Ductile and brittle deformation in Singapore: a record of Mesozoic orogeny and amalgamation in Sundaland, and of post-orogenic faulting

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Abstract: Singapore bedrock geology is dominated by late Permian to Triassic arc magmatism and a genetically related, essentially Middle to Upper Triassic, marine to fluvial volcano-sedimentary inner forearc succession. These Mesozoic strata are deformed into a pattern of NE-translated ductile–brittle deformation structures during the latest Triassic to earliest Jurassic collision and amalgamation of the Sibumasu continental block with the southern part of the Sukhothai Arc. The subduction-related magmatic complex represented in Singapore by the granitic to gabbroic plutons of the Bukit Timah Centre likely acted as a backstop to thrusting at this time. Collisional tectonics drove progressive shortening and steepened earlier-formed inclined asymmetrical folds, culminating in the regional-scale development of a non-coaxial, NE-vergent and NE-facing, fold and thrust system. In Singapore, the Murai Thrust and Pasir Laba Thrust are identified as major elements of this system; both are associated with SW-dipping thrust-imbricate duplex slices. Two distinct early Cretaceous (Berriasian and Barremian) sedimentary successions overstep these collisional tectonic structures. An array of mostly NE–SW and ENE–WSW trending faults and fractures acts as important control on bedrock unit distribution across Singapore and are most likely generated by Cenomanian dextral shear stress. That stress locally reactivated faults initiated during orogeny, or even earlier. Knowledge of the geotechnical impact of these structural features is critical to both future development and ongoing management of the subsurface in Singapore. [225 words]

[10996 words including titles, abstract, captions and references]

1. Introduction

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 (see review in Metcalfe, 2017). Peninsular Malaysia and Singapore can be geologically described in terms of three approximately N–S trending tectono-stratigraphical elements, namely the Western, Central and Eastern belts (Fig. 1A, *cf.* Metcalfe, 2013). The Bentong–Raub Suture Zone 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 rocks making up the Sukhothai Arc (*cf.* Ng *et al*. 2015a; Gillespie *et al.,* this volume). Previously published geology of Singapore (DSTA, 2009; Figure 1B) shows many broad-scale similarities with neighbouring Johor in the southern part of Peninsular Malaysia (*cf.* Hutchison and Tan, 2009) but its structural evolution is not well understood. The geological relationships in neighbouring Indonesia (Riau Islands Province) are less well-reported but share many characteristics of the geology in Singapore and Johor (*cf.* Vilpponen, 1988).

The 'Defence Science and Technology Agency' (DSTA) commented on a wide range of fold- and fault-related features in south and southwest Singapore including overturned steep bedding attitudes (DSTA, 2009). Folds are described as "vertical isoclinal to isoclinal over-folds but are normally open folds"; fold axes could not be traced for distances greater than a kilometre. Large-scale folds had been observed at a few localities within the then described 'Jurong Formation'; some of those unfortunately are now obscured by development (*cf.* Figures 3.2 and 3.3, DSTA, 2009). DSTA (2009) described fresh examples of Triassic 'Jurong Formation' strata as foliated and recrystallized, with preferred alignments of chlorite, sericite and other micas. Shear fabrics reported in incompetent beds indicate locally developed high strain and low grade metamorphic textures (*cf.* Fig. 3.4 in DSTA, 2009).

Folding of Triassic strata was thought to have started before sedimentation ceased in the early Jurassic, and to have been constrained in some manner by the adjacent "buttress of granite" (DSTA, 2009). At least one example of a north-easterly verging thrust structure interpreted as "slumping-related" had been reported during construction on the Nanyang Technological University (NTU) campus. Conversely, the 'Murai Fault' was described as having been "responsible for the dynamic metamorphism of the Triassic sediment" (DSTA, 2009). The majority of faults affecting Triassic and younger strata, and the plutonic rocks, were understood to be active in the late Cretaceous (Redding and Christensen, 1999; DSTA, 2009), and again in the Cenozoic; such tectonic activity was apparently minimal after the Neogene (DSTA, 2009).

Triassic Semantan Formation rocks in the Central Belt of Peninsular Malaysia show a similar deformational style to these broadly contemporaneous strata in Singapore, with upright, close to tight folds and a strong axial planar cleavage (Harbury *et al.*, 1990). Deformation there is attributed to Upper Triassic dextral transpression, likely associated with collision of Sibumasu and the Sukhothai Arc (Mustaffa, 2009).

From literature and outcrop, the British Geological Survey (BGS) assessed the structural geology of Singapore for the Building and Construction Authority of Singapore (BCA) in 2014, confirming that: (i) Triassic strata had been penetratively deformed, folded, and weakly metamorphosed; and (ii) discrete low-angle south-west dipping and north-east verging thrust structures (*cf.* Redding and Christensen, 1999) were likely to be responsible for stratigraphical repetition of Triassic strata. Samples associated with the 'Murai Fault' were seen to preserve variable and locally very intense strain (*cf.* Redding and Christensen, 1999; DSTA, 2009). Occurrences of phyllonitic rocks previously assigned to the 'Murai Schist' (DSTA, 2009) preserved a penetrative, anastomosing and mylonitic fabric defined by white and pale green micas. The intensity of strain recorded in those rocks was arguably capable of accommodating several hundreds of metres displacement, perhaps even a few kilometres (Krabbendam and Leslie, 2010; Leslie *et al.*, 2010).

BGS observed that Triassic strata, and the plutonic igneous rocks of the 'Singapore' or Bukit Timah Granite, had been transected by an array of mostly NNE–SSW trending brittle faults that had relatively straight traces and were thus likely to be steeply dipping. No definitive fault map based on observed cut-offs and/or offsets of mapped lithological boundaries existed at that time, precluding precise summary of the kinematics of these brittle fault arrays. Significant movement on the faults in Singapore was understood to have largely ceased by the Neogene, (DSTA, 2009).

BGS has now analysed data from *c.* 20,000 m of borehole core recovered from 121 *c.* 205 m deep boreholes commissioned by the BCA (Fig. 2). In addition, we have incorporated new interpretations of some 218 outcrop locations, predominantly located in southern and southwest Singapore and its 'Southern Islands' (Fig. 1B & Fig.2). In this paper, we report a fully revised understanding of the ductile and brittle structural geological evolution of Singapore. Lithostratigraphical units referred to henceforth in this paper cite the fully revised, International Commission on Stratigraphy (ICS)-compliant, stratigraphical framework and depositional environment analysis reported fully in Dodd *et al.*, (this volume). That new stratigraphy replaces the now obsolete 'Jurong Formation' of south-west Singapore (Fig. 3). All locations are reported as geodetic datum SVY21 Singapore co-ordinates.

Critical surface exposures in Singapore are somewhat limited; the ‘Southern Islands’ cluster to the south of mainland Singapore is an important exception (Fig. 1B). The Kent Ridge and Labrador Park areas in adjacent mainland Singapore are also instructive (K and L on Fig. 1B). In the west of mainland Singapore, exposures in the Western Water Catchment Live-Firing area reveal the scale and intensity of thrust-related deformation, including the Murai Thrust structure described in detail below (M on Fig. 1B).

