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# Kinematics of post-orogenic extension and exhumation of the Taku Schist, NE Peninsular Malaysia

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## ABSTRACT

Recent studies imply that the formation and evolution of many SE Asian basins was driven by extensional detachments or systems of low-angle normal faults that created significant crustal exhumation in their footwalls. In this context, the architecture of the Triassic Indosinian orogen presently exposed in Peninsular Malaysia is compatible with significant extension post-dating the orogenic event. In this study we performed a kinematic analysis based on fieldwork and microstructural observations in the Taku Schist, Kemahang granite and the surrounding Gua Musang sediments of northern Peninsular Malaysia in order to shed light on processes related to the build-up and subsequent demise of the Indosinian orogen. The first three phases of deformation were related to an overall period of E–W oriented contraction and burial metamorphism. These phases of deformation are characterized by isoclinal folding with flat lying axial plane cleavages (D1), asymmetrical folding, top-to-the-W–SW shearing (D2) and upright folding (D3). All are in general agreement with observations of the previously inferred Permo–Triassic Indosinian orogeny. During these times, the Taku Schist, a sequence of Paleozoic clastic sediments with mafic intercalations was metamorphosed to amphibolite facies. These rocks are most likely equivalent to the ones exposed in the Bentong–Raub suture zone. Structural relations suggest that the Triassic Kemahang pluton is syn-kinematic, which provides important constraints for the timing of these contractional events. We demonstrate that the overall shortening was followed by a hitherto undescribed extension in NW–SE direction resulting in the formation of a large-scale detachment, the Taku detachment, in northern Peninsular Malaysia. Extension probably reactivated the former subduction plane as a detachment and exhumed previously buried and metamorphosed rocks of similar lithological composition to the neighboring Bentong–Raub suture zone. Such a mechanism is similar to that observed in other regions, such as the Aegean, Apennines, Dinarides or the Betics–Rif system, where exhumation of (high-pressure) metamorphic rocks is largely controlled by detachments or low angle normal shear/fault systems.

## 1. Introduction

Recent SE Asia studies have demonstrated the coupling between the formation of sedimentary basins and the coeval evolution of large scale detachments accompanying significant crustal exhumation in their footwall, such as observed in onshore Thailand and Sulawesi (e.g. Camplin and Hall, 2014; Pubellier and Morley, 2014). Viewed as a first step in the gradual formation of the Sundaland continental mass (e.g. Hall, 2011), the Indosinian orogen of Peninsular Malaysia formed during the Devonian–Permian subduction and closure of the Paleo–Tethys Ocean and the subsequent Triassic collision between the East Malaya Block and Sibumasu continental unit (Metcalfe, 2000). Together with the more northerly located Suhkothai and Chantaburi terranes, the East Malaya Block of Peninsular Malaysia is part of the larger Sukhothai Arc originally formed at the margin of the Indochina continental unit (Fig. 1a; e.g. Hutchison, 2009; Metcalfe, 2013). This subduction and collision was accompanied by the emplacement of large volumes of intrusive rocks, generally organized into three parallel belts. Wellknown through detailed geochemical and absolute age-dating studies, the Permian–Lower Triassic I-type Eastern Belt is separated from the Late Triassic S-type Western Belt by the dominantly sedimentary Central Belt (Fig. 1b; e.g. Cobbing et al., 1992; Ghani et al., 2013; Ng et al., 2015; Searle et al., 2012 and references therein). These plutons intruded into a well studied sedimentary succession that displays gradual transitions from shallow to deep

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marine environments and locally affected the regionally metamorphosed rocks to varying degrees, including an accretionary mélange containing mafic rocks (the Bentong–Raub suture zone, Fig. 1b). The latter has been interpreted as the suture between the Sibumasu and East Malaya Block/Sukhothai Arc (Bignell and Snelling, 1977; Hutchison, 1973a; Hutchison and Tan, 2009; Metcalfe, 2000, 2013). Although a general structural framework has been defined at the scale of the whole of Peninsular Malaysia (Hutchison, 1973a; Shuib, 2000a, 2009), local structural geometries and a quantitative correlation with timing of vertical motions are largely unknown. This is relevant in the context of the significant deformation and exhumation that took place in Cretaceous–Paleogene times at the scale of the entire peninsula, as inferred by field and low temperature thermochronology studies (Cottam et al., 2013; Krahenbuhl, 1991; Shuib, 2000b).

The N–NE Peninsular Malaysia area of the Taku Schist and the Stong Complex (Fig. 1b) is particularly interesting because it exposes the highest grade metamorphic rocks in close proximity to Late Cretaceous magmatic intrusions (Ghani, 2000; Hutchison, 2009; Khoo, 1980; Khoo and Lim, 1983; Searle et al., 2012; Singh, 1963). The meta-sediments of the Taku Schist (Fig. 2a) display an amphibolite facies metamorphism, have a pervasive deformation fabric, contain remnants of metamorphosed mafic or acid intrusives, are intruded by a large pluton (the Kemahang granite) and are in contact with non-metamorphosed to sub-greenschist facies Permo–Triassic sediments (Hutchison, 1973a; Khoo and Lim, 1983). Such a structure strongly suggests a large-offset structural contact that post-dates the Permo–Triassic burial and metamorphism related to the Indosinian orogeny. We aimed to analyze this structure by means of a field and microstructural kinematic study combined with observations on the metamorphic evolution. In combination with the existing post-Triassic absolute-age and biostratigraphic data this allowed us to define a novel tectonic evolution scenario of burial and, more importantly, of Late Cretaceous–Paleogene exhumation in NE Peninsular Malaysia.

## 2. The Taku Schist in the overall evolution of Peninsular Malaysia

The Western, Central and Eastern belts of Peninsular Malaysia are separated by differences in magmatism, stratigraphy, structure and metamorphism (Fig. 1b; Foo, 1983; Hutchison, 1975; Metcalfe, 2013). While the Bentong–Raub suture zone is located near the transition between the Western and Central Belts and locally overlies the former, the contact between the Central and Eastern belts is generally interpreted as the Lebir Fault (Figs. 1 and 2a). However, the latter is not clearly identified by field geological mapping, being a diffuse transcurrent boundary defined by gravity anomalies whose position changes along the strike of the belt (Metcalfe, 2000; Ryall, 1982; Shuib, 2009; Tjia, 1969). The Triassic collision, the associated formation of the Bentong–Raub suture zone and the post-collisional evolution have been kinematically described in three stages (Shuib, 2000b, 2009). According to Shuib (2009), regional transpression during the Indosinian orogeny in Late Triassic–Early Jurassic times was followed by the opening of a continental pull-apart basin during Jurassic–Cretaceous times by major dextral strike-slip faults. These faults were further reactivated with

