The Ukay Perdana Shear Zone in Kuala Lumpur: a crustal-scale marker of early Jurassic orogenic deformation in Peninsular Malaysia

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Abstract: A 'top-to-the-east' ultramylonite zone is identified in north-eastern Kuala Lumpur and named here as the 'Ukay Perdana Shear Zone (UPSZ). The UPSZ is at least 250–300 m thick, east-verging, and superimposed on the later stages of assembly of the *c.* 200 Ma S-type 'Western Belt' granite plutons generated by crustal thickening and assigned to the Main Range Granite Province. Younger bodies of S-type granitic rocks cut the shear zone. These intensely deformed quartzofeldspathic rocks contain distinctive relict porphyroclasts of perthitic K-feldspar (microcline), oligoclase and quartz, entrained within the ultramylonitic fabric. Migrating sub-grain boundaries in quartz indicate deformation occurred under moderate to high temperature conditions during ductile deformation (*c.* 500–600°C); undulose extinction suggests down-temperature evolution of the deformation history. This deformation event implies that the final stages of collisional interaction between Sibumasu and the Sukhothai Arc would have involved now east-directed (080°N, then generally northward) over-thrusting of the leading edge of Sibumasu onto the Sukhothai Arc/Indochina-East Malaya margin after 198 ±2 Ma. Kenny Hill Formation strata in Kuala Lumpur preserve widespread evidence of a dominant phase of E- or ENE-verging, upward-facing fabrics and folds; that deformation is judged to be a hanging wall response to deformation in the UPSZ. This early-Mesozoic structural framework is significant during assembly of the Peninsular Malaysia region of Sundaland; evidence form Kuala Lumpur is combined with new published Singapore data. Dextral strike-slip tectonics is superimposed on this collisional framework in the later Mesozoic and Cenozoic; subsurface development across Peninsular Malaysia, and in Kuala Lumpur and Singapore in particular, should account for deformation structures linked with this expanded record of Mesozoic tectonics.

Introduction

In this paper we report discovery of a high temperature ductile shear zone in the Ampang Jaya district of Kuala Lumpur – the Ukay Perdana Shear Zone (Locn. 1, Fig. 1) – that comprises a minimum observed thickness of *c*. 250 m of ultramylonitic granite, the protolith for which was elements of local Main Range Province S-type granite plutons. The sense of shear is top-to-the-east. Metasedimentary successions that comprise parts of the geology of Kuala Lumpur (Jabatan Mineral dan Geosains Malaysia, 2011) are argued to lie in the hanging wall of this shear zone and to record patterns of brittle and ductile deformation consistent with that setting. Locations cited in this paper are based upon the GDM 2000 MRSO Peninsular Malaysia grid.

We relate this large-scale shear zone to the deformation fabrics that are widely developed elsewhere in the S-type granite plutons of the Kuala Lumpur area, and discuss that east-vergent deformation in terms of the regional-scale tectonics that accompanied the final collision and amalgamation of Sibumasu and the Sukhothai Arc. Field relationships are interpreted as indicating that this deformation must have occurred in the earliest Jurassic *c*. 200 Ma, overlapping the final stages of granite emplacement; precise dating of the deformation fabrics remains a priority.

The Jurong Group and Sentosa Group strata of Singapore (Dodd *et al.*, 2019) record fold and thrust deformation (Leslie *et al.*, 2019) and are argued below to record deformation in the regional-scale footwall of the Ukay Perdana Shear Zone. These patterns of east (or north-east) vergent tectonic structures are argued to have constrained the final consolidation of Sibumasu and the Sukhothai Arc (in the early Jurassic), and followed on from the preceding

westerly-directed accretionary tectonics that accompanied subduction of Palaeo-Tethys. Consolidation preceded the widespread development of dextral strike-slip faulting in Peninsular Malaysia and which greatly affected the geology of Kuala Lumpur (Fig. 1), and Singapore (Hutchison and Tan, 2009; Leslie *et al.*, 2019). The wider regional effects of this deformation should be the subject of further research.

Regional geological setting

Southeast Asia is made up of a collage of continental blocks and volcanic arc terranes welded together along suture zones marking the sites of destroyed Tethyan ocean basins (*cf.* Metcalfe, 2017; Morley, 2018). The regional-scale geology of Peninsular Malaysia, and of Singapore, can be described in terms of three approximately N–S trending tectono-stratigraphical elements, namely the *Western, Central and Eastern belts* (Fig. 2; *cf.* Metcalfe, 2013). The Bentong–Raub Suture Zone (BRSZ) forms the collisional boundary between the Western Belt (essentially the Sibumasu continental block, *cf.* Metcalfe, 2013) and the Central and Eastern belts that contain the (meta)sedimentary and magmatic rocks making up the Sukhothai Arc (*cf.* Ng *et al.* 2015a; Gillespie *et al.*, 2019).

Three N–S-trending granitoid provinces are recognised in the wider region (e.g. Cobbing *et al.*, 1986; Schwartz *et al.*, 1995; Hutchison, 2007; *cf.* Fig. 2); a wide-ranging, and sometimes overlapping, nomenclature has developed in the literature over time. In essence, the *Eastern Province* is characterised by I-type granitoids of Cisuralian (early Permian) to Upper Triassic age (e.g. Liew and McCulloch, 1985; Yong *et al.*, 2004; Ghani, 2009; Searle *et al.*, 2012; Ng *et al.*, 2015 a,b). Gillespie *et al.* (2019) have demonstrated that the I-type granitic plutons that make up the Bukit Timah Centre in Singapore share many of the characteristics of the Eastern Province intrusions. A similar lithological range (gabbroic to granitic rocks) show

comparable textures (including examples of the 'primary' and 'secondary' texture variants described by Cobbing *et al.*, 1986), the same granitoid typology ('I-type'), and a similar age range (based on new U-Pb zircon ages). These characteristics leave little doubt that the Bukit Timah Centre is part of the 'eastern belt' of the Eastern Province (*cf.* Fig. 2), providing further support for the widely accepted model that Eastern Province granitoids formed as Palaeo-Tethys Ocean crust descended beneath the Indochina–East Malaya block.