2. Regional setting and revised geology of Singapore

Singapore lies at the southern end of the Central Belt and Eastern Belt, 50 to 100 km east of the projected southerly continuation of the Bentong–Raub Suture Zone (Fig. 1). After the Sibumasu block rifted from Gondwana during the Permian, its then northward movement was accommodated by subduction of Palaeo-Tethys ocean crust beneath the Indochina–East Malaya block from the Permian at least and continuing throughout much of the Triassic. Subduction processes generated the Sukhothai Arc (Hall, 2009, 2012; Metcalfe, 2011, 2013, 2017 and references therein). The Permian and Triassic plutonic rocks of Singapore (and the adjacent Riau Islands) represent the southernmost exposures of the Sukhothai Arc.

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*., this volume). Marine to terrestrial, Devonian to Permo-Triassic, volcano-sedimentary successions in the Semantan Basin of Peninsular Malaysia are understood to have been deposited as part of this arc system (Abdullah, 2009).

The Jurong Group succession records Middle Triassic (Anisian to Ladinian) development of the active forearc in Singapore, and its subsequent brittle–ductile deformation (Figs. 3 & 4, *cf.* Fig. 2, Dodd *et al*., this volume). Numerous dated units of tuff constrain the age of these strata (*c*. 242 ±3 Ma, see Gillespie *et al.* this volume, Winn *et al*., 2018). Succeeding fluvial to marine Sentosa Group strata typically lack volcanogenic deposits and may reflect uplift and erosion of the mature arc. That change 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). In Singapore, two distinct early Cretaceous (Berriasian and Barremian) sedimentary successions overstep the earlier deformed strata (Fig. 3).

Figure 4 is a revised bedrock geological map of Singapore based upon our interpretation of all available new data; the major fold, thrust, and fault structures are superimposed on the principal lithostratigraphical and lithodemic units; the Jurong and Sentosa groups are shown undivided here for clarity (*cf*. Figs. 3 & 5). The Murai and Pasir Laba thrusts extend across southwest Singapore, the former from its 'type locality' at Murai Reservoir (Fig. 4). The principal steep, brittle faults identified onshore and here extrapolated offshore are: the Henderson Road Fault; the Pepys Road Fault; the Nee Soon Fault; the Seletar Fault and the Bukit Timah Fault Zone (Fig. 4).

3. Macro- to micro- ductile deformation in the metasedimentary strata of SW Singapore

The Jurong and Sentosa group strata in south-west Singapore record ductile and brittle–ductile deformation (D1) that can be observed at a variety of scales (see Figs. 4 & 5; Figs. 6, 7 & 8). Individual, outcrop-scale folds are often apparently upright, open or close but occur within a wider array of decametre-scale, inclined asymmetrical and close NW–SE striking F1 folds (inset stereonet, Fig. 5). Microstructural details demonstrate pervasive and penetrative, NE-vergent non-coaxial deformation (Figs. 7 & 8). Progressive shortening tightened folds during a finite timespan – in essence a single D1 event. As a consequence, structures became increasingly transposed by NE-directed tectonic transport. Tightening was achieved through steepening of originally NE-dipping fold limbs towards, and locally through, the vertical. Significant panels of Jurong and Sentosa group strata are overturned and inverted by folding; for example, borehole BH2A13 [33778.6 09748.8, Tuas, Fig. 2] has been drilled to a depth of 205.0 m and is all in tightly-folded inverted strata. The type section for the Tanjong Rimau Formation/Fort Siloso Formation boundary on Sentosa Island occurs within sub-vertical strata (Dodd *et al*., this volume). No strictly isoclinal folds have been observed. The D1 deformation is described further below.

D1 deformation, F1 folds and the S1 foliation

The most informative and representative examples of folded Jurong and Sentosa group strata occur on Pulau Jong (Jong or 'Junk' Island), Big Sister's Island (Pulau Subar Laut) and St John's and Lazarus islands (Fig. 6). Elsewhere, systematic variations in dip and/or bedding/cleavage geometries demonstrate folding (e.g. along South Buona Vista Road in the Kent Ridge area, and in the Hillside Park, Bukit Batok district (H), see Fig. 1B for locations).

On Pulau Jong [22769.9 22039.0, Figs. 2 & 5], Tanjong Rimau Formation sandstone and conglomerate units are steeply to very steeply dipping. Way-up overall is to the east-northeast though interrupted by upright metre-scale folding (Fig. 6a). An S1 phyllosilicate schistosity is well-developed in mudstone interlayers and opposed bedding/cleavage relationships are very clear on either limb of the exposed folds. On St. John's Island [29827.8 22611.9, Figs. 2 & 5], Fort

Siloso Formation strata show steeply NE-dipping, lenticular cross-bedded fine-grained sandstone units 1 to 2 cm thick, interbedded with mm-scale layers of planar laminated mudstone; bedding is right-way-up and younging to the north-east. A clearly-developed, moderately SW-dipping, north-east facing S1 cleavage is almost perpendicular to bedding and defined by preferred parallel arrangement of phyllosilicate minerals and a preferred shape fabric in quartz (Fig. 6b). Bedding/cleavage relationships here demonstrate broadly neutral fold vergence, placing these outcrops within a local hinge.

Right-way up, NE-younging, Fort Siloso Formation heterolithic interbedded sandstone and siltstone units on Lazarus Island [30169.0 22806.0, Figs. 2 & 5] preserve a sharply refracted S1 cleavage transecting bed boundaries (Fig. 6c). S1 is convergent in mudstone layers and approximately perpendicular to S0 in sandstone layers (diverging), indicating overall neutral vergence in a local but large-scale (possibly decimetre to decametre) inclined fold hinge zone.

Sandstone-dominated, folded Tanjong Rimau Formation units at Tanjong Lokos on St. John's Island [30076.6 21788.5, Figs. 2 & 5] demonstrate the progressive nature of the deformation affecting Jurong and Sentosa group strata. Here, the exposed part of the Lokos Anticline (*cf*. Figure 3.3, DSTA, 2009) is an upright, asymmetrical antiform. Opposed bedding/cleavage relationships are clear on the adjacent fold limbs, and intense crushing/shearing deformation developed in sandstone layers located in the inner arc of this structure as the fold tightened (Figs. 6d, 6e & 6f). The north-eastern limb is much more penetratively deformed than the southwest one, such that an intense south-west-dipping fracture cleavage is developed even in m-scale thick sandstone layers (Fig. 6f), strongly implying that the fold became increasingly inclined and overturned towards the north-east, rotating and shearing the steepening north-eastern limb (Fig. 6d).

Discrete folding is rarely observed at core scale. Amongst the best examples are the repeated, decimetre-scale tight, asymmetrical fold closures that occur in Pulau Ayer Chawan Formation strata in BH2A12, [31439.2 08515.2, Tuas, Fig. 2], for example the closure at 35.7 m featured in Fig. 7A. The hinge area of the featured fold demonstrates very clearly the non-coaxial, anastomosing nature of the S1 foliation in these strata (Fig. 7B). A well-developed grain shape fabric is observed in the sandstone layer; the boundary between the sandstone and mudstone layers is transected and offset by micro-shearing characteristic of non-coaxial translational deformation, rather than flexural folding indicative of simple coaxial shortening. BH2A12 demonstrates clearly that the most strongly folded intervals of Jurong Group strata are inverted at the broader scale, and that folding is most intensely developed on the short, overturned limbs of north-east-vergent asymmetrical folds.