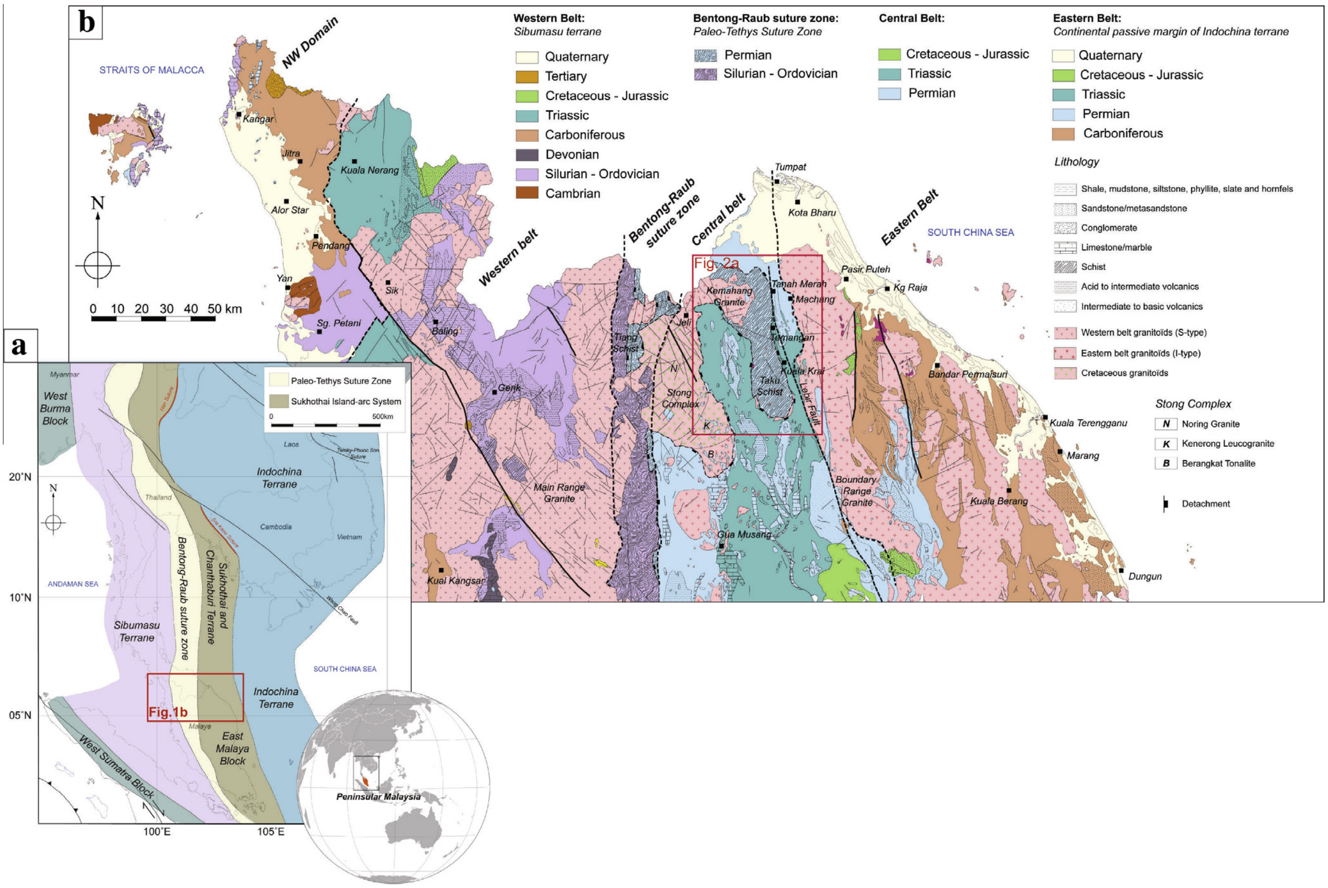

**Fig. 1.** (a) Simplified tectonic map of Peninsular Malaysia in overall context of the Asia continental units and suture zones. Note the separation of the Sibumasu continental unit and the East Malaya Block by the Bentong–Raub suture zone (modified after Metcalfe, 2013); (b) Simplified geological map of the northern part of Peninsular Malaysia with the distribution of the classical division in the Western, Central and Eastern belts, together with the location of the Bentong–Raub suture (modified from Tate et al., 2008). The rectangle is the location of Fig. 2a the area of this study.

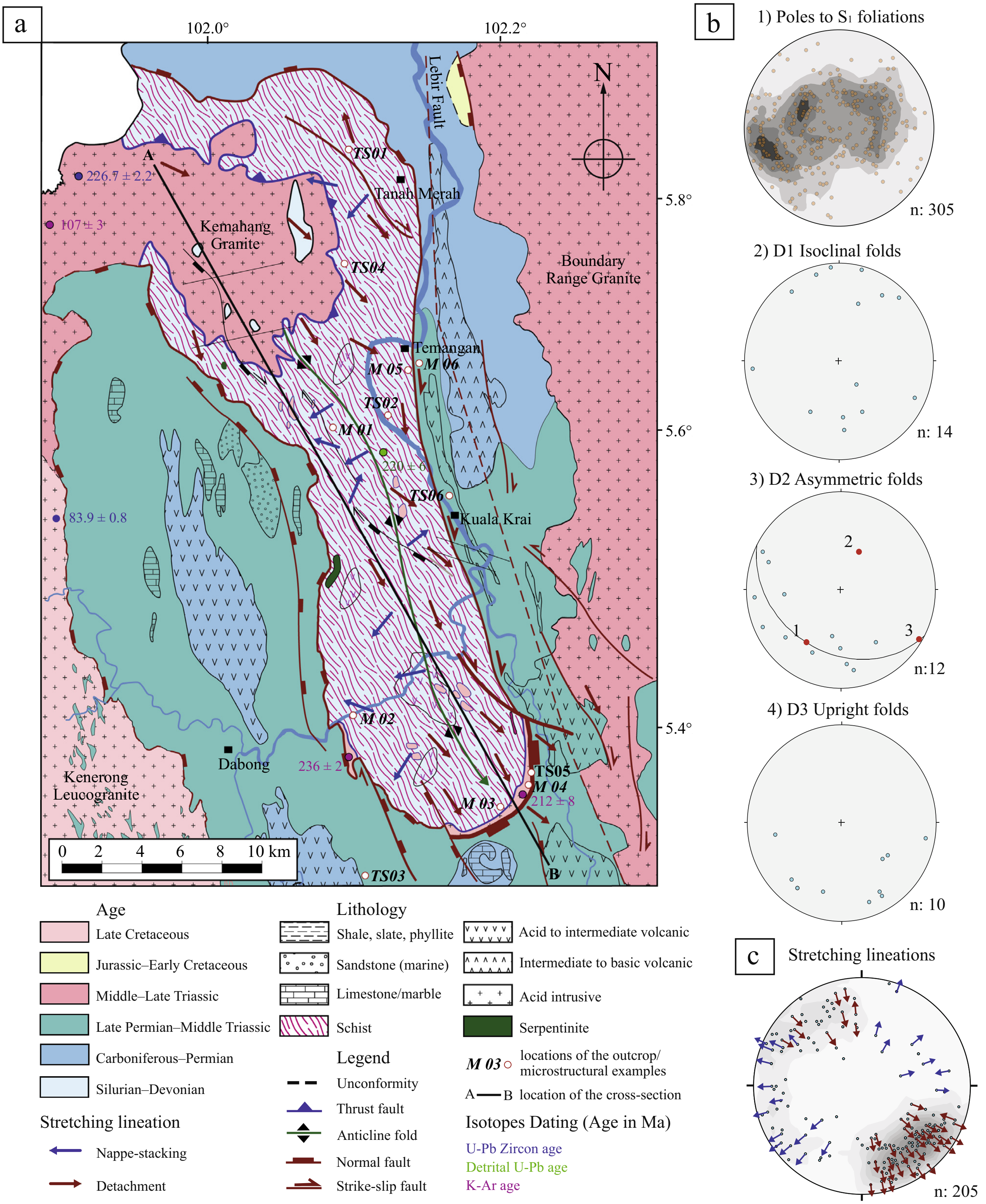

**Fig. 2.** (a) Detailed geological and structural map of the Taku Schist studied area (after MacDonald, 1968) with existing constraints from absolute age dating (after Bignell and Snelling, 1977; Ng et al., 2015; Searle et al., 2012) and with the kinematic results of the present study. Blue arrows indicate the direction of shearing related to nappe-stacking while red arrows indicate the direction of shearing related to extension. TS and M are the locations of the outcrop and microstructural examples in Figs. 4 and 5. The thick black line is the location of the cross-section on Fig. 6; (b) Stereoplots of kinematic structural data measured in the field. 1 – Stereoplot of poles and contour plots of S1 foliation; 2 – Stereoplot of D1 isoclinal fold axes; 3 – Stereoplot of D2 asymmetrical folds axes; 4 – Stereoplot of D3 upright symmetrical folds axes; (c) Stereoplot and contour plots of stretching lineations for nappe-stacking (D2, blue arrows) and extensional (D4, red arrows) shearing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a sinistral sense of shear during Late Cretaceous times, which was coeval with the emplacement of the Stong magmatic complex. This interpretation is inferred from the apparent control of N–S and NNW–SSE oriented faults on the deposition of Jurassic–Cretaceous strata (Shuib, 2009).

### 2.1. The Taku Schist

The Taku Schist belt in NE Peninsular Malaysia (Figs. 1 and 2a) forms a NNW–SSE oriented elongated body of sediments and subordinate magmatic rocks, metamorphosed to the amphibolite facies. The Triassic Kemahang granite intruded the dome shaped structure of the Taku Schist in the north (Hutchison, 1973a; MacDonald, 1968). In its central parts, this body contains lenses of amphibolites, which are remnants of mafic protoliths, while its flanks are dipping gently beneath the surrounding low grade Permo–Triassic sediments (Fig. 2a). Separated by a syncline from these Permo–Triassic rocks, the Taku Schist are bordered to the west by the Stong Complex multi-event Cretaceous intrusion, partly sheared and metamorphosed with the surrounding sediments into a high-grade metamorphic facies (Bignell and Snelling, 1977; Ghani, 2009).