The *Main Range (or Central) Granite Province* extends from west Thailand through west Malaysia and into east Indonesia (Fig. 2). In Peninsular Malaysia, numerous plutons of tin-bearing, peraluminous S-type granites comprise batholiths of Upper Triassic to earliest Lower Jurassic age (e.g. Liew and McCulloch, 1985; Cobbing *et al.*, 1986; Ghani, 2009; Searle *et al.*, 2012; Ghani *et al.*, 2013a; Ng *et al.*, 2015a,b). Main Range Granite Province plutons in Peninsular Malaysia are found in the tectono-stratigraphical Western Belt and in the BRSZ (Fig. 2) and have been referred to generally as 'Western Belt Granites' (e.g. Qalam *et al.*, 2019). The *Western Province*, in east Myanmar and southwest Thailand, consists of both I- and S-type granitoids of Upper Triassic to Cenozoic age (e.g. Ghani, 2000, 2009; Searle *et al.*, 2012; Gardiner *et al.*, 2017).

Cobbing *et al.* (1986) originally proposed that the Eastern Province granitoids were Cordilleran I-type granites formed above an east-dipping subduction zone now expressed in the accretionary sequences found in the BRSZ, while the Malaysian Main Range province granitoids were S-type granites, largely emplaced into Sibumasu to the west of the suture (*cf.* Fig. 2). A two-subduction-zone model has since been proposed to explain the variations in age and typology of the three granitoid provinces (Searle *et al.*, 2012; Ng *et al.*, 2015b; Metcalfe, 2017). In this model, the Eastern Province granitoids formed within the Sukhothai Arc, until subduction ceased in the Middle Triassic when Sibumasu and Indochina–East Malaya began to interact and dock. The voluminous Main Range Province granitoids formed within Sibumasu

in the Upper Triassic and earliest Lower Jurassic through orogenic crustal thickening (Searle *et al.*, 2012) and/or a thermal boost from upwelling asthenosphere as the remaining Palaeo-Tethys crust foundered (i.e. slab breakoff; *cf.* Metcalfe, 2017). At a later stage, the Western Province granitoids formed above a new north-dipping subduction zone that was initiated beneath the then southern margin of Sibumasu in the Middle Triassic, along which Meso-Tethys Ocean crust was being consumed (Searle *et al.*, 2012).

A variant of that tectonic model has been proposed by Oliver *et al.* (2014) who argued that subduction of Palaeo-Tethys oceanic crust beneath the Sukhothai Arc concluded with the then oceanward-facing margin of the arc system being thrust beneath the leading edge of the approaching Sibumasu plate. Underthrusting resulted in partial melting of thickened crust in Sibumasu and intrusion of S-type tin granites along the Main Ranges of western Malaysia. Ng *et al.* (2015b) however discount this scenario on various geochemical and petrogenetic grounds, concluding that no structural evidence had been reported for the westward underthrusting claimed by Oliver *et al.* (2014). The overthrust tectonics reported here and associated with the Ukay Perdana Shear Zone shed light on that debate.

The geology of Kuala Lumpur and Singapore

Kuala Lumpur and Singapore lie on opposite sides of the BRSZ, the locus in Peninsular Malaysia of amalgamation and consolidation of the Sibumasu Block with the southern part of the Sukhothai Arc and the Indochina-East Malaya Block. Singapore lies at the southern end of the Central Belt and Eastern Belt of Peninsular Malaysia, 50 to 100 km east of the projected southerly continuation of the Bentong–Raub Suture Zone (Fig. 2); Kuala Lumpur is located on the leading edge of Sibumasu, some 50 km or so west of the BRSZ.

The bedrock geology of Kuala Lumpur comprises a number of very different rock types (e.g. Gobbett, 1964; Kong and Komoo, 1990; Gue and Singh, 2000; Jabatan Mineral dan Geosains Malaysia, 2011; Hareyani and De Freitas, 2011); an outline of that geology is provided in figure 1. The stratigraphical succession in Kuala Lumpur (Fig. 3) and the surrounding region has been informally divided and includes the Lower Palaeozoic non-fossiliferous Dinding Formation and the overlying Hawthornden Formation (Fig. 4A, B), both of which underlie the Silurian Kuala Lumpur Limestone (Fig. 4C), (*cf.* Gobbett, 1964). Parts at least of the Dinding Formation are clearly derived from an acid to intermediate volcanic origin (Quek *et al.*, 2018), the Hawthornden Formation is uniformly metasedimentary at the current level of understanding, and predominantly composed of intensely (poly)deformed pelitic and semipelitic schist. The Kuala Lumpur Limestone is unconformably overlain by the Kajang Formation (regarded as possibly deposited in the Devonian), and the early Permian Kenny Hill Formation (*cf.* Hutchison and Tan, 2009). The Kajang Formation strata comprise sandstone and mudstone, pyrite-rich limestone and carbonaceous shale, and have been interpreted as deposits in a "confined reducing environment … probably a shallow marine to swampy area" (Rosly, 1980). Like the underlying strata, units that can be assigned to the Kajang Formation typically display intense (and polyphase) ductile deformation (Fig. 4D). All of these units are folded, often intensely, such that isoclinal folds occur in each unit; no modern structural geology analysis of these rocks has been published however, either in relation to the individual units or with regard to any possible tectonic inter-relationships. Kajang strata are also typically intensely weathered and can occur as a palaeo-regolith beneath more competent, and much less weathered Kenny Hill Formation strata. The base of the Kenny Hill Formation is unconformable on all older strata (Yee, 1983), and the unit as a whole is typically more gently folded than all the underlying strata (Fig. 4E); less competent units (mudstones etc.) do however always show a penetrative planar schistosity (Fig. 4F) that is consistently E- or ENE-verging and upward-facing.

The higher hills that surround Kuala Lumpur on the east, north and west expose Triassic (*c*. 220-198 Ma) granite, part of the tin-bearing 'Western Belt' Main Range Granite Province suite of Peninsular Malaysia (e.g. Ghani *et al.*, 2013). Granite plutons are intruded into all of the bedrock succession of Kuala Lumpur (Fig. 2). A series of WNW-ESE striking faults cut across all of the above units (Fig. 1), these structures are locally accommodate thick metre- decametre-scale quartz veins such as the 'Klang Gates Quartz Reef' in the Kuala Lumpur Fault Zone (Stauffer, 1968; Shu, 1969).