At the broader (decametre)-scale in Singapore, outcropping anticlinal fold hinges and closures dominate such that any complimentary synclinal hinges and closures are apparently lacking in field and borehole observations. As strain intensifies in these steepening/overturning fold trains, we would predict a progressive development of penetrative fabrics that intensify downwards onto discrete thrust discontinuities disrupting the common limbs of asymmetrical fold structures and underlying synclinal structures. The much larger-scale Murai and Pasir Laba thrusts (see below) demonstrate this deformational style across southwest Singapore.

Across southwest Singapore, the S1 cleavage typically dips south-westwards often displaying convergent or divergent fans in fold hinges, as constrained by the rheology of the folded strata (*cf.* Fig. 6). The S1 fabric is readily developed in incompetent Jurong and Sentosa group lithologies; fine- to very fine-grained sandstone and mudstone layers commonly preserve a penetrative anastomosing S1 schistosity defined by the preferred parallel alignment of phyllosilicate minerals and chlorite (Fig. 8a). Lithic clasts become progressively altered to aggregates of fine-grained, secondary minerals and are increasingly attenuated in the S1 foliation. In contrast, larger quartz grains remain robust and are wrapped by the new schistosity. Concentrations of iron oxide along the foliation seams are a common feature where the lithic clasts show progressive alteration and modification (Fig. 8b). A spaced fracture cleavage is observed locally in more competent sandstone units, especially so in very steeply-dipping to overturned strata (*cf.* Fig. 6e).

Carbonate rocks are strongly affected by pressure solution processes and are characterised by phyllosilicate-defined S1 foliation seams that are axial planar to microfolds of tectonically-generated stylolite seams (Figs. 8c, 8d & 8e). The S1 foliation deflects around macrofossil fragments leaving the latter largely intact (Fig. 8d). Tuffaceous rocks do not typically become foliated or cleave penetratively; in thin section sericitic/chloritic alteration products are arranged as anastomosing linear trails aligned parallel to the penetrative S1 cleavage in more incompetent lithologies interlayered with the volcanogenic strata (Fig. 8f). The implied grade of metamorphism is never greater than lowermost epizone (prehnite-pumpellyite facies) with no development of sub-grain morphologies observed in quartz.

4. Progressive deformation in the Murai Thrust Belt

The Western Water Catchment/SAFTI Live Firing area in Western Singapore exposes critical detail of the Murai Thrust structure (Figs. 1 & 4). At Murai Reservoir, excavations have created three-dimensional outcrops that reveal the complexity of features in the hanging wall of the Murai Thrust (Fig. 9). The line interpretation shown in the lower panel of Figure 9 includes the principal dislocation surfaces; the overall antiformal nature of this particular thrust stack; the discrete faults accommodating extensional surge on the leading edge of the stack; and the over-steepened ramp that now lies within the sub-vertical imbricate structure of the trailing edge of the overall structure. The variability in structural attitude revealed here is a clear indication of what should locally be anticipated elsewhere along the trace of the Murai and Pasir Laba thrusts, superimposed upon any broader-scale variability in bedding dip that results from folding in those same areas. Shearing deformation has been observed in outcrop in former excavations off Pepys Road, Bukit Panjang (Figure 3.4 in DSTA, 2009), coincident with the south-eastern part of the Murai Thrust trace.

At Murai Reservoir, an anastomosing, sinuous penetrative fabric is ubiquitous; any discrete lithological units that can be identified are lenticular at all scales in response to the intense shearing deformation (Fig. 10). At the larger scale, this lenticular geometry is apparent in the arrangement of the pale greyish-white quartz-arenite layers that are outlined on Figure 9 in the central part of the antiformal stack. Secondary shears cut across the earlier-formed shear fabric; that secondary stacking culminates in formation of the observed antiformal stack (Figs. 9 and 10). Grain-scale attenuation of original clasts is demonstrated by elongated quartz clasts on foliation surfaces that also preserve a weak mineral-stretching lineation aligned parallel to the long axes of these clasts and demonstrating top-to-the NE tectonic transport (050°N).

Petrographic examination (Fig. 11), of these intensely deformed rocks indicates that:

a) deformation affects units of sandstone, volcaniclastic sandstone, mudstone and tuff that can all now be assigned to the Boon Lay Formation (Jurong Group, Dodd *et al.*, this volume);

b) the grade of metamorphic recrystallisation is always low (lowermost epizone with no development of sub-grain morphologies in quartz); and

c) the sense of shear is consistently top to the north-east, as constrained by the measured lineations at outcrop.

At the broader scale across south-west Singapore, the Murai Thrust places the older Pulau Ayer Chawan, Pandan, and lower parts of Boon Lay, formations structurally over the upper (younger) parts of the Boon Lay Formation, including the distinctive Clementi Member. The Pulau Ayer Chawan and Pandan formations have not been identified in the near surface in the footwall of the Murai Thrust, either at outcrop or in the numerous boreholes in this region (Figs. 1B and 2). Thin remnants of Tanjong Rimau Formation strata are identified locally in the hanging wall of the Murai Thrust structure in the Kent Ridge area (in BH1F5, Fig. 2, Dodd *et al.* this volume). The limited occurrences of Tanjong Rimau Formation strata that occur to the north-west of the Henderson Road Fault contrast sharply with the much greater thicknesses found to the south-east of the same fault (Fig. 4). This disparity argues strongly that significant (down-to-the-SE) displacement must have occurred on the Henderson Road Fault, prior to any fold and thrust deformation (see further discussion below).

Strongly deformed, locally mylonitic, Buona Vista Formation strata are conspicuous in the footwall of the Murai Thrust (Fig. 4); unconformably overlying older Boon Lay Formation strata (Dodd *et al*., this volume). A similar relationship is preserved in the immediate footwall of the Pasir Laba Thrust on the NTU campus (NTU on Fig.4). There, feature mapping based on 1976 vintage B&W aerial photography (pre-dating campus development) constrains limits on the distribution of sheared Buona Vista Formation strata (BH1B1 and BH1B2, Fig. 2) that are clearly discordant and overstepping with respect to folded Pulau Ayer Chawan, Pandan and Boon Lay Formation strata (Dodd *et al*., this volume). A syn-deformation 'piggy back' depositional setting is proposed for these distinctive conglomeratic strata (*cf*. Ori and Friend, 1984).

The scale of displacement on the Murai Thrust cannot directly be constrained by measurement but the style of deformation, and the thickness of phyllonitic rocks exposed at Murai Reservoir, suggests that NE-directed translation on a scale of several hundred metres, even a few kilometres, is possible (Figs. 9, 10 and 11).

5. Deformation model, sub-surface architecture, and the timing of deformation

Shortening locally culminated in the disruption and attenuation of steepening and overturning limbs as strain became partitioned, leading to the development of a large-scale NE-vergent thrust system, elements of which are distributed all across south-west Singapore (Fig. 4). The long limbs of the hanging wall anticline structures above thrusts are more broadly flat-lying though undulating, displaying open to close upright folding at < 1 km wavelength. In lower strain regions, bedding dips either to the north-east or, more commonly, to the south-west. Any tectonic foliation typically dips moderately to steeply south-west. At locations where the orientation of bedding and the S1 fabric can be directly compared, a small clockwise transection angle is observed (*c*. 5°, S1 on bedding) suggesting that this ductile deformation is, strictly speaking, dextrally transpressive.