Several metamorphic studies have described in details the petrology of the Taku Schist (Aw, 1974; Hutchison, 1973b; MacDonald, 1968). According to MacDonald (1968), the main lithology is a garnet-bearing mica schist and quartz mica schist with narrow bands of quartz schist and quartz veins (Fig. 3). The foliation is defined by preferred alignment of muscovite minerals, accompanied by garnet (almandine) porphyroblasts containing quartz inclusions. The amphibolite facies metamorphism is inferred from the mineral assemblage of muscovite, biotite and garnet (almandine). Additionally, the presence of kyanite as very local occurrence within the eastern margin of the unit was observed (MacDonald, 1968), and is a possible indication of localized higher pressure conditions. The Taku Schist also contains calc-silicate metasomatic rocks, localized serpentinitic bands and amphibolites (Fig. 2a), the latter within the southern center of the dome, with an assemblage of hornblende, plagioclase, clinozoisite and epidote in occurrence with tremolite, garnet and biotite (Hutchison, 1973b; MacDonald, 1968). Serpentinites were also observed near the western contact with the overlying Permo–Triassic rocks and are characterized by an assemblage of antigorite, calcite, chrysotile, chlorite, chromite, magnetite and ilmenite, which suggests an ultrabasic origin. Interlayered bands of a meta-biotite granite (orthogneiss) within the main schistose body have thicknesses of up to 1 km near the southern margin (Hutchison, 1973b). These bands are often truncated by cataclastic shear zones with a fine sericite matrix. In the north, the Kemahang

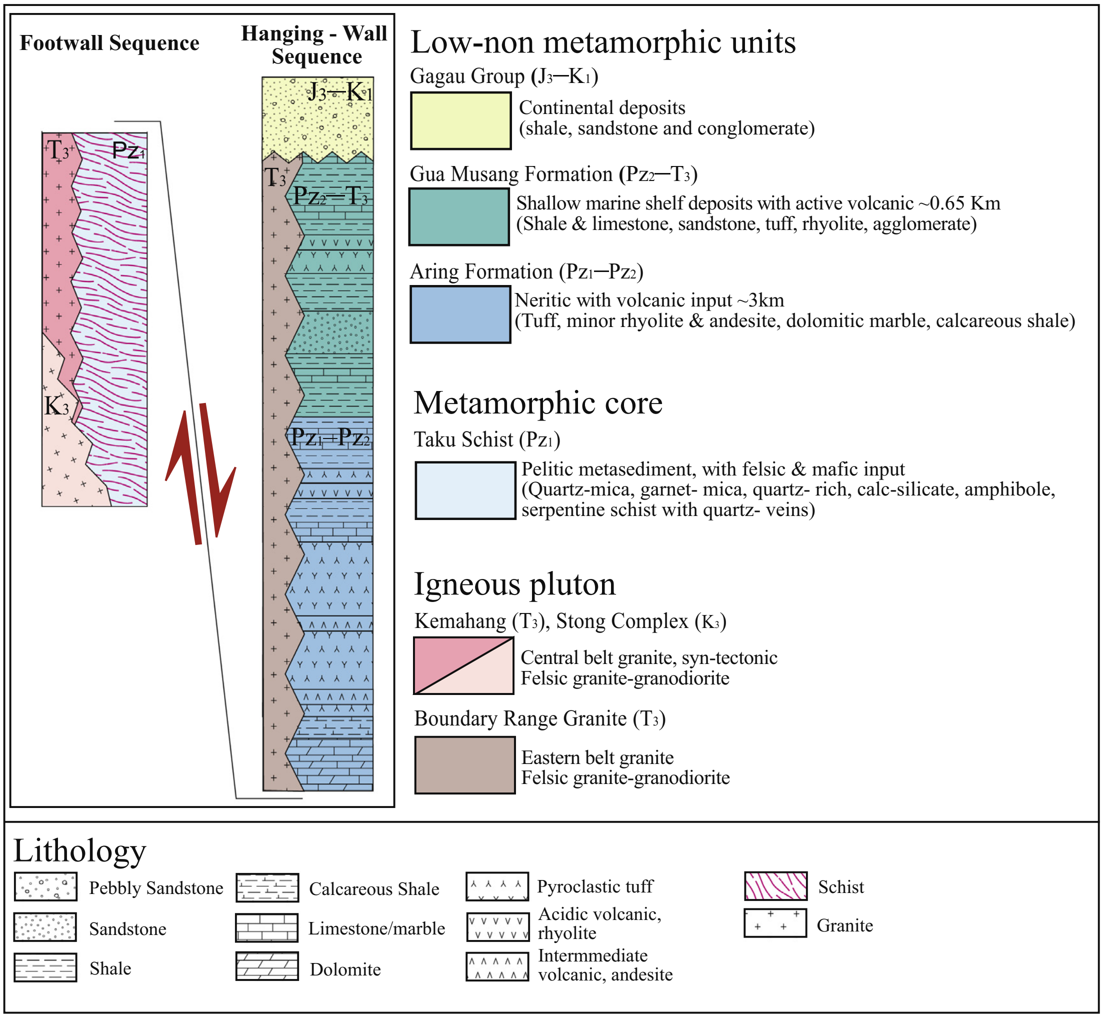

**Fig. 3.** Tectonostratigraphic columns of the Taku Schist and their hanging-wall units. The Taku Schist is made up of an amphibolitic facies metamorphosed fine clastic sequence with mafic, volcaniclastics and stock intrusions, intruded by a large Triassic granite along its northern border. The hanging-wall sequence is composed of the Carboniferous–Permian Aring Formation made up of distal deep water sediments, radiolarites and turbidites with volcaniclastics and mafic intercalations, overlain by the shallower water Gua Musang forearc deposits.

granite is similarly foliated and cataclastically sheared, in particular near its contact with the schists and Permo–Triassic sediments, and contains numerous schist xenoliths (MacDonald, 1968).

K-Ar biotite dating (Bignell and Snelling, 1977) of the Taku Schist yields a Late Triassic (212 ± 8 Ma) age of metamorphism near the western margin of the dome. Schist "xenoliths" in the Kemahang granite indicate an age of 107 ± 3 Ma. More recent U-Pb dating yielded an age of 226.7 ± 2.2 Ma for the Kemahang granite, which is close to the emplacement age of the neighboring Berangkat tonalite of the Stong complex at 220.4 ± 3.9 Ma (Ng et al., 2015). This age contrasts with the Late Cretaceous emplacement ages of the other intrusions in the Stong Complex (Kenerong leucogranite at 83.9 ± 0.8 Ma; Noring granite at 75.7 ± 0.6 Ma, Ng et al., 2015). U-Pb thermochronological analysis of detrital zircons from modern river sediments in the central part of the Taku Schist and Noring granite has yielded Late Triassic and Late Cretaceous ages in both bodies (Sevastjanova et al., 2011). In the northern region of the Central and Eastern Belt, the few available low temperature thermochronological data (zircon and apatite U-Th/He) indicate a period of major exhumation during Late Cretaceous and Paleogene times (~100–90 Ma, Cottam et al., 2013).

The protoliths of the Taku Schist are dominantly fine-grained clastic sediments intercalated with volcanics of mainly mafic and ultrabasic composition (Hutchison, 1973b; MacDonald, 1968). These rocks were metamorphosed to amphibolite facies. In the neighboring Stong complex, migmatized amphibolites were interpreted as resulting from mantle upwelling during the Late Triassic final orogenic stages of an adiabatic decompression (Shuib, 2009). A subsequent regional uplift created the open anticlinal structure of the Taku Schist and was followed by the exhumation of the amphibolite facies rocks. These tectonic phases are coeval with the magmatic emplacement in the Stong Complex, which is characterized by boudinage, ptygmatic folds and migmatization of the host rocks (Hutchison, 2009; Shuib, 2009). Outside the study area, the N–S aligned Lower Paleozoic units along the Bentong–Raub suture zone in north Peninsular Malaysia are described as the Tiang Schist (Fig. 1b). These are made up of foliated quartz-mica schists with garnet and cordierite minerals and local amphibolites containing actinolite and tremolite, and were metamorphosed and deformed during the Indosinian orogeny (Metcalfe, 2013; Shuib, 2009).

### 2.2. The overlying sediments

Surrounding the Taku Schist, the Middle Permian to Upper Triassic Gua Musang Formation (Fig. 3) comprises a succession of predominantly argillaceous fissile shales with subordinate pyroclastic or acidic flows and acidic porphyritic lava, as well as calcareous and arenaceous sediments, and overlies the older Paleozoic Aring Formation (Foo, 1983; Lee, 2009; Shafeea Leman, 2004; Yin, 1965). The Gua Musang Formation has been metamorphosed to sub-greenschist facies (Khoo and Lim, 1983), and in microscopic studies, the metamorphosed sediments were described as having a phyllitic fabric represented by preferred alignment of white micas, whereas relict feldspar is cataclastic, zoned and strongly saussuritized (Khoo and Lim, 1983). The upper part of the Gua Musang Formation laterally inter-fingers with the Triassic Semantan Formation, predominantly composed of carbonaceous shales and is inter-bedded with siltstones and rhyolites (Lee, 2009). These carbonaceous shales have been interpreted as marine forearc basin sediments, deposited over the accretionary wedge on the southern edge of the Sukhothai Arc (Hutchison, 1989; Metcalfe, 2000). The Gua Musang Formation is overlain by the Late Jurassic–Cretaceous Gagau (or Tembeling) Formation (Fig. 3). These late Mesozoic sediments are composed of conglomerates inter-bedded with sandstones and are interpreted as molasse and continental deposits (Lee, 2009). They are deformed in proximity to the contact with the Eastern Belt, where they are steeply dipping, presumably because of tectonic activity along the Lebir Fault (see also Shuib, 2000b). This NNW–SSE oriented fault system (Fig. 2a) is up to 4 km wide and consists of three discrete shear zones that crosscut the non-metamorphosed Semantan Formation (Tjia, 1969).

The geological contact between the Taku Schist and surrounding Gua Musang formations has been a matter of significant discussion. The contact has been interpreted as an unconformity, a tectonic disconformity or as a conformable contact with a rapidly increasing metamorphic grade into the Taku Schist (Aw, 1974; Hutchison, 1973b; Khoo and Lim, 1983; MacDonald, 1968).