The Permian and Triassic plutonic rocks of Singapore represent part of the southernmost exposures of the Sukhothai Arc (Fig. 2). Widely distributed I-type granitoids show Permian and Triassic U/Pb zircon emplacement ages that reflect the span of arc and back arc development in Peninsular Malaysia and Singapore (*c*. 265–220 Ma, see Oliver *et al.*, 2014; Ng *et al.*, 2015a,b; Searle *et al.*, 2012; Gillespie *et al.*, 2019). Devonian to Permo-Triassic, marine to terrestrial volcano-sedimentary successions that accumulated in the Semantan Basin of Peninsular Malaysia are understood to have been deposited as part of this arc system (Abdullah, 2009). In Singapore, the Jurong Group succession records Middle Triassic (Anisian to Ladinian) development of the active forearc in Singapore, and its subsequent brittle–ductile deformation (Dodd *et al.*, 2019; Leslie *et al.*, 2019). Numerous dated units of tuff constrain the age of these strata around 242 ±3 Ma (Winn *et al.*, 2018; Gillespie *et al.*, 2019). Somewhat younger fluvial to marine Sentosa Group strata typically lack volcanogenic deposits and may reflect uplift and erosion of the mature arc during Norian to Rhaetian times, prior to the onset of fold and thrust deformation (Leslie *et al.*, 2019). In Singapore, that basin-scale change to more fluvial settings is consistent with the relative abundance of conglomerate in the upper part of the Semantan Basin sequence described by Metcalfe (1990) and may even relate to geodynamic recovery following slab-break off beneath the Sukhothai Arc (*cf.* Metcalfe, 2017).

The 'Western Belt' Main Range Province comprises several large granitic batholiths made up of numerous individual plutons. These batholiths extend all along the watershed mountain range of Peninsular Malaysia and are an important bedrock unit in western and south-eastern Kuala Lumpur as well as in parts of adjacent Shah Alam and Kajang (Fig. 1). Along the peninsula, the main intrusive centres lie west of the BRSZ; reference to these plutons as 'Western Belt Granites' is preferred in some contexts (e.g. Qalam *et al*., 2019). Though now exposed at surface, the batholiths were originally deep-seated; meta-sedimentary enclaves are common at all scales. The main rock type is a coarse- to very coarse-grained megacrystic biotite granite; cm-scale K-feldspar phenocrysts are common (*cf*. Ghani, 2008).

Main Range Province plutons in Kuala Lumpur and the Ukay Perdana Shear Zone

In Kuala Lumpur, the mineralogy observed at outcrop in the 'Western Belt' Main Range Province granitic rocks is K-feldspar (orthoclase and microcline), quartz, oligoclase, biotite and muscovite with allanite, zircon, sphene and apatite. Epidote, tourmaline and ilmenite are secondary; garnet may be observed locally (*cf*. Ghani, 2008). North of Bandar Baru Selayang [Grid Ref. 407012 361387] and in southern parts of Ampang Jaya [420688 348319] (Fig. 1), quarries reveal leucocratic, generally equigranular unfoliated, granitic rock and weakly porphyritic muscovite-biotite granite, interspersed with conspicuously porphyritic (K-feldspar) granite. In these examples, the granitic rocks are cross-cut locally by narrow and steeply inclined, NW-SE trending mm- to cm-wide quartz veins. NW-SE and (N)NE-(S)SW trending, discrete and narrow planar zones (cm- to decimetre-scale) of both ductile and brittle deformation are observed locally and marked by occurrences of respectively mylonitic and/or cataclastic granitic rock. Earlier-formed mylonitic fabric may be reworked by cataclastic deformation along the same alignment.

Elsewhere however, penetrative pre- and post-full crystallisation fabrics can be observed in large -scale rock volumes; the syn-tectonic nature of emplacement of parts at least of these plutonic complexes is readily observed in the very large quarries near Kampung Jaya Sepakat [397277 327485], southwest of Kuala Lumpur (Locn. 2, Fig. 1). Here, the granitic rocks are foliated throughout and vary texturally over a few metres distance horizontally. Rocks that display a well-developed pre-full crystallisation fabric defined by aligned and elongate K-feldspar and quartz phenocrysts pass into mylonitic granite with very elongate sigmoidal porphyroclasts of quartz and more typically disrupted feldspar (Fig. 5A, B and D). Trains of biotite and muscovite define a variably intense fabric enclosing the phenocrysts/porphyroclasts in all of these deformed rocks. Indurated semipelitic meta-sedimentary relicts are elongate and aligned within the observed fabric (Fig. 5C); the fabric is always steeply dipping (*c.* 60–70°) to the NNW or north. The most pervasively mylonitic examples also carry an intense down-dip stretching lineation (in quartz) on foliation surfaces; the sense of shear is top-down-to-the-north (extensional) at this location (Fig. 5D, E).

The most spectacular deformation affecting the Main Range province granitic rocks of Kuala Lumpur can be observed in the northern part of Ampang Jaya, in an area previously attributed to either the Hawthornden Formation (e.g. Jabatan Mineral dan Geosains Malaysia, 2011; Hareyani and De Freitas, 2011) or to the Dinding Formation (e.g. Gobbett, 1964; Kong and Komoo, 1990). A well-exposed roadside section on Jalan Ukay Perdana 4 [420155 354436] (Locn. 1, Fig. 1), reveals grey, intensely foliated and lineated, hard and strong siliceous ultramylonitic rocks (Fig. 6A). In profile view (perpendicular to the observed stretching lineation) the anastomosing mica-fabric, and the sigmoidal form of annealed quartz porphyroclasts entrained within that fabric, show consistent and clear evidence for top-to-the-east (082°N) overthrust deformation. The moderately west-dipping (*c.* 35–40°) mylonitic fabric is locally folded by mm- to cm-scale kink-band folds that argue for down-temperature evolution

of the deformation recorded in this high strain shear zone. Petrographic examination shows that the most likely protolith was elements of the local 'Western Belt' S-type Main Range Province granite plutons. At the Ukay Perdana locality, the ultramylonitic rocks are intruded by veins of almost undeformed granite, suggesting that the latter stages of granite emplacement overlap the intense mylonitic deformation. The ultramylonite is also cut by quartz-tourmaline veins, which are a common late-stage hydrothermal feature of the Main Range Province granitic rocks throughout the Kuala Lumpur area (*cf.* Ghani 2008; Ghani *et al.* 2013).

These intensely foliated ultramylonitic rocks are composed of quartz, oligoclase, orthoclase, muscovite, biotite, and chlorite; relict clasts of perthitic K-feldspar (microcline), oligoclase and quartz are entrained within the ultramylonitic fabric (Fig. 6B). The very fine-grained (<0.02 mm) groundmass is largely composed of thoroughly annealed granoblastic aggregates of quartz, orthoclase and oligoclase; prisms of fresh muscovite and biotite grow along the quartzo-feldspathic grain boundaries and are very strongly aligned within the ultramylonitic fabric (Fig. 7A). Biotite-rich layers define bands within the foliation spaced at *c.* 1 mm; in these micaceous layers micas are up to 0.25 mm long (Fig. 7B). Such foliae may locally contain chlorite in addition to biotite; the chlorite is predominantly primary and did not form as a result of retrogressive metamorphic effects. Secondary chlorite does occur in, and immediately adjacent to, sub-mm wide brittle fractures transecting the ultramylonitic foliation and indicating alteration-fluid migration.