A composite model for the ductile deformation affecting the Jurong and Sentosa group strata in south and south-west Singapore is summarised in the schematic cross-section of Figure 12. Tectonic transport overall is towards the north-east. In relatively low strain areas, such as Tanjong Lokos on St. John's Island, folds are asymmetrical but broadly upright. In higher strain volumes, bedding would be progressively steepened and transposed on the north-eastern limbs of fold sets such that the stratigraphy becomes increasingly tightly folded, more strongly cleaved, and more typically inverted, e.g. as seen in the boreholes in northern Tuas (*cf.* Fig. 7). Ultimately, gently to moderately dipping laterally extensive thrust discontinuities are developed, such as the Murai (and Pasir Laba) Thrust. Strata are intensely deformed in the immediate hanging wall of these structures, thrust over younger strata such as the Boon Lay Formation in the Hillside Park region of Bukit Batok (see Fig. 1B for location).

The structural evolution and broad-scale architecture of the (meta)sedimentary strata in south-west Singapore is illustrated in Figure 13. These cross-sections illustrate the geometry of the folding that affects the Jurong and Sentosa group strata as well as the gross 'older-over-younger' nature of the discontinuities associated with the Murai Thrust and the related Pasir Laba Thrust. Deformation and displacement expressed at such a scale means that it is appropriate to regard the panel of lithostratigraphy transported in the hanging wall of the Murai Thrust as constituting a thrust nappe, named here as the Murai Nappe (Fig. 13). As currently understood, the Pasir Laba Thrust is associated with intraformational offsets of Pulau Ayer Chawan and Pandan formation strata and possibly represents rather smaller-scale shortening within the Murai Nappe, presumably preceding major translation and shortening accommodated on the structurally lower Murai Thrust structure.

The position of the Buona Vista Formation strata in the immediate footwall of the Pasir Laba Thrust is clear (around BH1B1 and BH1B2 on Fig. 13); likewise, the unconformable overstep of the earlier orogenic deformation that occurs at the base of the Bukit Batok Formation (around BH2B4). The interpreted multiple strands of the Bukit Timah Fault Zone are shown around the location of BH2B5 on figure 13; also shown are the likely moderate to steeply-dipping nature of the intrusive contacts within the Bukit Timah Centre.

Fold and thrust deformation in Singapore is clearly superimposed on Jurong and Sentosa group strata whose age is now well-constrained by U/Pb zircon dating (Dodd *et al.*, this volume; Gillespie et al. this volume; Winn *et al*. 2018). Numerous intervals of tuff interbedded with the Pulau Ayer Chawan, Pandan and Boon Lay formation strata all were erupted at *c*. 242 Ma. The youngest U/Pb detrital zircon age recorded to date in Tanjong Rimau Formation strata (209 Ma, Oliver *et al.,* 2014) shows that orogenic collision of Sibumasu and the Indochina–East Malaya block must have culminated after this date, at least in the future Singapore region. The youngest dated S-type granites in the Western Belt of Peninsular Malaysia are *c*. 195 – 200 Ma (U/Pb zircon, Liew and McCulloch, 1985; Ng *et al.,* 2015b) suggesting that collision was essentially complete by this time in the earliest Jurassic. No more refined age constraints are currently available from Singapore; no other Jurassic strata are known to occur in Singapore and the next youngest strata overstepping the fold and thrust deformation are believed to be no older than Berriasian in age (<145 Ma, Dodd *et al*., this volume).

6. Brittle deformation and the large-scale pattern of faulting in Singapore

The most significant fault features which can be interpreted in the current understanding of the bedrock geology of Singapore are arrays of NE–SW, NNW–SSE, and NW–SE striking discontinuities (Fig. 4). Brittle deformation leading to faulting is an important factor in the geological evolution of Singapore and is a very significant constraint on the distribution of lithological units in the sub-surface. However, very few faults are actually exposed in the modern urban landscape of Singapore; modern imagery (satellite or similar) is severely compromised by that landscape. Positional inferences can be drawn from physiographical features captured in 1976-vintage B&W aerial photography that pre-dates much of this urban landscape, and from offset geological features, as well as from an assessment of publically available marine bathymetrical data. The majority of brittle faults in Singapore bedrock are likely to be very steeply dipping or sub-vertical, judging by the relatively straight fault traces interpreted from the currently available data. Those observed in outcrop are small-scale features with centimetre- to decimetre-scale displacements typically; no natural exposure of cataclasite, or other fault rock is known. Most of the new BCA-commissioned ground investigation boreholes were drilled vertically, and virtually none of them have intersected major faults.

Only a handful of fault features have been named previously (DSTA, 2009; Oliver and Gupta, 2019). These include the Henderson Road, Pepys Road, Nee Soon, and Seletar faults, and the Bukit Timah Fault Zone. Given the orientation of this fault array (Fig. 4), and the regional-scale Mesozoic/Cenozoic stress regime (and thus σ_1), it is likely that many of the individual fault features in these arrays will have been re-activated, perhaps multiple times, since the end of the Triassic and throughout the Cenozoic.

6.1 Bukit Timah Fault Zone

The Bukit Timah Fault Zone (BTFZ on Fig. 4) is the largest and arguably most important discontinuity in Singapore. The BTFZ essentially delineates the boundary between the plutonic rocks of the Bukit Timah Centre and the (meta)sedimentary Jurong and Sentosa group strata to the south-west. Occurrences of Lower Cretaceous Bukit Batok Formation strata are spatially associated with this structure, apparently occurring as fault-bound lenses arranged within the fault damage zone. Despite its size, the BTFZ is not currently exposed anywhere at surface, and its character and even its precise location is not well understood. Borehole BH2F5 [21620.8 34315.0, Bukit Batok, Fig. 2] is the only available borehole that clearly intersects a major strand of the

BTFZ juxtaposing igneous and metasedimentary rock. The distribution and character of deformation in the cored interval indicates that cataclasite and more intensely ductile-deformed mylonitic rock was produced more or less contemporaneously, with the cataclasite representing 'failure' zones in the rock mass or in damage zones that otherwise responded to strain in a more brittle–ductile fashion.

There is little evidence to constrain the size of the horizontal displacement on the BTFZ; the fact that plutonic igneous rocks and sedimentary/metasedimentary rocks are juxtaposed across it indicates that the vertical displacement is at least several, and possibly as much as ten, kilometres. A fault of that size will have formed as a set of anastomosing strands within a fault zone that pinched and swelled vertically and laterally. Thus, in places the structure may consist of a single substantial strand, while elsewhere several smaller strands may accommodate strain as demonstrated in the closely spaced BH2B6 and BH1B10 borehole arrays (Fig. 2), (see Fig. 14).