## 3. Structural analysis

We analyzed the Taku Schist, the intruding plutons and their overlying sediments by means of a field kinematic study supplemented by microstructural and metamorphic facies observations (Fig. 2a). Our field observations were collected from 130 outcrops within river valleys, along road sections and on jungle paths. Overall, the quality of the outcrops was unexpectedly good given the tropical weathering observed in Peninsular Malaysia. We have mapped and described various types of planar and linear structures, including foliations and stretching lineations, folds, faults and striations, as well as shear zones. The structures have been grouped into deformation events based on overprinting relationships. The direction of transport has been mapped in rock and thin sections and lies parallel to the often prominently developed stretching lineation on mylonitic foliation planes. Following Simpson and Schmid (1983), we derived the sense of shear from widespread shear bands of all types (S–C, S–C′, C–C′), sigma and delta clasts, sheared clasts and the consistency of shearing direction from asymmetrical folds. The microstructural analysis was performed on structurally oriented samples, parallel to stretching lineations and perpendicular to foliation planes. Around 200 stretching lineations were measured, with the sense of shear observed in outcrops or on thin sections (Fig. 2a and c).

### 3.1. The first phase of deformation and metamorphism (D1)

The Taku Schists are affected by a pervasive metamorphic foliation (S1) that is an axial plane foliation to isoclinally folded bedding planes (S0) observed in millimetre–centimetre scale structures (Figs. 4a and 5a). Some of the rare marble layers show boudinage with moderately E–SE plunging axes orthogonal to the flattening direction. Transposition of the original bedding into the main foliation has led to parallelism or low angle relationships of bedding and foliation planes. The structures described above define the first phase of deformation and metamorphism (D1). The main foliation is generally steeply dipping towards its western and eastern flanks and is flatter along its anticlinal culmination with the periclinal end plunging towards SSE (Fig. 2a and b1). The isoclinal folds (F1) have on average N–S oriented hinges and are generally aligned along this antiformal trend (Fig. 2b2), although some of these folds and the primary foliation were refolded and sheared by subsequent deformation.

The foliation fabric of the Taku Schist is expressed in thin sections by the preferred orientation of elongated muscovite, separated by ribbon quartz, forming spaced disjunctive cleavages that commonly form compositional banding (Fig. 5a). The main minerals observed are white mica, quartz and K-feldspar indicating a pelitic protolith containing quartz-rich layers, possibly tuffaceous sandstones that are still visible through the subsequent burial metamorphism. The initial burial flattening is associated with prograde metamorphism in amphibolitic facies, resulting in an overall

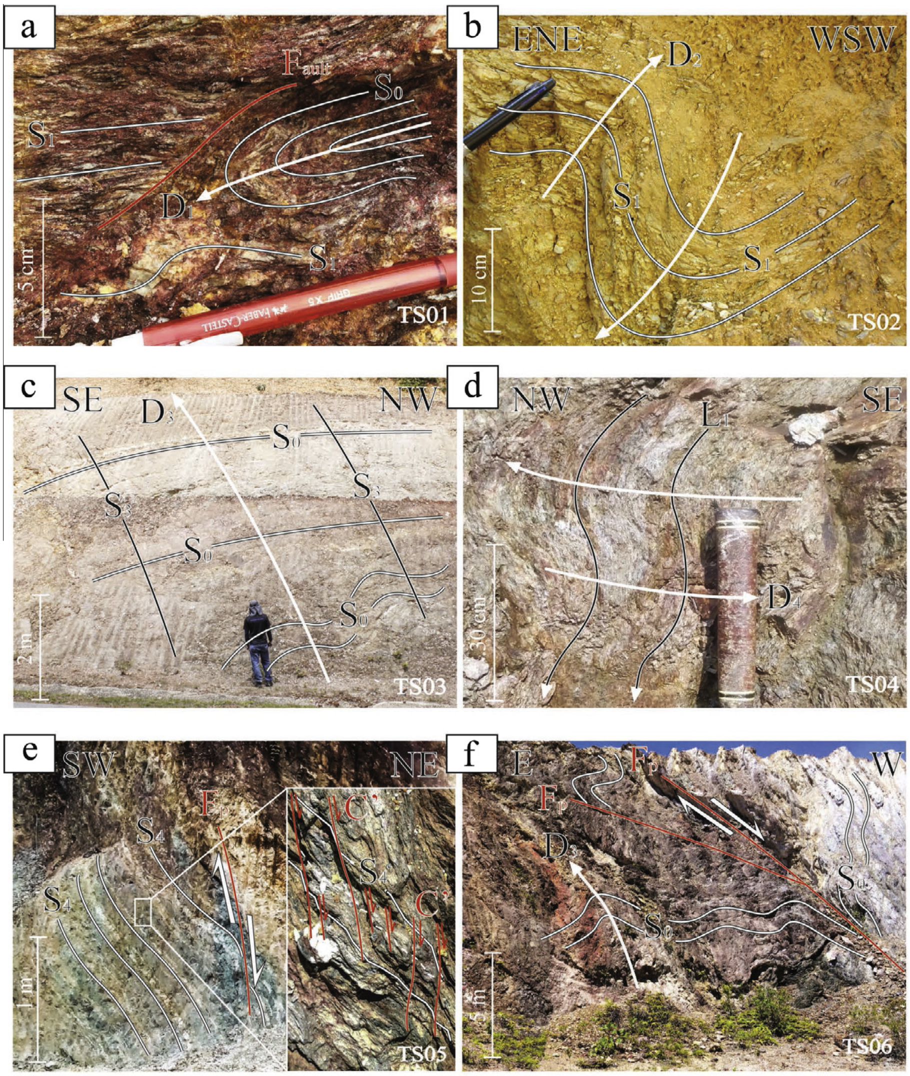

**Fig. 4.** Field kinematic examples, all locations are displayed in Fig. 2. (a) TS01 – Example of D1 structures in a quartz-muscovite-garnet schist containing intra-folial layers of an isoclinal fold adjacent to boudinaged marbles; footwall unit; (b) TS02 – D2, W-vergent asymmetrical fold, footwall unit; (c) TS03 – Part of a D3 steeply inclined symmetrical fold in the Gua Musang Formation that displays alternating thick carbonatic shales and thin red siltstones and a S3 axial plane cleavage, hanging-wall unit; (d) TS04 – Re-folded D2 stretching lineation (L2) by D4 folds with (sub-) horizontal axial planes, footwall unit; (e) TS05 – Outcrop of SE dipping mylonites within the Taku schist cut by late stage normal faults (Fp). Inset shows C–C′ relations documenting top-to-the-SE normal sense of shear. S4 is mylonitic foliation and equivalent to the C planes in the inset; C′ is shear band cleavage; footwall unit; the pertinent microstructure is displayed in Fig. 5c; (f) TS06 – sequence of normal faults (Fp) crosscutting metrescale open folds in Gua Musang Formation, hanging-wall unit.

mineral assemblage that consists of muscovite, biotite, garnet and K-feldspar. Numerous garnets (almandine) up to 5 mm in size contain an internal foliation defined by quartz inclusions that is not related to the external foliation in the matrix (Fig. 5a). This relationship indicates that garnet growth occurred during or slightly after the formation of the internal foliation, probably reflecting prograde metamorphic conditions, and prior to the formation of the external foliation. In thin sections, quartz rich domains are dynamically recrystallized by subgrain rotation and grain boundary migration recrystallization as indicated by amoeboid texture with high angle contacts to adjacent grains (Fig. 5b). The prograde mineral assemblage and quartz recrystallization indicate metamorphic conditions in the order of 500–550 °C.

In contrast, the adjacent parts of the Gua Musang Formation that were metamorphosed to sub-greenschist facies display a steeply dipping slaty cleavage sub-parallel to the original layering (Fig. 5f). This becomes clear in the light greyish carbonaceous to calcareous mudstones within the eastern part of the studied areas. Tight, symmetrical centimetre-scale isoclinal folds show axial plane cleavage (S1) almost parallel to the bedding planes (S0). These isoclinal folds and the pertinent cleavage were refolded by subsequent deformation phases. The cleavage is absent in the widespread rhyolite and volcaniclastic sediments observed along the eastern flank, as well as in the mudstone and shale exposures located more to the south. This suggests that these rocks were deposited after the main deformation. The rhyolites were subsequently deformed by an array of NNW–SSE oriented normal faults during later deformation.

In thin sections, these sub-greenschist facies rhyolites, volcaniclastics and shales contain a very fine-grained clastic matrix of quartz, K-feldspar and plagioclase, together with sericite and chlorite as the cleavage forming phases (compare Fig. 5a and f). Sediments along the SE flank of the antiform differ slightly, because they contain abundant sericite with strongly crenulated phyllitic cleavage and asymmetrical folds. These affect the original cleavage therefore, formed in a later deformation event.