Quartz porphyroclasts are stretched and may be up to 4–5 mm long within the foliation, but *c.* 1 mm wide (Fig. 7C). These elongate porphyroclasts are frequently sigmoidal in overall form and swept around by the mica fabric; as a result, the overall top-to-the-east sense of shear (present day orientation) is never in doubt (Figs. 6A, 6B and 7C). The quartz porphyroclasts are always composed of sub-grains with conspicuously lobate-cuspate boundaries indicating migration of those sub-grain boundaries under moderate to high temperature conditions during

ductile deformation (*c*. 500–600°C). Sub-grains internally show undulose extinction again suggesting down-temperature evolution of the deformation history (Fig. 7C). In contrast, feldspar porphyroclasts are much less elongate and are blocky in form though still clearly swept by (and abraded within) the enclosing ultramylonitic fabric. Examples of K-feldspar porphyroclasts locally retain evidence of coarsely perthitic exsolution textures comprising intergrowths of orthoclase and microcline (Fig. 7D). Simple and repeated twins observed in oligoclase feldspar are frequently bent and support the interpretation of high temperatures attained during ductile deformation. Small grains of monazite, titanite and *c*. 50 µm zircon can be observed in thin section with some difficulty within the ultramylonitic foliation, along with occasional needles of apatite.

The high strain zone observed at Jalan Ukay Perdana is *c*. 250 m thick but, in the exposures observed to date, there is no sense that the intensity of deformation is diminishing up or down section. That being so, the true thickness of this shear zone is likely to be at least 250–300 m or so but could be much greater. If this style of deformation is characteristic of what has been mapped as Dinding Formation in this area (*cf*. Gobbet, 1964; Kong and Komoo, 1990) then a thickness of several hundred metres may be possible.

To the east of Kuala Lumpur city, and in the granite quarries to the west of the city around Kampung Jaya Sepakat (Locn. 2, Fig. 1), the observed style and character of the ductile deformation affecting these 'Western Belt' Main Range Province granitic rocks is sufficiently consistent to be considered as part of a single event, both in terms of the grade and likely pressure-temperature conditions prevailing during deformation. Deformation typified by the Ukay Perdana Shear Zone exposures likely overlapped the last stages of 'Western Belt' Main Range Province granite emplacement. In the absence of critical age-dating of the deformation fabrics at the time of writing, an age of 200–198 Ma is considered appropriate (*cf*. Liew and McCulloch, 1985; Ng *et al.*, 2005b). To date, isolated examples of comparable and typically less than m-scale

high temperature ductile deformation zones have been observed elsewhere in the granitic rocks in and around Kuala Lumpur, and are considered likely to be contemporaneous.

When the combined geometry of all these occurrences is considered, a regime of sinistral transpression is indicated with ENE-WSW aligned shortening (overthrust) acting along with components of NNW-SSE aligned extension. That framework allows for synchronous development of the very thick zone of overthrust deformation in the east marked by the Ukay Perdana Shear Zone (UPSZ) and contemporaneous ENE-WSW aligned zones of ductile stretching (ductile normal faults) in the UPSZ hanging wall.

Conjugate, steeply dipping zones of NW-SE (sinistral) and NNE-SSW (dextral) ductile Riedel shear are also possible. Structures on both orientations would be appropriately aligned to be re-activated during later cataclastic deformation (faulting) occurring in the Cretaceous and in the Cenozoic. It is possible that the narrow but repeated zones of deformation observed in granite in the southern parts of Ampang Jaya relate to this aspect of the deformation affecting the Main Range Province granite plutons in Kuala Lumpur and surrounding districts.

Discussion

Regional Geology: The Ukay Perdana location coincides approximately with the eastern edge of an area of strongly deformed rocks identified as the 'Quartzite member of the Dinding Schist' by Gobbett (1964, Plates 27 and 28). Quek *et al.* (2018) have obtained an Ordovician age (479.1±3.3 Ma) from a sample of strongly deformed meta-crystal tuff from [420169 354684]; this location is only some 200 m north of the ultramylonitic granite identified at the Ukay Perdana 4 location (Locn. 1, Fig. 1), and would lie structurally beneath the latter. The outcrop sampled for the dated sample of Quek *et al.* (2018) also displays a mylonitic fabric and is cross-cut by an undeformed granite vein; the dated sample was collected from a relatively undeformed lens of metavolcanic

rock. It seems therefore that the Dinding Formation in this area may comprise both a metavolcanic (Ordovician as proven, Quek *et al.*, 2018), and a (Main Range) granitic protolith (Figs. 6 and 7). The Dinding Schist of Gobbett (1964) very likely has a mixed protolith therefore; the shared mylonitic deformation would largely define the character (and minimum age) of the mappable unit overall. The rocks of the WSW-dipping highly Dinding Formation in this area are apparently banded (in terms of their protolith – volcanic vs granitic) and affected by intense ductile deformation that is younger (if only just) than the youngest protolith component, presumed in this case to be Main Range Province granite. The UPSZ may well incorporate elements derived from several bedrock stratigraphic units.

It will be important to constrain the age of this high temperature ductile shearing event more precisely. That said, the general geological relationships that can be observed in outcrop strongly suggest that intense ductile deformation overlapped the latter stages of emplacement of the 'Western Belt' Main Range Province granite plutons in this region of Peninsular Malaysia. An important phase of overthrust (top-to-the-east) shearing affected this leading edge of Sibumasu at *c.* 200 Ma. The final stages of amalgamation and consolidation of Sibumasu, and the then oceanward-facing margin of the Sukhothai Arc, apparently involved obduction of Sibumasu onto the mature arc. Such kinematics must have followed on from the cessation of Palaeo-Tethys subduction (then northward) beneath the Sukhothai Arc in the Middle to Upper Triassic (end-Carnian(?), *cf.* Ng *et al.,* 2015b; Gillespie *et al.*, 2019). Assuming that a slab-breakoff event would have occurred at this time, then loss of any slab-pull effect and the buoyancy effects of hot rising asthenosphere and crustal melting in the lower leading edge of Sibumasu would have made overthrust tectonics in the leading edge of Sibumasu more likely than continued underthrusting during the last stages of closure against the Sukhothai Arc. Subduction initiation beneath the western, trailing edge of Sibumasu will have imparted continued convergent stresses across the Sibumasu/Sukhothai margin for finite period in the

lower Jurassic. This scenario has some geometric parallels with the model for late stage underthrusting of the Sukhothai arc beneath Sibumasu as proposed by Oliver *et al.*, (2014). Although the geometry envisaged by those authors would be comparable to some degree, the causal mechanism as proposed here is different and better fitted to the structural features observed, and reported here.