The BTFZ is displaced locally by NE–SW striking structures. That, and the range of mylonitic and cataclastic fault rocks intersected in boreholes, implies that this structure has a long and complex history. The oldest displacement on the BTFZ for which direct evidence has been observed has a brittle–ductile style of deformation. However, the size of the vertical displacement alone (perhaps around 10 kilometres) required to juxtapose the Bukit Timah Centre and metasedimentary Jurong Group strata, suggests an earlier, possibly essentially ductile, phase of displacement would have been involved. The oldest intrusion in the Bukit Timah Centre, the Choa Chu Kang Granodiorite–tonalite Pluton, crops out on the north-east side of the BTFZ, and is the only part of the Bukit Timah Centre to display a widely developed tectonic fabric (Gillespie *et al.*, this volume). A band of mylonite around 17 metres thick (true thickness) dipping east at 55º, is developed within the granodiorite of borehole BH1E4 [20773.3 39668.1, Fig. 2], approximately 3 km from the nearest part of the BTFZ trace; other such deformation zones in this pluton may occur in unsampled ground. This zone of ductile 'shear' may be typical of structures that accommodated the earliest displacements on a 'proto-BTFZ'. Such structures may have accommodated much of the early, reverse displacement that brought parts of this pluton to shallower levels in the middle part of the Permian Period (i.e. before younger plutons lacking a tectonic fabric were emplaced in the Bukit Timah Centre, Gillespie *et al.*, this volume). As the rock mass moved to shallower levels, perhaps accompanied by a contemporaneous reduction in regional compressive stress, the deformation became more focussed and more brittle, creating much the damage zone encountered today in the BTFZ.

Some control upon the patterns of deposition in the Jurong Group strata across the alignment of any ‘proto-BTFZ’ cannot be ruled out (*cf.* Oliver and Prave, 2013; Oliver and Gupta, 2019). A ‘proto-BTFZ’ structure may have partially accommodated uplift of the arc plutonic complex so that erosion then supplied granitic detritus into the Tanjong Rimau Formation depocentre (*cf.* Dodd *et al.*, this volume). In addition, it seems likely that the plutonic rocks of the Bukit Timah Centre will have acted as a backstop to thrusting and ductile deformation in the latest Triassic to earliest Jurassic, so that the fault zone may have accommodated very significant movements at this time. Later, the structure is suitably orientated to act as a P-shear during late Cretaceous dextral shear (Fig.4 inset; *cf.* Hutchison and Tan, 2009).

6.2 Henderson Road Fault

The Henderson Road Fault (HRF on Fig. 4) is one of the most prominent fault structures now identified in Singapore but is not exposed in any section today. As originally identified (DSTA, 2009), the Henderson Road Fault follows the line of the modern roadway of that name but does not appear as a significant feature on the aerial photography that pre-dates the modern urban development and the present-day road alignment. It is apparent however that there is a marked change in distribution of pre-Cretaceous and Cretaceous strata across the fault zone, which is interpreted to extend from the Fort Canning area, across the Kent Ridge/Mount Faber area (K on Fig.1B), and apparently continuing south of Jurong Island. The extent to which this fault can be traced to the north-east of the BTFZ is not clear, but it is likely to have been re-activated locally at least during any Cretaceous strike-slip faulting.

The revised trace for the Henderson Road Fault separates older Jurong Group strata (Pulau Ayer Chawan, Pandan and Boon Lay formations) that dominate the north-western wall of the fault from the younger Sentosa Group strata (Tanjong Rimau and Fort Siloso formations) that dominate the south-east wall of the fault (Figs. 4 & 5). This abrupt change in preserved lithostratigraphical level suggests that significant (down-to-the-SE) displacement occurred across the trace of what is now the Henderson Road Fault, prior to fold and thrust deformation. Other (E)NE–(W)SW trending structures may have been similarly active at this time. The Henderson Road Fault apparently bends from an ENE–WSW to a NE–SW strike in the Kent Ridge to Fort Canning area forming a (sinistral) pull-apart feature in conjunction with the Pepys Road Fault; the north-western limit of the pull-apart structure marks the north-western extent of the Kusu Formation (Dodd *et al.*, this volume; Fig. 4).

6.3 Pepys Road Fault

This fault (PRF on Fig. 4) has not been encountered in the new borehole cores, or at outcrop. A slightly revised trace does however coincide with a significant NE–SW trending topographical feature and mappable offsets of geological boundaries between Kent Ridge and Telok Blangah (Fig. 1B; *cf.* DSTA, 2009). It should be noted that although Kusu Formation strata have been identified at Telok Blangah (south-east of the Pepys Road Fault), the formation has not been identified anywhere to the north-west of the PRF. Our geological interpretation suggests that this fault will have likely been hard-linked to a significant extent with the Henderson Road Fault, sharing at least part of their displacement history.

6.4 Nee Soon Fault and Seletar Fault

The traces of these fault structures (NST and SF on Fig. 4), have not been significantly modified from previous interpretations (DSTA, 2009), though some minor adjustments have been made locally to account for topography. There is a strong spatial association between the Nee Soon Fault and the western limit of the Bedok Formation against the plutonic rocks of the Bukit Timah Centre. However, the extent to which this fault (or the Seletar Fault) may have been active before, during, or after deposition of the Bedok Formation remains unclear however (*cf.* Dodd *et al*., this volume).

Significant movement on the faults in Singapore appears to have largely ceased by the time the Bedok Formation was deposited in the Neogene or later. Minor offsets of bedding reflectors detected in new seismic data acquired by BCA in the Seletar/Punggol area have been interpreted by BGS as possible fault offsets affecting Bedok Formation strata, but no borehole core that would allow this to be tested has been recovered from the offset reflector package. A regional consideration of fault history suggests that Cenozoic movements are likely on suitably oriented faults (see review in Hutchison and Tan, 2009).

7. Discussion: Mesozoic to Cenozoic geological evolution of Singapore

7.1 Mesozoic collision

A single progressive D1 ductile to brittle–ductile deformation is recorded throughout the Jurong and Sentosa group (meta)sedimentary and volcanogenic strata that dominate the sub-surface geology of south and south-west Singapore, including the offshore islands in that region. Deformation is very strongly partitioned, the highest strains being expressed on discrete NE–vergent thrust structures that disrupt the developing NW–SE striking and NE-vergent fold patterns. The most important of these thrust structures is the Murai Thrust; the related Pasir Laba Thrust sub-divides the Murai Nappe (Fig. 13). Fold structures are typically inclined and overturned when viewed at decametre-scale. Fold axes are generally sub-horizontal to gently SE-plunging overall, though NW-plunges may be anticipated locally. Folding thus has a very significant impact on the geology of south and south-west Singapore and is responsible for the wide range of bedding dip values, including panels of overturned strata. Thrust structures will create low-angle high-strain discontinuities in the sub-surface.

Jurong and Sentosa group strata record metamorphic conditions that, at maximum, are equivalent to lowermost epizone (prehnite-pumpellyite facies); new minerals such as sericite mica, chlorite, and epidote show a preferred parallel alignment growing on penetrative foliation surfaces that are a consequence of non-coaxial (translational) deformation processes. Quartz overgrowths on original detrital quartz grains are very well-developed. Growth of new phyllosilicate minerals and epidote means that Jurong Group strata in particular are pervasively recrystallized to the extent that no primary porosity survives. Sentosa Group strata, and especially the Tanjong Rimau Formation strata, are more open-textured locally and may retain a greater degree of primary depositional porosity, suggesting slightly shallower burial after compaction and deformation than the Jurong Group strata.