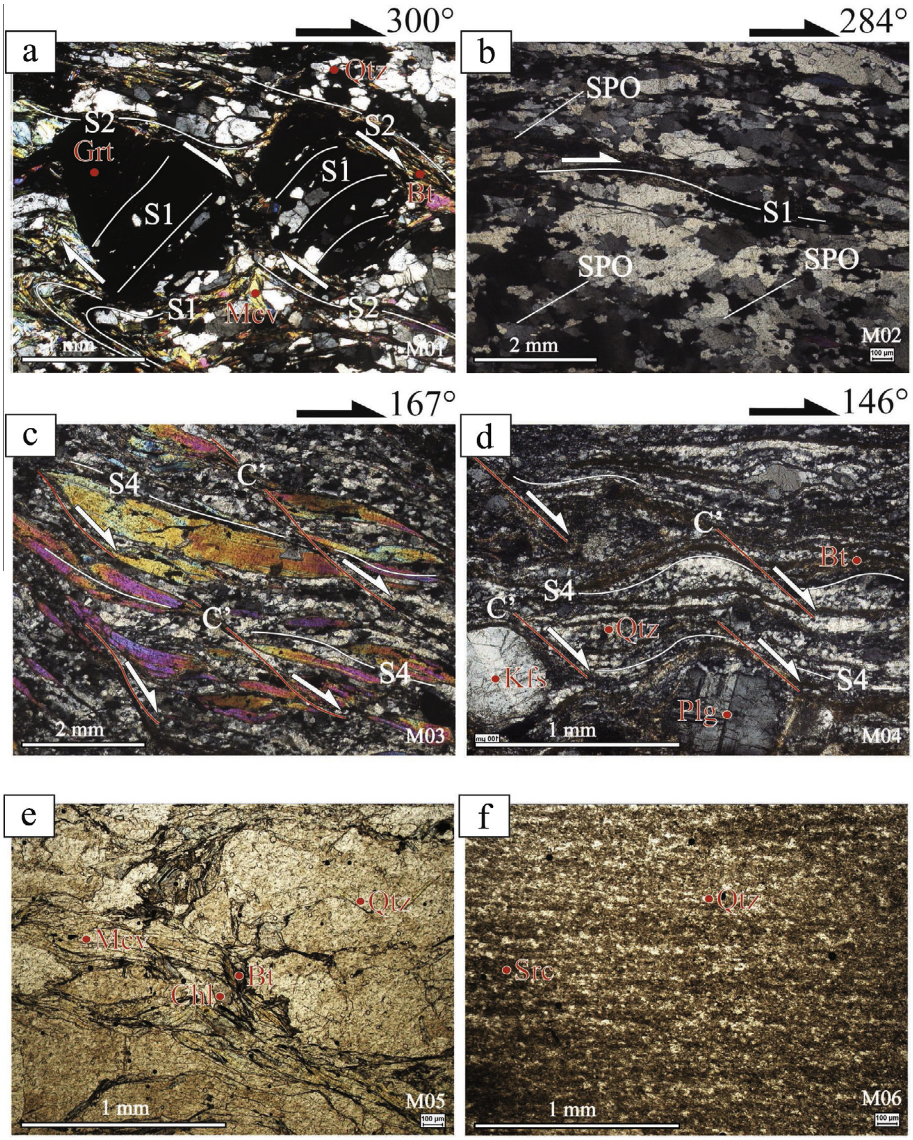

**Fig. 5.** Examples of microstructural observations in the footwall. All locations are displayed in Fig. 2. (a) M01 – compositional banding of preferentially aligned muscovite and ribbon quartz enclosing a garnet prophyroblast displaying straight internal inclusion. S2 is the axial plane foliation to a tightly folded S1. The kinematic shows top-to-the-300° sense of shear; (b) M02 – A quartz-rich schist displaying shape preferred orientation (SPO) of quartz grains between shear foliation (C), grain size reduction and undulose extinction. Recrystallization of quartz is predominantly by grain-boundary rotations. SPO indicates top-to-the-284° sense of shear; (c) M03 – Mylonitized quartz-muscovite schist displaying grain size reduction. Quartz is recrystallized by sub-grain rotation. Top-to-the-167° sense of shear is documented by C–C′ structures, bounding mica fish; for field relation see Fig. 4e; (d) M04 – Mylonitized leucogranite displaying feldspar prophyroclasts within a matrix of quartz recrystallized by sub-grain rotation. Shear band (C′) structure indicates top-to-the-146° sense of shear; footwall unit; (e) M05 – Coarse mineral fabrics containing muscovite and biotite transformed to chlorite within steep C′-shear band structure; (f) M06 – Fine grains matrix of sericite and quartz minerals defining a slaty cleavage; hanging-wall unit.

### *3.2. Top-to-the-SW to W directed shearing and asymmetrical folding (D2)*

The prograde metamorphism of the initial burial continued during a second stage of deformation (D2) characterized by top-to-the-SW shearing associated with flattening and asymmetrical folding. These structures are particularly well developed in the central part of the Taku Schist antiform and its western flank, including the flanking Gua Musang Formation. In the Taku Schist, a pervasive stretching lineation (L2) is observed, together with kinematic indicators such as shear bands, sigma-clasts and shapepreferred orientations indicating a dominantly top-to-the-W–SW sense of shear in both outcrops and thin sections (blue arrows, Figs. 2a, c and 5b). Layers of marble are commonly intercalated within the foliated layers, and are similarly affected by shearing with sigmoidal boudinage portraying asymmetrical deformation (Fig. 4a). Roughly one third of the observed structures show an opposite sense of shear, in particular observed along the eastern flank of the antiform. Field and microstructural observations indicate that such opposite senses of shear are the result of flattening (Fig. 2a and c). A common feature of D2 are south-plunging asymmetrical folds bounded by C′-planes striking E–W. These asymmetrical folds (F2) with steep axial planes and tight to open hinges (Fig. 2b3) are consistently W–SW-vergent (Fig. 4b). These folds often plunge along their strike perpendicular to the direction of the stretching lineation. Elongated bands of strongly aligned quartz-feldspathic schists of higher metamorphic facies when compared with rocks elsewehere in the Taku Schist characterize the mylonitic contact with the Kemahang granite in the north. In more detail, the granite was not affected by the D1 deformation event and its western part shows the same top-to-the-SW directed D2 shearing as the Taku Schist (known locally as the Tiang Schist). These observations demonstrate that the Kemahang granite is syn-kinematic to the D2 deformation event, or its emplacement could have slightly predated this deformation in such a way that the pluton still retained a high temperature at the moment of deformation. This is in agreement with the Late Triassic U-Pb age of the Kemahang granite (Ng et al., 2015). A number of other minor granitic intrusions were observed throughout the Taku Schist (Figs. 2a and 4e), and larger ones are found near the southern contact with the overlying Gua Musang sediments. These are made up of biotite-granite injections into the original foliation. In contrast to the Kemahang granite, these biotite-granites were sheared within the mylonitic foliation at a later time during the subsequent top-SE D4 deformation event (described below).

The D2 deformation event can be observed in thin sections by isoclinal folding of S1, the rotation of earlier garnet (almandine) enveloped within biotite strain shadows forming prophyroblast structures (Fig. 5a), and the formation of steep C′-shear bands indicating top-to-the WNW sense of shear. The spread of shear directions (top-to-the SW-WNW) is a reflection of younger deformation phases rotating earlier formed structures. In other cases the S1 foliation fabric is still preserved. The sheet silicate forming the S–C shear bands is mostly muscovite with minor biotite minerals forming mica fishes that confirm an overall shear direction of top-to-the-W–SW. Similar kinematics is observed within quartz-rich domains, where well developed sub-grains display a shapepreferred orientation oblique to penetrative foliation fabric (Fig. 5b). In metapelitic rocks, the external foliation wraps around the prophyroblasts, which contain an older foliation. Such prophyroblasts entail earlier formed garnet (almandine), tourmaline and staurolite, the former commonly containing straight or spiral inclusions parallel to the external foliation. The latter indicates shearing during burial and prograde metamorphism. However, the internal foliation is asymmetric with respect to the external foliation in overprinted fabrics, suggesting a younger deformational event (Fig. 5a). Similar kinematics are represented within the amphibolitic schists by C′ shear bands within an association of amphiboles and chlorite enveloping clinozoisite prophyroblasts. This fabric is generally crosscut by brittle faults or discrete, steeply dipping shear bands with opposing shear sense. This later shearing is associated with chlorite formation within sheet silicates and post-dates the D2 deformation event (see below).

### 3.3. Upright folding (D3)

The third stage of deformation (D3) is well observed in the Gua Musang Formation, along the southern and eastern flanks of the Taku antiform. This deformation stage is represented by steeply inclined to upright folds (F3) with an average NNW–SSE orientation of their hinges (Fig. 2b4). These folds are well developed in outcrops containing meta-pelitic rocks. The wavelength of these folds is variable, but may reach ∼100 m and display a steeply dipping axial plane cleavage (S3, Fig. 4c). Along the same eastern flank, these folds have a N–S strike and are locally visible as smaller symmetrical buckle folds superposed over larger symmetrical antiforms or synforms. These were truncated by subsequent normal faulting associated with folds that have horizontal to low-dipping axial planes (Fig. 4f). The upright symmetrical folds are also observed in the Taku Schist, but are less common and are crosscut or otherwise affected by subsequent deformation. Although folded subsequently (Fig. 2b4), this event is likely to be responsible for the initial formation of the NNW–SSE striking Taku antiform with its E and W dipping flanks (Fig. 2a). Overall, the eastern limb of the antiform is steeper, suggesting a slight E-ward vergence. These large-scale gentle folds suggest that the symmetrical horizontal contraction is not associated with significant shearing.