At a wider regional scale, the bedrock geology of Kuala Lumpur and adjoining regions of western Peninsular Malaysia are generally situated in the hanging wall of the UPSZ. The NE-vergent ductile fold and thrust deformation that affected the Jurong and Sentosa group strata in Singapore (and related strata in Johor) is set in the footwall of the UPSZ. The general timing and geometry of the ductile deformation observed in the Kenny Hill Formation strata in Kuala Lumpur (Dodd *et al.*, in prep.) must be broadly synchronous with the deformation of the Triassic to earliest Jurassic strata in Singapore (see Murai Thrust, Fig. 9 in Leslie *et al.*, 2019). Both deformations are also very likely to overlap the deformation occurring in the UPSZ. This relationship is shown schematically in figure 8, with the Jurong and Sentosa group strata arranged in a region characterised by collapse and (now east-directed) propagation and advance of the UPSZ footwall. The Kenny Hill Formation strata of Kuala Lumpur were actively shortening in the shear zone hanging wall; 'Western Belt' Main Range Province granite magmas rose into, and along, the developing UPSZ perhaps contributing to the broadly linear eastern extent of this magmatic province. Such a configuration would have led to significant amounts of uplift and erosion, which leaves open the question of sediment routing and supply of detritus at this time; that detritus must presumably have included large numbers of *c.* 200 Ma old zircons, as well as older grains.

Application to the Urban Geology of Kuala Lumpur: Recognition of significant zones of high temperature ductile shearing in the bedrock geology of Kuala Lumpur, and down temperature evolution of that deformation including reactivation of earlier formed discontinuities as brittle

zones of faulting and cataclasis, will have important implications for hydrogeological and geotechnical studies of bedrock in Kuala Lumpur and its environs. The engineering and hydrogeological properties of rock volumes are profoundly affected by geological structures (Hoek, 2007; Scesi and Gattinoni, 2012); a comprehensive understanding of sub-surface geology is therefore critical to future buildings and infrastructure development, minimising risk, and for ongoing management of the urban subsurface.

Driven by the pressures of sustainable land-use and the needs of an ever-growing population, urban development in Southeast Asia looks increasingly to the subsurface to meet many of its future development needs. That subsurface has become an attractive space for energy production and infrastructure, waste disposal and treatment, water storage and groundwater abstraction, as well as transportation infrastructure and industrial manufacturing and logistics. Fractal distributions of geological structures (*cf.* Kruhl, 1994; Barton and La Pointe, 1995) mean that an understanding of the nature and geometry of continental/orogenic-scale structures can be part of the contextual reasoning employed to inform geoscience practitioners of the likely style and scale of deformation features and discontinuities that can be encountered in site-scale construction developments.

Preliminary observations imply that strong though pervasively foliated silicate mylonite occurring in zones of variable thickness and orientation (moderately to steeply dipping) are likely to occur in the granitic rocks of Kuala Lumpur. Where suitably orientated, these zones of ductile deformation will likely have been reactivated (perhaps repeatedly) as zones of more brittle cataclastic deformation (faulting), leading to a reduction in overall strength and continuity of rock masses. The location and size of these brittle fault zones will likely influence rock mass properties, which are a key concern in the design of engineered excavations, and in the assessment and remediation of natural slopes to mitigate landslide risk (Jabatan Mineral dan Geosains Malaysia, 2015).

Major discontinuities will also be the dominant control on fluid flow within crystalline bedrock; better understanding of the local (and regional) fault network is therefore critical to understanding the potential connectivity of hydrothermal fluids, which could present both a potential resource for geothermal exploitation, but also a hazard to subsurface excavation in altered rock. The strength and abrasivity of granitic rocks will also be increased by grainsize reduction associated with mylonitisation and cataclasis. Microcrystalline, cryptocrystalline and strained quartz (Nixon and Sims, 2016; ASTM, 2019) also present a risk of alkali-silica reaction (ASR) if aggregate derived from mylonitic and cataclastic granitic rock is used in concrete.

Boundaries between individual large-scale bedrock units in Kuala Lumpur may have been strongly affected, even constrained in places, by this shearing deformation, e.g. the inter-relationships of the Dinding and Hawthornden formations and the Kuala Lumpur Limestone (*cf.* Gobbett, 1964), the Kajang Formation schists, and the nature of the contacts of all those units with the intruding granitic plutons. Predicting the transition between subsurface volumes dominated by limestone, granite, sandstone, mudstone or schist is particularly important for tunnelling projects and for predicting the potential for shallow geohazards that might affect both buildings and infrastructure, for example karst within the Kuala Lumpur Limestone (Jabatan Mineral dan Geosains Malaysia. 2015).

The general disposition of the UPSZ suggests that the intensity of any shearing in the shear zone hanging wall is likely to diminish westwards at surface, but that the shear zone itself will dip westwards beneath Kuala Lumpur. Rocks in the shear zone hanging wall will possibly have been subject to tectonic repetition through thrusting. Such discontinuities might be indicated for example by the authors observations of north-south aligned trains of discrete occurrences of what would normally be regarded as older (?Kajang) strata within the broader outcrop of the Kenny Hill Formation, indicating probable 'structural complications'. Kenny Hill Formation strata are typically folded and cleaved (Fig. 4F), the superimposed tectonic fabric will have a

measurable effect on rock performance, not least in the way in which failure surfaces might be expressed on orientations other than bedding surfaces and recognised discrete faults.

Work is currently under way to develop and build a digital 3D geological model of Kuala Lumpur (3DKL) (Qalam *et al.*, 2019). That model will attempt to configure the sub-surface geometry and architecture of all the bedrock geology and superficial deposits encountered in Kuala Lumpur, as well as the record of ductile and brittle tectonic deformation that has affected the surface and sub-surface distribution of geological units. A better understanding of the geometry of major fault structures, and of the overall style of deformation within the Kuala Lumpur subsurface, is required in order to resolve the geometries of the different modelling units and of their respective relationships.

Conclusions

The core of the Ukay Perdana Shear Zone (UPSZ) is identified at surface in north-eastern Kuala Lumpur.

- The shear zone comprises a 'top-to-the-east' ultramylonite zone at least 250–300 m thick, superimposed on the later stages of assembly of the *c.* 200 Ma S-type 'Western Belt' granite plutons generated by crustal thickening, and typically assigned to the Main Range Granite Province. Younger bodies of similar S-type granitic rocks cut the shear zone.