Deposition of the Jurong Group strata was broadly contemporaneous with the emplacement of the various plutons that make up the Bukit Timah Centre. Tuffs and tuffaceous sandstones form a conspicuous element of the Pandan, Pulau Ayer Chawan, and Boon Lay formations of the Jurong Group succession, with the maximum development of eruptive volcanic activity at *c.* 242 Ma (Dodd *et al.*, this volume; Gillespie *et al.*, this volume). The younger Sentosa Group strata contain abundant eroded volcanic detritus and so apparently post-date the period of active arc magmatism (*cf.* Dodd *et al.*, this volume). Indeed, given that uplift and erosion was now apparently affecting the mature Sukhothai Arc, it may be that deposition of the Sentosa Group coincided with the timing of break-off of the old Paleo-Tethys oceanic slab. In any case, deformation in the Jurong and Sentosa group strata is thus younger than the period spanned by active arc magmatism (Fig.15, *cf.* Metcalfe 2017).

Polyphase ductile deformation and greenschist facies (biotite grade) metamorphism has affected Sajahat Formation strata found in the eastern (Pulau Sajahat) and northern (Punggol) parts of Singapore (Gillespie *et al.*, this volume; Oliver and Gupta, 2019). That polyphase deformation in Sajahat Formation strata is now understood to be Carboniferous in age (Oliver and Gupta, 2019), is clearly overprinted by the contact metamorphic effects of the developing Bukit Timah Centre plutons (DSTA, 2009), and so must wholly predate the age span of the active arc magmatism and the subsequent deformation of the Jurong and Sentosa group strata. We find no clear evidence of any pervasive tectonic overprint in Sajahat Formation rocks that might be related to the deformation events recorded in the younger Jurong and Sentosa group strata.

The age of the ductile deformation affecting the Jurong Group and Sentosa Group strata must post-date the youngest analysed detrital zircon reported from strata that are now assigned to the Sentosa Group Tanjong Rimau Formation (*c*. 209 Ma; Oliver *et al*., 2011, 2014; *cf*. Dodd *et al*. this volume). It is possible, though currently unproven, that deposition of the Sentosa Group could have extended from the uppermost Triassic into the earliest Jurassic after 201.3 Ma. The deformation recorded in Singapore suggests strongly that the last stages of closure of Palaeo-Tethys and the consolidation of Sundaland must also have straddled the Triassic/Jurassic boundary (*cf*. Carter *et al*., 2001; Hutchison and Tan, 2009; Metcalfe, 2017; Zhang *et al*., 2019),

We attribute deformation of the Jurong and Sentosa group strata of Singapore to the final stages of broadly east-directed (present day co-ordinates) suturing and amalgamation of the southern regions of Sibumasu and the Sukhothai Arc with the Indochina–East Malaya block (Fig.15). Other authors (e.g. Sone and Metcalfe, 2008, Sevastjanova *et al*., 2011; Metcalfe, 2013, 2017; Oliver *et al*., 2014, Ng *et al*., 2015b) have argued that collision of Sibumasu with the ocean-facing margin of the Sukhothai Arc across the Bentong–Raub Suture Zone occurred during the Late Triassic, and followed Early Triassic, Permian, or older deformation events attributed separately to accretion in the Bentong–Raub Suture Zone or to back-arc collapse and suturing of the Sukhothai Arc onto Indochina–East Malaya. These events have all been cited as parts of the Indosinian Orogeny leading to the assembly of 'proto-Southeast Asia' and Sundaland (*op.cit*.), following on from an original designation of 'Indosinian' in reference to tectonic events affecting Vietnam (Fromaget, 1938, 1941; *cf*. Tran van Tri, 2011). It is clear that orogenic deformation affecting the Jurong and Sentosa group strata in Singapore can only have succeeded deposition (after 209 Ma at least), and therefore occurred close to the Triassic/Jurassic boundary. This implies that strain accommodating final amalgamation and consolidation of Sundaland must have continued, if only locally, until this time. Oliver *et al*. (2014) proposed that Sibumasu overrode the Indochina–East Malaya Block during terminal stages of collision – the north-east-vergent accretionary tectonics observed in the Mesozoic strata of Singapore are consistent with this model. These more recent observations suggest that further regional-scale investigation would be of value in Johor and other parts of Peninsular Malaysia, and including Singapore and the adjacent Riau Islands.

7.2 Patterns of faulting in Singapore, regional stress and the timing of brittle deformation

Taken together, the full array of (E)NE–(W)SW, NNW–SSE, and NW–SE (and N–S) striking fault structures that transect the Singapore region (Fig. 4), fit well with a dextral shear regime in which the maximum compression direction (σ1) is oriented about 010 to 190°N (Fig.4 inset). NNW–SSE oriented fractures would equate to R1 Riedel shears (dextral); NE–SW oriented fractures to R2 Riedel shears (sinistral, as observed); and the subsidiary N–S fractures would equate to extension/normal faults in this regime. The NE–SW trending features are very likely to have formed by re-activation of fractures formed as ductile deformation, folding and thrusting waned and the stacked and deformed Jurong and Sentosa group strata cooled.

NW–SE oriented fractures, such as the BTFZ, would equate to P-shears (dextral) in this late Cretaceous regional stress regime; and ENE–WSW oriented fractures would equate to X-shears (sinistral, as observed). These last two fracture sets typically form somewhat later than the R1, R2 Riedel shears as strain intensifies in the same regional stress regime; in this case, ENE–WSW striking faults aligned with the Singapore Strait seem to the longest-lived (X) shears in the array as a whole and perhaps were reactivated later still in the Cenozoic. The R1, R2 Riedel shear offsets in this array seem typically to be small (of the order of 100 m or less, apparent left-lateral offset for R2); the X-shears seem to represent larger offsets of perhaps 500 m or so. In the absence of any tightly constrained fault cut-off data these estimates are however speculative.

The orientation of these fracture sets is consistent with an array of fractures associated with a dextral strike-slip principal displacement zone aligned sub-parallel to Peninsular Malaysia *(cf*. Bok Bak Fault Zone, Hutchison and Tan, 2009, p263). This deformation would likely have strongly overprinted any earlier brittle deformation developed towards the end of the waning fold and thrust deformation.

Dating of these long-lived structures is relative and unclear. There is no direct-dating evidence for the age of any fault structures in Singapore. Faulting clearly disrupts the Permo-Triassic plutonic igneous rocks of the Bukit Timah Centre. Faulting also clearly offsets the Triassic Jurong Group, Sentosa Group, and Lower Jurassic Buona Vista Formation lithostratigraphy and the patterns of ductile deformation that formed prior to, and after, the latest Triassic to earliest Jurassic brittle-ductile fold and thrust deformation. The Kusu and Bukit Batok formation strata are also clearly affected so that a significant component of the brittle (strictly fault-related) deformation must post-date deposition of these Lower Cretaceous strata. Tectonic activity appears to be much reduced after deposition of the Bedok Formation, though the western boundary of this formation against the granitic rocks of the Bukit Timah Centre is likely to have been modified to some extent by faulting (Nee Soon Fault, DSTA, 2009).

Hutchison and Tan (2009) concluded that dextral shear affected Peninsular Malaysia in the late Cretaceous, with subsequent sinistral reactivation of the fault systems in the Cenozoic. A modern systematic appraisal is lacking; a late Cretaceous to early Cenozoic (Palaeogene, <95 Ma) age for this extensive pattern of faulting across Singapore seems realistic and would allow for some localised reactivation after deposition of the Bedok Formation in the last two million years or so.