### 3.4. Top-to-the-SE directed extension (D4)

The last stage of deformation (D4) documented by field and thin section observations is a pervasive top-to-the-SE shearing in the Taku Schist and widespread normal faulting in the overlying Gua Musang Formation. The contact between them is a mylonitic shear zone formed during this deformation event that is particularly visible in the southern part of the Taku antiform. The deformation in the Taku Schist is associated with the development of a pervasive stretching lineation (L4) observed in the entire unit with consistent top-to-the-SE sense of shear (red arrows, Fig. 2a and c). In the center and N–NE part of the unit, lineations plunge locally in the opposite direction. The stretching lineations are generally shallow plunging and shear senses parallel to the lineations are fairly constant (Fig. 2a). The rocks near the SE margin of the Taku Schist include strongly mylonitized leucogranites and mica schists, suggesting that intensely localized deformation post-dates the injection of granitic bodies (Fig. 4e). The top-SE C–C′ structures are overprinted by brittle normal faults, which also portray SE directed stretching suggesting that D4 structures document deformation during cooling of the Taku Schist. The shearing is associated with vertical flattening of an already steeply inclined foliation, observed by the formation of folds with low-angle, NW–SE trending axial planes, consistent with collapse folds (Faure et al., 1996; Froitzheim, 1992; Froitzheim et al., 1997). These structures fold the earlier formed stretching lineations with top-to-the-W–SW sense of shear (Fig. 4d). The Gua Musang Formation in the hanging-wall of the major top-SE shear zone displays a strongly folded and crenulated fabric often associated with kink folds in grayish phyllite. These consistently asymmetrical crenulations might relate to the same top-to-the-SE shearing. Often normal faults with a similar roughly NW–SE oriented extensional direction crosscut both the Taku Schist and the Gua Musang Formation (Fig. 4e and f). In all observed locations the Taku Schist, together with the Kemahang granite is separated by the top-SE mylonitic shear zone and the associated normal faults from the Gua Musang Formation. The widespread rhyolite volcaniclastics observed along the eastern flank of the Taku Schist are deformed by an array of NW–SE oriented normal faults. The degree of deformation gradually increases in the direction of the Taku Schist. There is a transition from brittle normal faulting at far distances to S–C shear bands in its immediate proximity, which is complemented by an increase of cleavage spacing in the phyllites, characterizing a higher metamorphic grade.

The exception to the above described deformation is a major N–S oriented fault zone at eastern margin of the Taku Schist near the Temangan mine (Fig. 2a). This dextral strike-slip fault accommodates the displacement of the weakly metamorphosed slates of the Gua Musang formation towards the SE relative to the Taku Schist. In or near the mine, the staurolite-bearing schists are separated by a 10 m thick cataclastic shear zone from the sub-greenschist facies mudstones. This steep cataclastic fault zone can otherwise reach 50 m in thickness and is often observed as sequence of fault arrays.

In thin section, the deformation in the Taku Schist (in particular along its southern boundary) shows mylonitization within mica schists (Fig. 5c) and meta-granites (Fig. 5d), indicated by a strong reduction in grain-size of quartz. The quartz is dynamically recrystallized and forms the matrix surrounding large white micas (Fig. 5c), which characterize a mylonitic foliation. Mica fish together with late stage C′-shear bands, which define a shear band cleavage, allows the determination of top-to-the-SE sense of shear (Fig. 5c). The analysis of these thin sections suggests that shearing took place during decreasing temperature and thus retrograde metamorphism, as indicated by the growth of chlorite along C′ structures. In all cases the shear sense is top-to-the-SE. Sub-grain rotation is the main mechanism of recrystallization within quartz aggregates (Fig. 5c and d), which contrasts with the earlier burial metamorphism by strongly preferred oblique C-axis of fine quartz sub-grains. The shearing and retrograde metamorphism developed without any newly formed minerals, the earlier formed garnet (almandine) and tourmaline being enveloped within a shearing fabric with the same top-to-the-SE shear sense movement. The retrograde metamorphism is associated with pervasive brittle–ductile shearing and widespread sericitization of K-feldspar and garnet (almandine) minerals in addition to replacement of biotite by chlorite (Fig. 5e). Thin sections indicate an increase of strain intensity within the ductile deformation towards the SE margin of Taku Schist, where the shearing and mylonitization has the highest intensity and decreases N-wards to more brittle microstructures. In other samples, these microstructures include discrete steep shear bands that continue as brittle faults and drag folded sheet silicates indicating similar top-to-the-SE sense of shear. In the Gua Musang hanging-wall, thin sections indicate that the foliation fabric is defined by finely aligned muscovite/sericite at a very low degree of metamorphism (Fig. 5f).

## 4. A tectonic model for the Taku Schist and its overlying sediments in a regional context

The convergence between the Sibumasu continental unit and the Sukhothai Arc that ultimately led to the final stages of Permo–Triassic subduction and collision in Peninsular Malaysia (Arboit et al., 2015, 2016; Metcalfe, 2013; Morley et al., 2013; Sone and Metcalfe, 2008) is documented in our studied area by the first two stages of contraction observed in the Taku Schist and the surrounding Gua Musang sediments (Fig. 7a and b). In both units, this resulted in the formation of the primary metamorphic foliation and isoclinal folding, followed by top-to-the-W–SW shearing and flattening, associated with asymmetrical folding. These tectonic events were responsible for the burial metamorphism up to amphibolite facies recorded in the Taku Schist. Notable is the presence of the relatively high-pressure $Al_2Si0_5$ polymorph, kyanite (MacDonald, 1968), which marks the contact between two major units in the nappe stack sequence. The synkinematic character of the Kemahang granite demonstrates that the second stage of top-to-the-W–SW shearing took place near the Middle/Late Triassic (~220 Ma) transition, i.e. during collision, significantly pre-dating its exhumation (Fig. 7b). This means that the onset of metamorphic burial and isoclinal folding is older, having likely commenced during the late(st) Paleozoic onset of continental subduction (Metcalfe, 2000) and lasting until Early Triassic time.

The third stage of open symmetrical folding is rather difficult to date, but must post-date the Middle Triassic and pre-date the late Cretaceous onset of subsequent extension. Kinematic studies in other orogenic areas have shown that nappe stack shearing and metamorphism during subduction and collision is often post-dated by a period of more symmetrical contraction during the late stages of collision. This takes place when subduction zones are locked due to the entrance of buoyant continental material into the subduction systems and is recorded by the onset of more symmetrical out-of sequence contraction (Mattauer et al., 1981; Ziegler et al., 1995). This is likely to be the case in the studied area. Locking of subduction and symmetrical contraction in Late Triassic times was coeval with the intrusion of large quantities of Western Belt granites (Fig. 7b). An alternative hypothesis is that the open folding is responsible for the widespread tilting with similarly steeply plunging hinges that affects the Jurassic and Cretaceous