- This shear zone accommodated final consolidation and amalgamation of Sibumasu and the Sukhothai Arc after 198 ±2 Ma; a then relatively buoyant leading edge of Sibumasu was overthrust (towards present day 080°N) onto the oceanward-facing margin of the Sukhothai Arc/Indochina-East Malaya block.

- The preceding largely accretionary and subduction-related BRSZ was probably over-ridden at this time by the top-to-the-east UPSZ.

- E- or ENE-verging, upward-facing ductile deformation affecting Kenny Hill Formation strata in Kuala Lumpur likely formed in the regional-scale shear zone hanging wall in response to translation on the UPSZ.

- The UPSZ extends at depth beneath Kuala Lumpur; subsurface development in Kuala Lumpur, and across Peninsular Malaysia, should account for this record of Mesozoic thrust tectonics and the tectonostratigraphic repetitions that might be expected to occur in association with the UPSZ.

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Figures and Captions:

Fig. 1: General geological map of Kuala Lumpur, the principal locations described in the text are superimposed (after Jabatan Mineral dan Geosains Malaysia, 2011). The principle localities at Jalan Ukay Perdana 4 [420155 354436] and Kampung Jaya Sepakat [397277 327485] are numbered (1 and 2 respectively); other localities discussed in the text and illustrated in figure 4 are located as black dots.
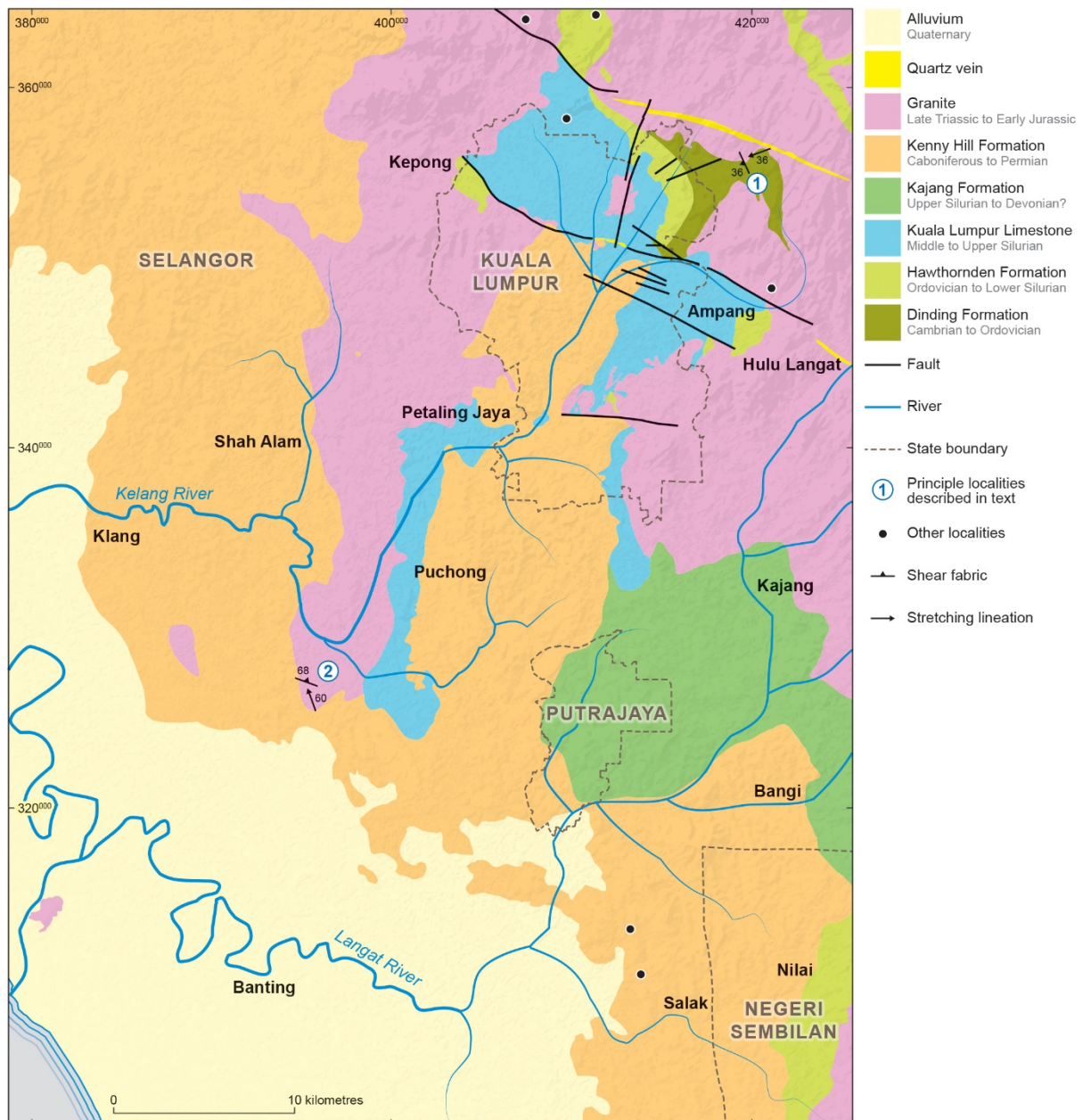
Fig. 2: Simplified regional geological map of Peninsular Malaysia. The map shows the limits of the tectono-stratigraphical Western, Central and Eastern belts, and the trace of the BRSZ that marks the orogenic suture between Sibumasu (Western Belt) and the Sukhothai Arc (Central and Eastern belts); (after Metcalfe, 2013). The BRSZ apparently passes some *c.* 50 km east of Kuala Lumpur and *c.* 100 km west of Singapore; boxed area, including Kuala Lumpur, is shown in more detail in figure 1.
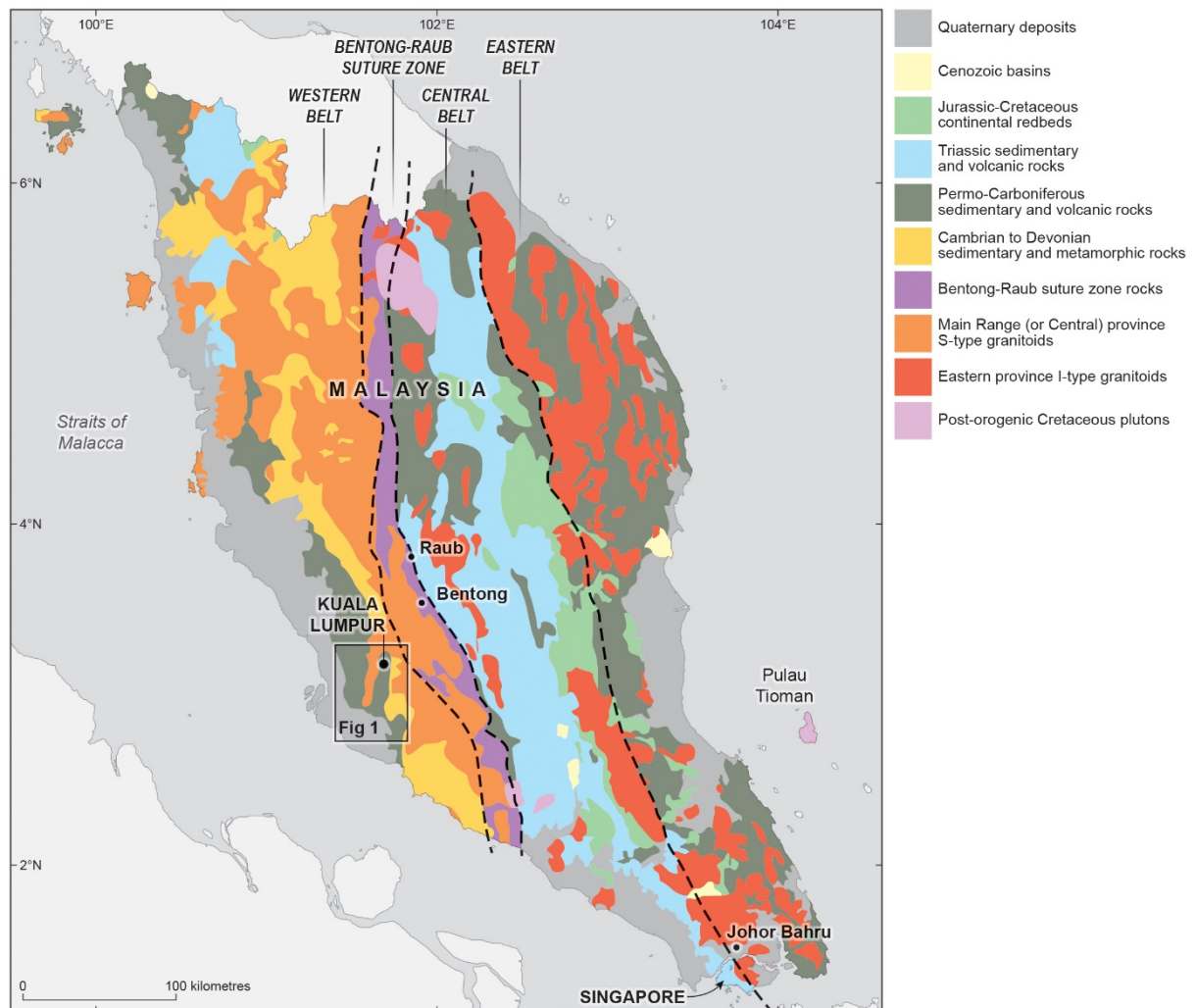
Fig. 3: Simplified GVS for Kuala Lumpur and the Selangor region, based on JMG (2011) and the authors' own observations.

