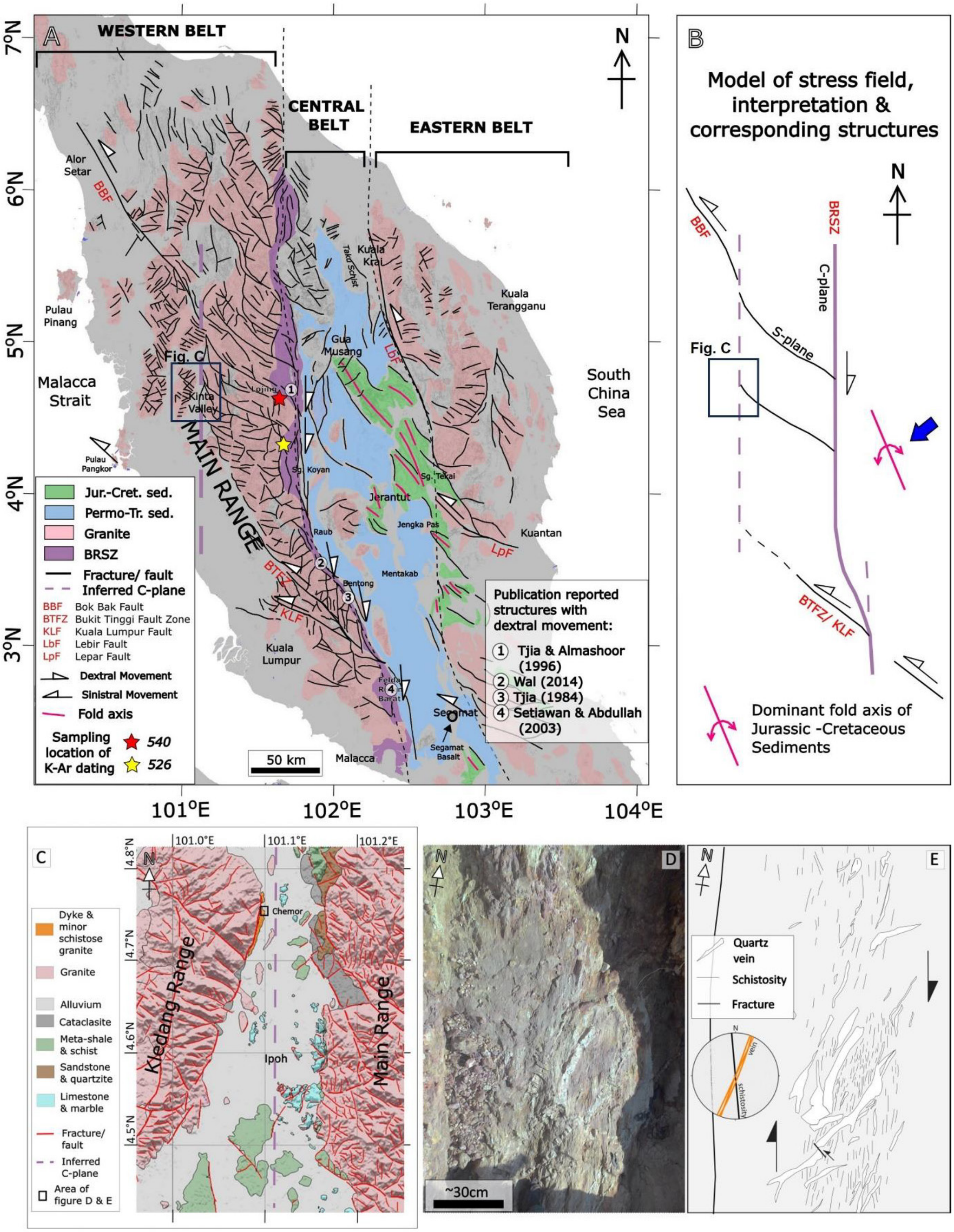

Figure 10: [A] Late Cretaceous fault movements and dominant fold axes of late Jurassic – early Cretaceous sedimentary rocks in Peninsular Malaysia. [B] Simplified model of stress field and structures in BRSZ and Peninsular Malaysia. This model illustrates the stress field and structural features observed in the BRSZ and the rest of Peninsular Malaysia. It suggests a conceptual C-S fabric where N-S fractures act as the C-plane (indicating dextral movement), and NW-SE fractures act as the S-plane (indicating sinistral movement). BRSZ is one of the C-planes and another diffuse C-plane is inferred to be located west of the Main Range, in the Kinta Valley. The structural system includes NNW-SSE trending folds and deduces a ~ENE-WSW maximum principal stress direction (σ_1)/ maximum horizontal stress (S_{hmax}) (blue arrow). The displacement of the main C-plane near the BTFZ/KLF could be related to a local complex framework of the "duplex" in the C-S band. [C] Geological map of the Kinta Valley. Another C-plane is inferred to cross Kinta Valley and a locality at foothill of Kledang Range granite, west of Chemor, shows [D] NNE-SSW striking, en echelon-like quartz veins formed in schistose granite. [E] The sketch of figure [D] and the orientation of the en echelon-like quartz veins (NNE-SSW striking) have been interpreted to indicate dextral shear motion.

CONCLUSION

The current study describes the reactivation of Paleo-Tethys suture zones i.e., the BRSZ due to regional tectonic forces in the post-Indosinian Orogeny period, and incorporates two newly acquired K-Ar ages. Three structural events have been interpreted based on outcrop studies in the Lojing and Pos Betau transects of BRSZ: ~E-W shortening (D1), ENE-WSW shortening with dextral shear in a N-S trend (D2), and ~E-W extension (D3) in ascending order. D2 and some D3 structures seem to reactivate the pre-existing steeply dipping bedding/foliation planes of the suture rocks, which originate from the D1 event. Both ductile and brittle deformation are observed in the D2 event. Rock samples of schistose granite and andesitic rock collected from the outcrops affected by the D2 event have been dated using the K-Ar method, yielding ages of 100 Ma (biotite) and 91 Ma (whole rock). Based on the current dating results and published data from the BRSZ and surrounding areas, the D2 shear event is interpreted to have occurred in the Upper Cretaceous and may be linked to the successive diffuse compression episodes along the western Sunda margin. The widespread N-S dextral shear zones (D2) in BRSZ are interpreted to represent the C-plane of a regional C-S fabric. The orientation of the regional fold axes of the late Jurassic-early Cretaceous Tembeling Group sediments is also compatible with the stress field of the D2 event. Eventually, the Cenozoic ~NW-SE extension (D3) reactivated some of the pre-existing structures, which could be associated with exhumation of adjacent granitic batholith, regional Cenozoic basin development and changes in the boundary conditions of the Sunda Plate.

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AUTHORS CONTRIBUTION

CCM, AAK and BS conducted field observation. CCM performed data collection, analysis, interpretation, drafted and wrote the manuscript. BS, AAK and AB provided technical oversight. BS, AAK and AB reviewed the writing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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