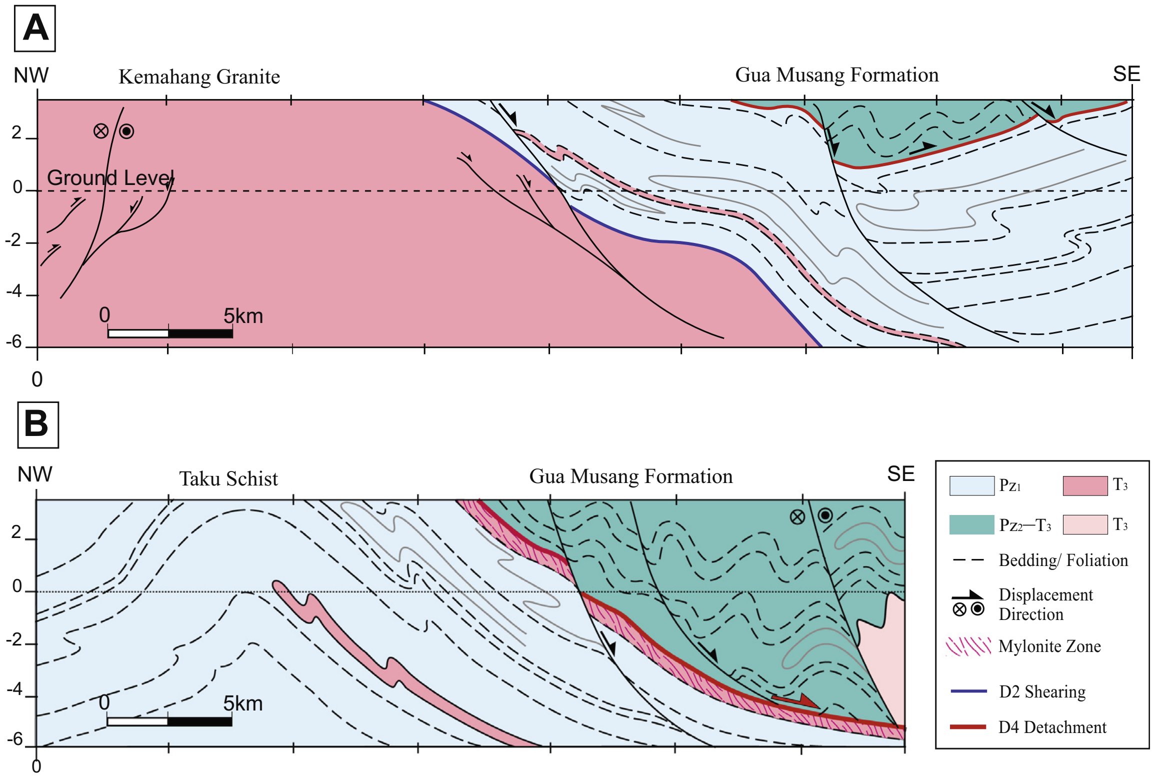

**Fig. 6.** Structural and geological cross-section across the Taku Schist and its hanging-wall derived from field kinematic mapping. The Taku Schist body and intruded Kemahang granite are separated by an extensional detachment from the Gua Musang Formation in the hanging-wall. In the Taku Schist footwall, the expression of shearing changes from brittle-faults to mylonitic detachment towards SSE margin. The steeply inclined symmetrical folds in the overlying Gua Musang Formation are crosscut by normal and dextral strike slip faults, in contact with the Boundary Range Granite. Section B follows section A to the right. The horizontal and vertical scales are 80 km and 10 km respectively.

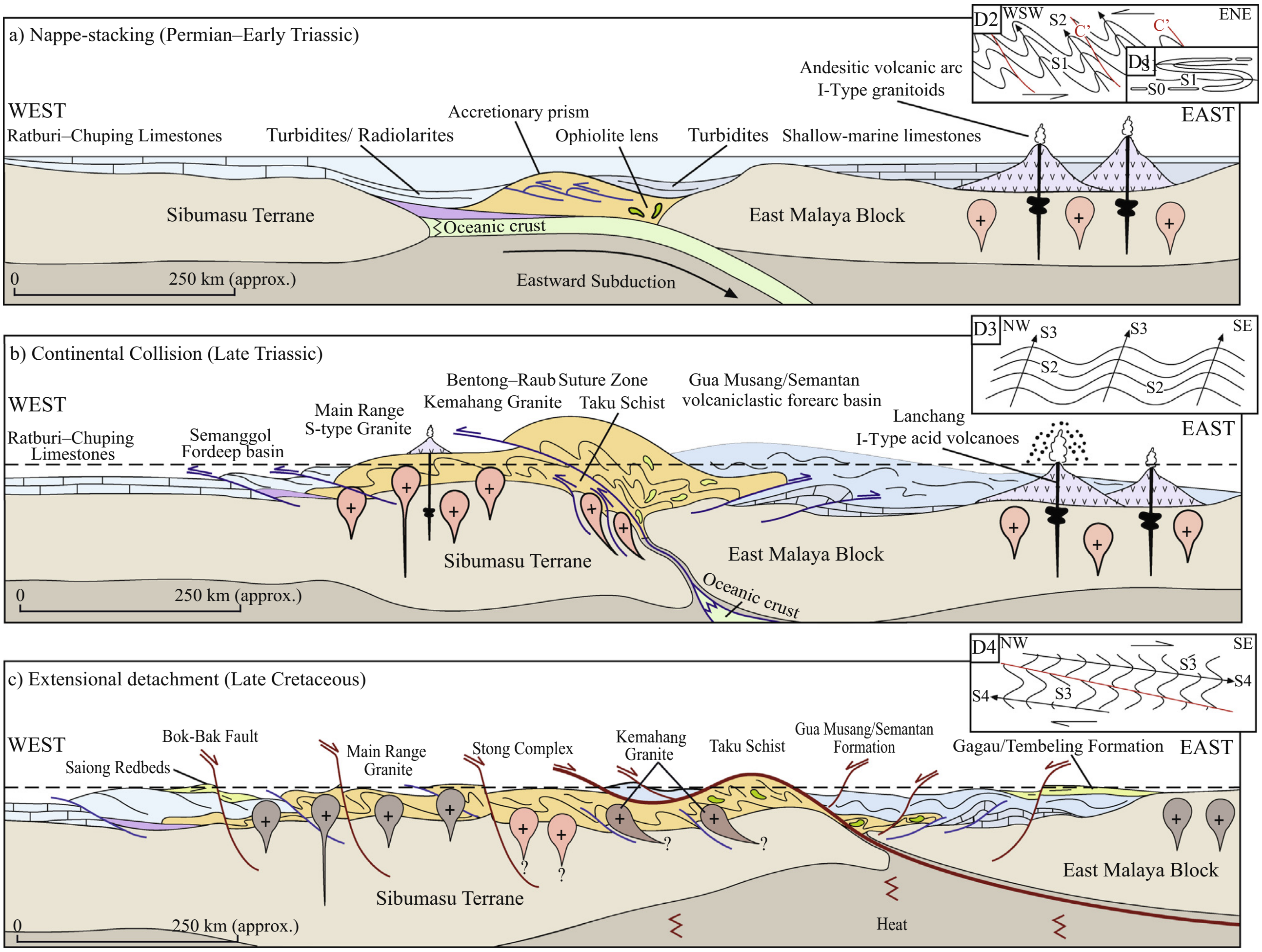

**Fig. 7.** Sketch model of the evolution of the Taku Schist in the context of the subduction and collision between Sibumasu and East Malaya Block/Sukhothai Arc (modified and adapted following the results of the present study from an original cartoon interpretation of Metcalfe, 2000); (a) The highly deformed deep water accretionary wedge was covered by the Gua Musang/Semantan forearc sediments during the Permian–Early Triassic subduction; (b) Late Triassic collision led to continental nappe stacking, accompanied by burial and metamorphism of the Taku Schist to amphibolite facies. Contraction and metamorphism is recorded in the succession from isoclinal folding, asymmetrical folding and shearing, and upright folding; (c) The subsequent Late Cretaceous–Paleogene exhumation of the Taku Schist by a detachment that formed a core-complex type of extensional dome. Isostatic rebound has exhumed the dome, while its flanks remained buried beneath the hanging-wall accretionary wedge and forearc sediments.

sediments of the Central Belt (Shuib, 2000b). Considering that the extensional structures crosscut the open folding, the age of this deformational event should be restricted to Jurassic–Early Cretaceous, a period in which deformation is largely unconstrained in Peninsular Malaysia.

Inferences from reliable field and microstructural data generated by this study lead us to the conclusion that the separation between the Taku Schist and the Gua Musang Formation is a large-scale detachment, herewith named the Taku Detachment. This structure displays a wide array of structures from high-temperature mylonites to brittle structures formed during top-to-the-SE shearing. The earlier ductile mylonitic detachment is crosscut by normal faults, formed in a later stage during exhumation and is also crosscut by the late stage dextral strike-slip faults with a top-to-the-SE sense of shear observed at the E margin of the exhumed footwall, which is parallel to the sense of shear (Fig. 2a). These late normal faults have also tilted and steepened the primary foliation. Therefore, we explain the contact between these two formations as a detachment. This creates a significant tectonic omission in the order of 300 °C, representing ~12–15 km of differential vertical exhumation during extension given an average geothermal gradient (Figs. 2a and 7c). This top-to-the-SE extension was associated with the formation of collapse folds with horizontal axial planes that refolded an inherited steep foliation and with the formation of normal faults crosscutting the detachments and its Gua Musang hanging-wall. Evidence for strain during deformation shows a decrease in the Taku Schist footwall from a pervasive mylonitisation in the SSE to more discrete shear zones and brittle structures in the NNW. This shows the typical asymmetry of a detachment: while the NNW areas were exhumed from shallower levels, the SSE part is exhumed from depths of 12–15 km and is the site of maximum tectonic omission. The top-to-the-SE detachment resulted in the exhumation of the Taku Schist and was accompanied by retrograde metamorphism. This is generally observed by the new formation of lower greenschist facies minerals, such as sericite and chlorite, in particular near the SE margin (Fig. 5e). This retrograde metamorphism was also responsible for the microstructures observed, such as grain-boundary rotation and bulging, and the transition into the brittle domain where late normal faults crosscut the ductile fabric (Figs. 4e and 5c, d).