Generalised GVS for Bedrock Geology, Kuala Lumpur and Selangor
Mainly after 1:63 360 scale geological map, Kuala Lumpur,
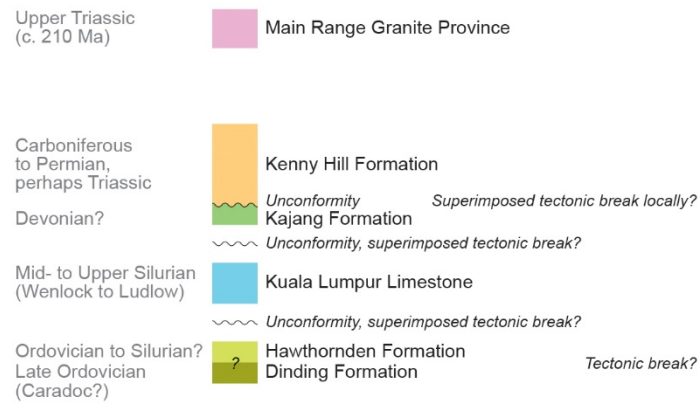*Sheet 94, Geological Survey, Malaysia (1976).*

Upper Triassic (c. 210 Ma)		Main Range Granite Province
Carboniferous to Permian, perhaps Triassic		Kenny Hill Formation
	Unconformity	*Superimposed tectonic break locally?*
Devonian?		Kajang Formation
	Unconformity, superimposed tectonic break?	
Mid- to Upper Silurian (Wenlock to Ludlow)		Kuala Lumpur Limestone
	Unconformity, superimposed tectonic break?	
Ordovician to Silurian? Late Ordovician (Caradoc?)	?	Hawthornden Formation, Dinding Formation *Tectonic break?*