7.3 Current in situ *stress regime*

A number of studies of the current *in situ* stress regime have been undertaken in Singapore using hydraulic fracturing methods (Zhao *et al.,* 2005; Winn and Ng, 2013; Meng *et al.,* 2012). While there is some variability in the results, there is also broad agreement on the following:

- the setting is a thrusting regime ($\sigma H > \sigma h > \sigma v$)
- maximum horizontal stress is oriented NNE–SSW
- maximum principal stress varies from approximately 3 – 9 MPa
- at c. 250 m depth, the stress ratio is broadly 2:1.5:1. (σH:σh:σv).

The current *in situ* stress regime is therefore aligned within the Triassic to earliest Jurassic thrusting regime that produced the Murai and Pasir Laba thrust faults and the broad range of brittle fault orientations interpreted in the bedrock geology of Singapore.

8. Conclusions

Middle to Upper Triassic, deep marine to fluvial volcano-sedimentary inner forearc strata assigned to Jurong and Sentosa group successions in Singapore (Dodd *et al*., this volume) were deformed during compressional tectonics in the latest Triassic to earliest Jurassic climactic stages of Sundaland amalgamation and consolidation (*cf.* Hall, 2012; Metcalfe, 2017). Key features of the structural geology of Singapore include:

- Progressive shortening that transposed and tightened earlier-formed NW–SE trending inclined asymmetrical folds, culminating in the regional-scale development of a non-coaxial, NE-vergent and NE-facing, locally dextrally transpressive, fold and thrust system.
- The Murai Thrust and Pasir Laba Thrust are confirmed and extrapolated as major thrusts in this system; both structures are associated with SW-dipping imbricate thrust duplexes.
- The subduction-related magmatic complex represented by granitic to gabbroic plutons of the Bukit Timah Centre likely acted as a backstop to thrusting at this time.
- Lower Cretaceous Kusu and Bukit Batok formation strata overstep the orogenic deformation.
- Linked arrays of mostly NE–SW and ENE–WSW trending faults had developed by the late Cretaceous (possibly Cenomanian at least), and are an important control upon the surface and sub-surface distribution of bedrock units in Singapore.

- The disposition and movement history of these brittle faults was strongly influenced by dextral shear stress aligned parallel to Peninsular Malaysia, though this deformation will likely have reactivated faults initiated during Mesozoic orogenesis, or even earlier.

An understanding of the distribution and geotechnical impact of these structural features will be important for both future development and ongoing management of the subsurface in Singapore.

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Figures and Figure Captions:

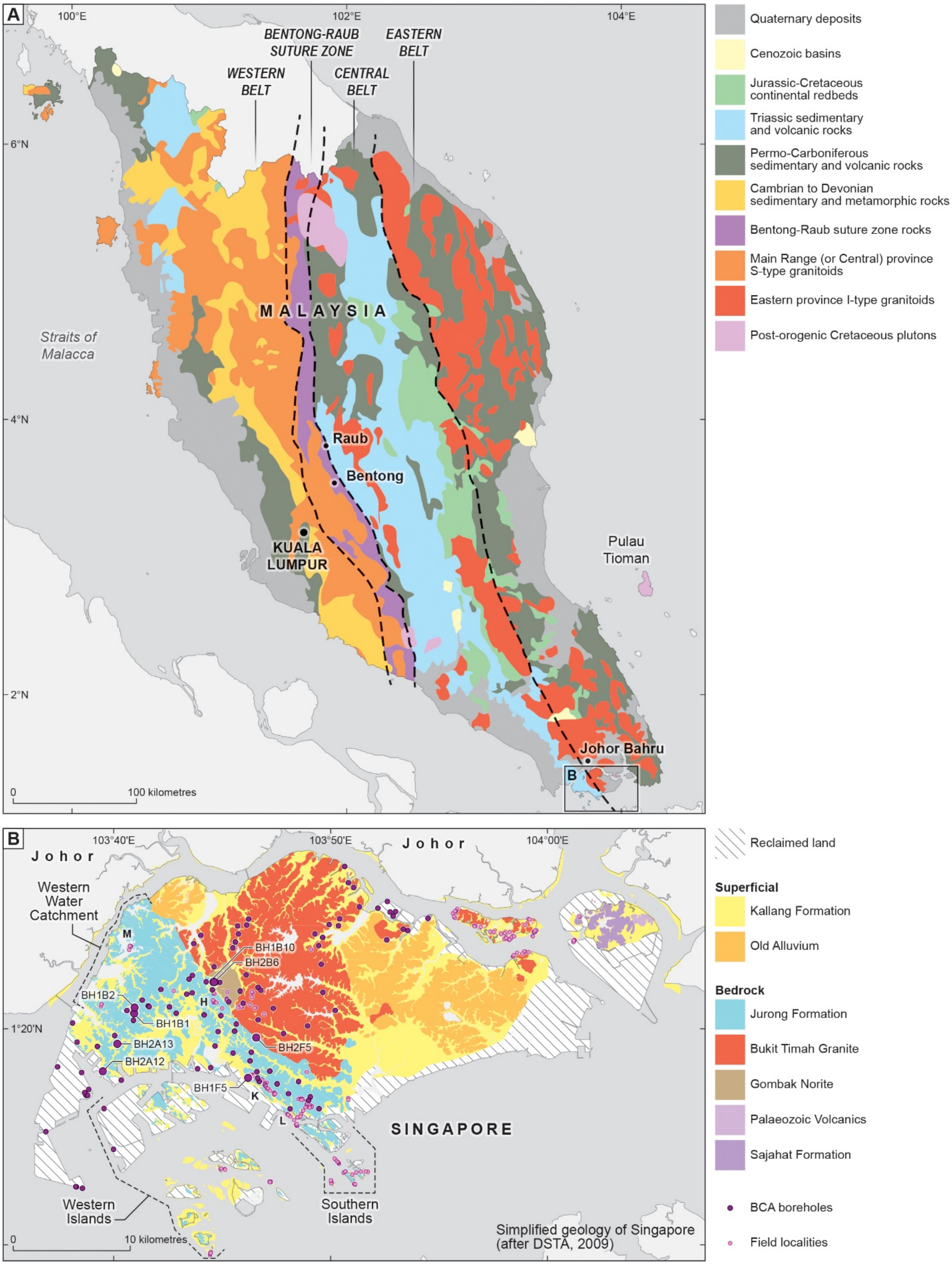


Figure 1

A – Simplified regional geological map of Peninsular Malaysia and Singapore including the tectono-stratigraphical Western, Central and Eastern belts, and the trace of the Bentong–Raub Suture Zone that marks the orogenic suture between Sibumasu (Western Belt) and the Sukhothai Arc (Central and Eastern belts), (after Metcalfe, 2013). This suture zone apparently passes some 50–100 km west of Singapore. Boxed area is shown in more detail in map B of Singapore.

B – Simplified, previously published, geological map of Singapore (box in A), showing the principal geological units (all unit names as previously published by DSTA, 2009). The Mesozoic (meta)sedimentary 'Jurong Formation' strata of southern and southwest Singapore shown here in blue should now be assigned to the Jurong and Sentosa groups (Dodd *et al*., this volume and Fig. 3). The location of new borehole cores acquired by BCA and described by BGS are superimposed (see also Fig.2), as well as the outcrop locations examined by BGS across Singapore; H – Hillside Park; K – Kent Ridge; L – Labrador Park; M – Murai Reservoir. Boreholes specifically referred to in the text are labelled.