## 5. Discussion and implications for the tectonics of Peninsular Malaysia

The top-to-the-SE detachment and the dextral strike-slip fault crosscutting the eastern parts of the Taku Schist have the same sense of shear. The most likely interpretation is that these two structures are coeval, the dextral faulting accommodating the top-SE movement of the hanging-wall during extension along the lateral ENE margin of the footwall, as similarly observed in many other extensional domes (e.g. Matenco and Schmid, 1999). The strike-slip structure cannot be the expression of the Lebir fault system because of its opposite (dextral) kinematics. Our study shows that the NNW Kemahang granite lies in the footwall of the Taku detachment. This Triassic granite and the hosting Taku/Tiang Schist were intruded by the Late Cretaceous Stong granite. These rocks are exposed from beneath the Gua Musang formation in a similar structural setting as the Taku Schist (Fig. 1b). It is very likely that the high temperature Tiang Schist intruded by the Stong magmatic rocks (Singh et al., 1984) is located in the footwall of a detachment that creates a similar antiformal dome geometry to the Taku Schist one. In fact, we suggest that the same Taku detachment is responsible for both domes, expressed in map view by the changing strike direction of the structure from ~NNW–SSE in the east to ~E–W and ultimately back to ~NNW–SSE in the west (Fig. 1b). Such geometry would indicate a top-to-the-SE detachment folded coevally with subsequent ~E–W contraction. This is in agreement with the observation of steeply dipping Jurassic–Cretaceous continental sediments, interpreted as an effect of regional ~WSW–ENE contraction/transpression (Shuib, 2000b; Tjia, 1996). It would also explain the steep inclinations of foliation planes observed locally in the footwall of the Taku Schist detachment (Fig. 2b1), which are in contrast with the usual flat-lying foliations of a core-complex type structure. Alternatively, the overall regional antiformal–synformal structures and the deformation of the Jurassic and Cretaceous sediments could represent the effect of a later transpressional event whose primary expression would be the Lebir fault system (Fig. 1b; Shuib, 2009; Tjia, 1996; Zaiton, 2002). This system was inferred regionally by the interpretation of the gravity anomaly as a westward transition from thick to thin crust (Ryall, 1982). This fault system has not been yet observed in the field. It is more likely that the difference in crustal thickness is the expression of thinning that affected the Central Belt during the same extension that exhumed the Taku Schist.

In agreement with previous research, our study demonstrates that the original protolith of the Taku Schist was composed of a dominant pelitic succession intercalated locally with turbidites, mafic material and less important acidic volcaniclastics. We interpret the metamorphic facies of the Taku Schist as a high grade equivalent of the non-metamorphic or sub-greenschist facies sediments of the Bentong–Raub suture zone (e.g. Hutchison, 1975; Metcalfe, 2000; Sone and Metcalfe, 2008). They consist also of fairly similar lithologies and deformation structures when compared with the Tiang Schist at the northern extension of Bentong–Raub suture zone (Hutchison, 1973b). When correlated, the resulting structure would be a far simpler one that follows the anti cline–syncline–anticline Stong–Taku structure (Fig. 1b). This supports the conclusion that the Taku Schist is the deeply buried equivalent of the rocks of the Bentong–Raub suture zone, which were subsequently exhumed along the detachment by the late extensional detachment (Fig. 7c).

In the absence of low-temperature thermochronological data in the Taku Schist, a number of possible interpretations of the timing of its exhumation remain speculative in our study. Cottam et al. (2013) published low-temperature thermochronological data from the Central and Eastern belts of Peninsular Malaysia, which showed an enhanced period of Late Cretaceous–Eocene exhumation in the hanging-wall of the Taku detachment. In the absence of other relevant kinematic data onshore Peninsular Malaysia, this exhumation was interpreted to be an effect of Late Cretaceous, possibly also Early Palaeogene subduction along the southern Sundaland margin followed by Eocene contraction due to resumption of the same subduction system (Cottam et al., 2013). The only contractional structures post-dating the Triassic nappe-stacking detected in our study are the open symmetrical folds. However, this deformation is rather modest and cannot explain the values of exhumation required by thermochronology in the hanging-wall of the Taku detachment. The Late Cretaceous–Eocene regional exhumation was more likely the result of the extension speculatively inferred by other studies (Morley, 2012), which might have happened due to the Taku detachment or similar extensional structures that have not been studied in the Peninsular Malaysia yet. Further studies analyzing these uncertainties may result in novel geodynamic scenarios or support other existing ones among the multitude available in the SE Asia (e.g., Cottam et al., 2013; Pubellier and Morley, 2014). In all these tectonic scenarios, the age of extension must be Late Cretaceous–Eocene or younger to cause the exhumation of the hanging-wall and the observed tectonic omission.

The age of the detachment is critical for understanding the coupling between footwall exhumation and the potential formation of supra-detachment extensional basins (e.g. Friedmann and Burbank, 1995). Such basins are often shallow and filled only with thin continental sediments, such as in the Basin and Range province (e.g. Wernicke, 1992). The Jurassic and/or Cretaceous continental sedimentation of the Central Belt could possibly be associated with such an extensional basin. Alternatively, the synkinematic sedimentation could lie beneath, or at the base of the large extensional basins observed offshore Malaysia (e.g. the adjacent Malay Basin, Mansor et al., 2014).

The SE direction of tectonic transport during extension is almost parallel to the strike of the inherited orogenic structure and perpendicular to the contraction/transpression affecting the Jurassic and Cretaceous continental sediments. This may support the alternative explanation of an orogen-parallel extensional dome (the type 2 extensional dome of Brun and Vandendriessche, 1994). Such domes are aligned parallel to main thrust front developed during crustal thickening and form due to coeval orogen perpendicular contraction and orogen parallel extension. One geodynamic process commonly inferred for their formation is continental escape, as interpreted for instance in the case of the Tauern or Danubian windows of the Alps and Carpathians (Matenco and Schmid, 1999; Ratschbacher et al., 1991; Schmid et al., 2013). In such a situation, the Taku top-to-the-SE extensional detachment would be associated with coeval ~ENE–WSW oriented contraction. Such an interpretation would be compatible for the post-Late Cretaceous break-up of Sundaland, because the S to SE-ward directed roll-back was accompanied by back-arc extension and advancing subduction along the western Sunda margin (Hall, 2011; Hall et al., 2011). Further understanding of such a scenario would require kinematic correlations at the scale of the entire Peninsular Malaysia.

## 6. Conclusions

We have performed a kinematic study based on fieldwork and microstructural observations in the Taku Schist and the surrounding Gua Musang sediments of northern Peninsular Malaysia. These form part of the Indosinian orogenic and post-orogenic structure of SE Asia that resulted from the subduction and collision of the Sibumasu continental unit and the Sukhothai Arc during Permo–Triassic times (Fontaine and Workman, 1978; Ferrari et al., 2008; Metcalfe, 2002, 2005, 2011; Morley et al., 2013; Ridd, 2012). This kinematic study has resulted in the definition of four successive stages of deformation, three contractional events being followed by the formation of the large-scale Taku extensional detachment that differentially exhumed a vertical sequence on the order of 12–15 km.

The first kinematic phase of deformation related to shortening and regional metamorphic burial observed in our study is in general agreement with previous results, which suggests that the Taku Schists contain an original Early Paleozoic protolith with mafic intercalations metamorphosed to amphibolite facies during the Indosinian orogeny (Aw, 1974; Hutchison, 1973b; Khoo and Lim, 1983; Lee et al., 2004; Shuib, 2009). By establishing that the Triassic Kemahang granite is a syn-kinematic intrusion, we are able to be more precise on the timing of these contractional events. A first stage of burial (D1) and formation of the primary metamorphic foliation was followed near the boundary between Middle and Late Triassic by top-to-the-W–SW shearing and asymmetrical folding with a similar vergence (D2). Although the open folding with steeply inclined axial planes (D3) has been previously observed at the scale of the entire peninsula (Shuib, 2000b, 2009), we infer that this is event postdates the main Early to earliest Late Triassic shortening and pre-dates the Late Cretaceous onset of extension. This event is likely to be the expression of a Late Triassic shortening coeval with the locking of subduction during late stages of contraction, out of sequence deformation and large scale S-type magmatism. Our observations imply that the Taku Schist is the metamorphosed equivalent of the Bentong–Raub suture zone.

The interpretation of an extensional detachment is novel and has major consequences for the post-orogenic architecture of northern Peninsular Malaysia. It demonstrates that Peninsular Malaysia was affected by post-orogenic extension, expressed in the formation of major detachments, reactivating inherited subduction zones or nappe contacts, such as is widely observed in other SE Asia regions, such as Thailand and Indonesia (e.g. Camplin and Hall, 2014; Morley, 2012; Pubellier and Morley, 2014). The Taku Detachment has probably reactivated a former thrust plane and exhumed the previously deeply buried and metamorphosed rocks close to the suture zone in a similar fashion with what is observed in post-orogenic extension in the Mediterranean system (such as the Aegean, Apennines, Betics–Rif and Dinarides, Brun and Faccenna, 2008; Jolivet and Faccenna, 2000; van Gelder et al., 2015; Vissers, 2012).

The Taku detachment was active during a period of extension that took place on a regional scale in SE Asia (Morley, 2012). It may be partly associated with Jurassic and Cretaceous sedimentation in Peninsular Malaysia or otherwise in the large basins observed in its eastern offshore. Alternatively, the top-SE directed extensional detachment may possibly have formed as result of top-to-the-(S)SE orogen parallel extension associated with ~ENE–WSW oriented contraction during renewed subduction along western Sunda margin (Hall et al., 2011; Morley, 2012). However, such inferences remain speculative in the absence of low-temperature thermochronological data in the Taku Schist and other parts of the Peninsular Malaysia.

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