Fig. 4: The principal mappable bedrock lithostratigraphic units encountered in Kuala Lumpur. A) SSW-dipping foliation (32°/202°N) in felsic volcanic rock of the Dinding Formation viewed downdip, [416875 356321], (Fig. 2). B) A *c*. 2 m high exposure in biotite-rich phyllonite of the Hawthornden Formation, near Batu Dam [410411 362120]. Foliation dips 70°/192°N. C) Folded and foliated Kuala Lumpur Limestone, Batu Cave, [409573 358227]; the tablet is 20 x 25 cm. Foliation dips south – (52°/172°N). D) Complexly deformed and penetratively weathered Kajang Formation pelitic and semipelitic schist, near Bandar Baru [414151 309883]; a moderately west-dipping cm-spaced crenulation cleavage transects a steeply-dipping composite foliation, view to north. E) Interbedded sandstone and mudstone, Kenny Hill Formation, [414304 314546]; bedding dips 20° to 150°N. The white square in the centre right of the view is the compass-clinometer resting on the cleaved mudstone of Fig. 4F; view is to the south. F) East-verging cleavage in mudstone, Kenny Hill Formation, [414304 314546]; foliation dips 30° to 290°N.
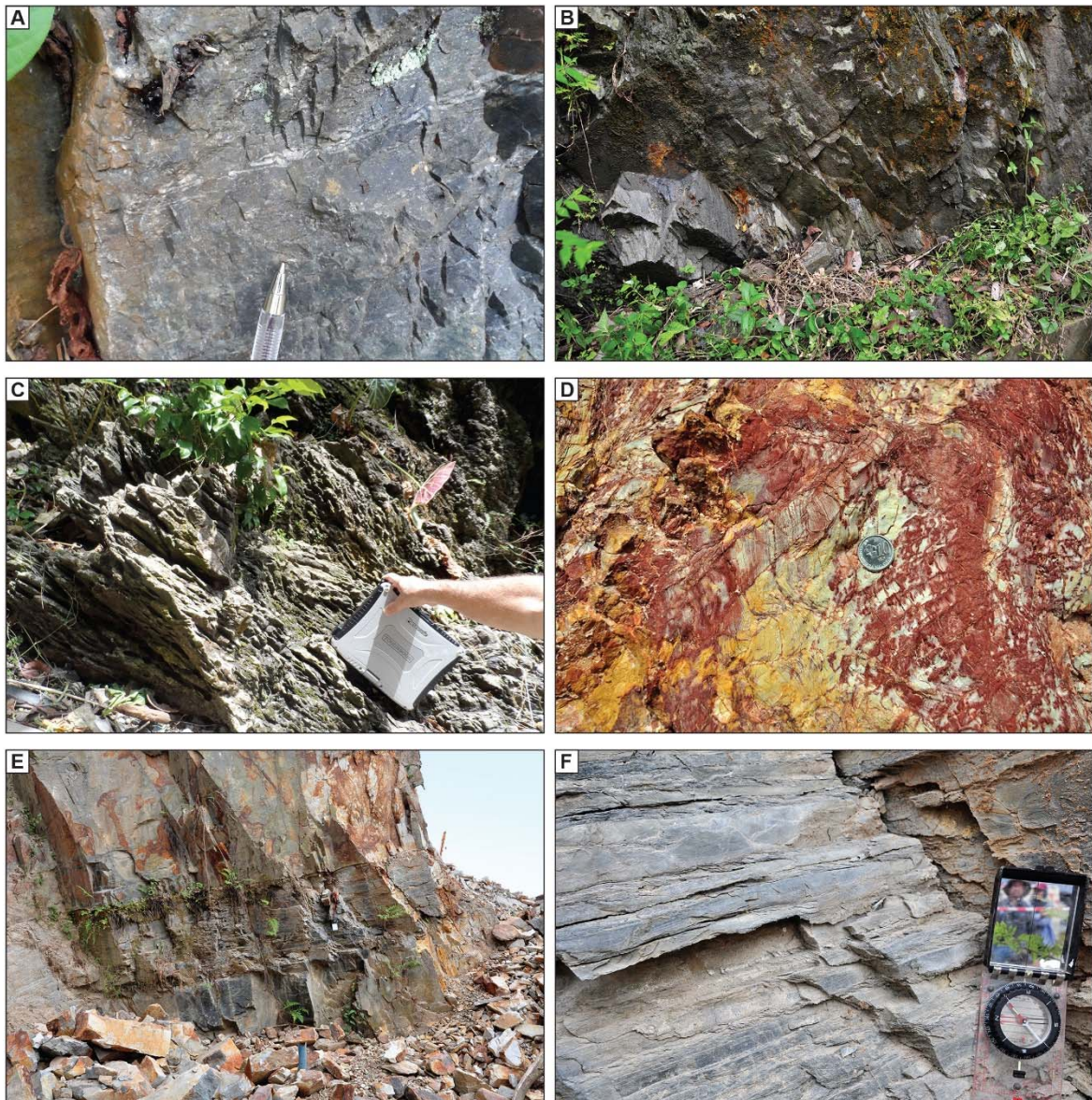
Fig. 5: Main Range Granite Province rocks exposed near Kampung Jaya Sepakat [397277 327485], southwest of Kuala Lumpur (Locn2, Fig. 2); showing the range of well-developed pre- and post-full crystallisation fabrics, including mylonitic granite: A, B) elongate quartz and K-feldspar megacrysts in foliated granitic rocks; C) elongate grey, semipelitic xenolith aligned within pre-full crystallisation fabric; D) intensely foliated granitic mylonite, fabric encloses strongly sigmoidal porphyroclasts of quartz and K-feldspar; E) intensely lineated granitic mylonite, down-to-north transport, down-dip and away from the viewer. The foliation dips 68° to 020°N; the lineation in E plunges 60° towards 342°N. View is generally to north for all frames.

Fig. 6: Intensely foliated and lineated, hard siliceous ultramylonitic rocks, Jalan Ukay Perdana 4 (Locn. 2, Fig. 2), [420155 354436]; at outcrop (Fig. 6a) and in thin section (XPL, Fig. 6b). The sense of shear is top-to-the ENE (082°N). The foliation dips 36° to 262°N, the transport lineation is aligned perfectly down-dip.

Fig. 7: Intensely foliated granitic ultramylonite, Jalan Ukay Perdana 4 [420155 354436], thin section views. A) Thoroughly annealed granoblastic aggregates of quartz, orthoclase and oligoclase; prisms of fresh muscovite and biotite grow along the quartzo-feldspathic grain boundaries and are very strongly aligned within the mylonitic fabric. B) Biotite-rich layers define bands within the foliation spaced at *c.* 1 mm; in these micaceous layers micas are up to 0.25 mm long. C) Stretched and polygonised quartz porphyroclasts may be up to 4 mm long within the foliation, and *c.* 1 mm wide, sigmoidal in overall form and swept around by the mica fabric; these quartz porphyroclasts are always composed of sub-grains with conspicuously lobate-cuspate migrating sub-grain. D) K-feldspar porphyroclasts are blocky in form though still swept by (and abraded within) the enclosing mylonitic fabric and locally retain evidence of coarsely perthitic exsolution textures comprising intergrowths of orthoclase and microcline.

Fig. 8: Cartoon showing the tectonic evolution of the Singapore/Kuala Lumpur crustal region during late Triassic to earliest Jurassic times when subduction was generally north-directed; the section therefore has a general N-S alignment at that time. This representation relates to the orogenic deformation in this now southern sector of Sibumasu and the Sukhothai Arc, and the amalgamation of Sundaland (after Sone and Metcalfe, 2008). The Sibumasu and Indochina-East Malaya blocks are shown in simplified form (see also Metcalfe, 2017 for details of these elements). The Ukay Perdana Shear Zone (UPSZ) identified in north-eastern Kuala Lumpur is proposed as a marker for a major crustal boundary between the leading edge of the Sibumasu Block (Kuala Lumpur) and the now-shortened forearc basin of the Sukhothai Arc (Singapore). The accretionary Bentong-Raub Suture Zone was probably over-ridden in these later stages of collision and amalgamation.