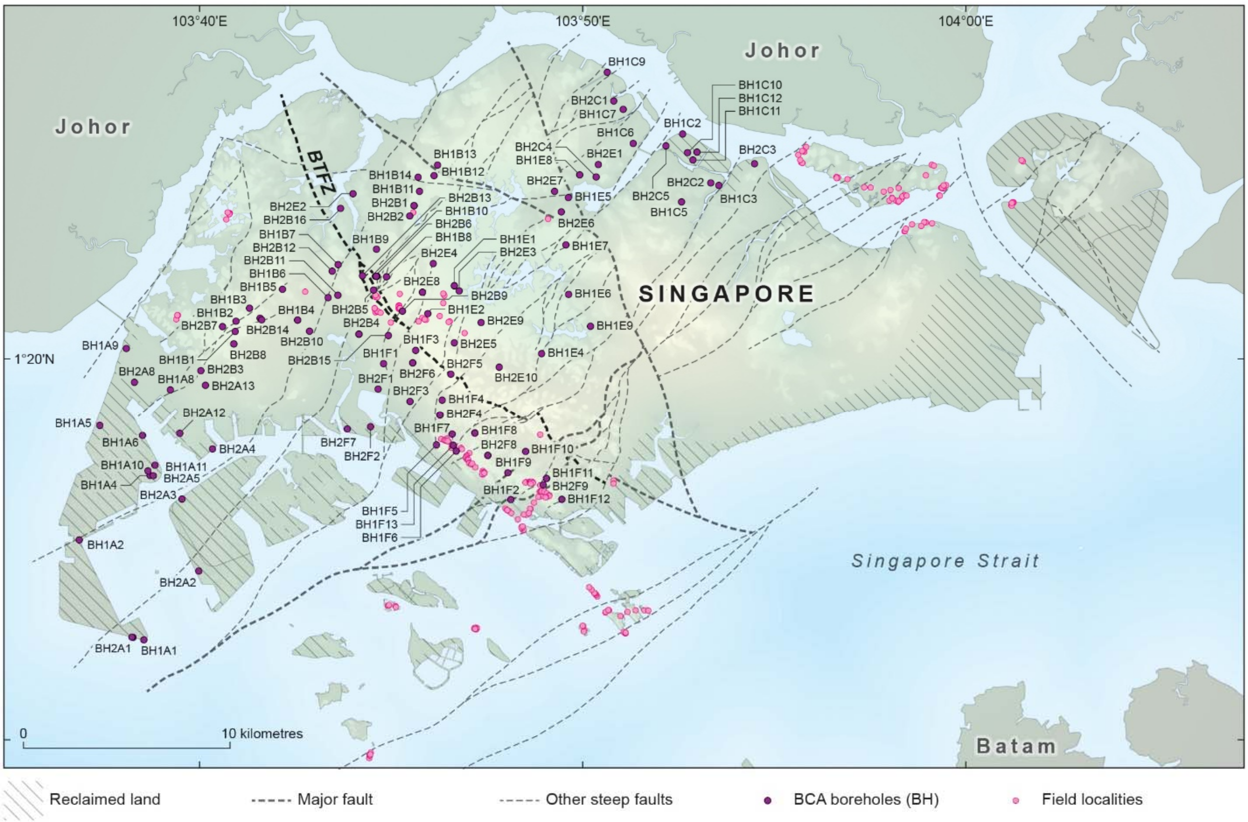


Figure 2

The distribution of BCA boreholes and field localities analysed as part of this study, superimposed on a new, and here simplified, geological linework showing the major geological boundaries including thrusts and other faults (*cf*. Figure 4). The Bukit Timah Fault Zone (BTFZ) essentially forms a boundary between the pre-Cenozoic (meta)sedimentary and igneous rocks of Singapore. In general, this study focuses on the boreholes and field localities in metasedimentary rocks in the southern and western parts of Singapore (see also Dodd *et al*., this volume); the remainder mainly access the igneous rocks of the Bukit Timah Centre (Gillespie *et al*., this volume).

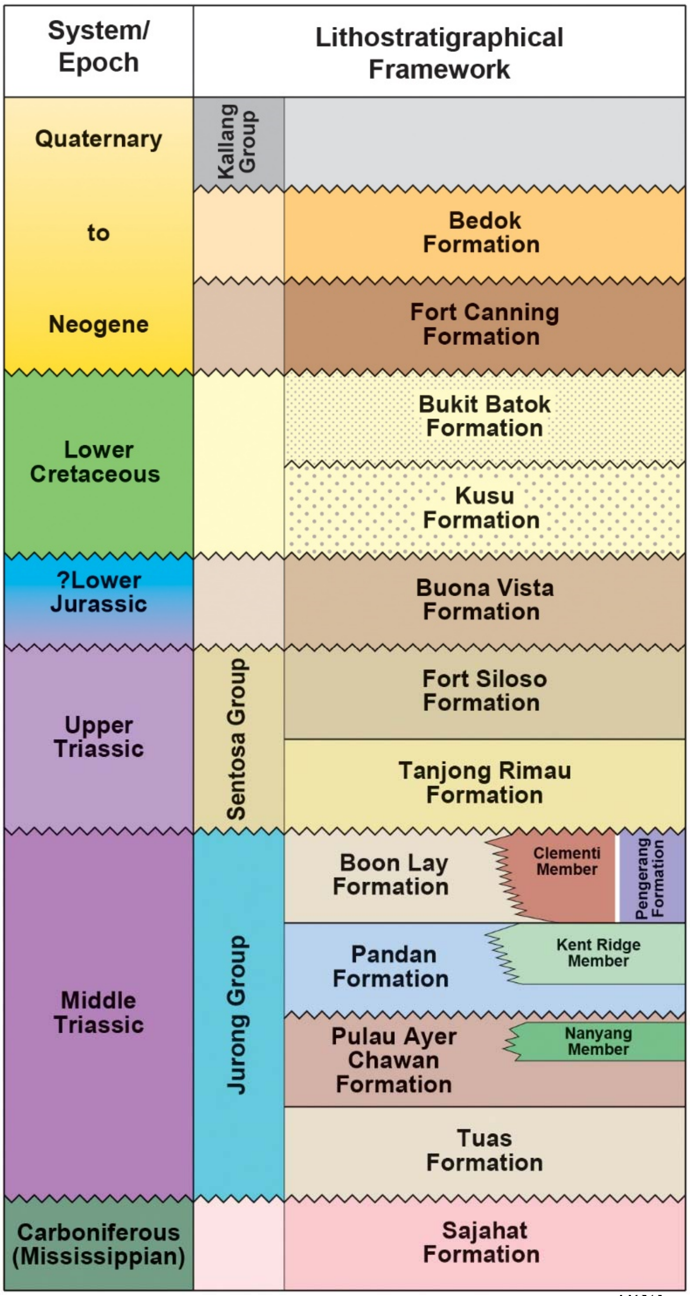


Figure 3

ICS-compliant lithostratigraphical column for Singapore bedrock geology. The Jurong Group is now subdivided as four new formations, the Sentosa Group comprises two new formations. The strata comprising these two groups in Singapore were formerly referred to collectively as the Jurong Formation (DSTA, 2009). The Lower Cretaceous Kusu and Bukit Batok formations have not previously been identified and were also previously assigned as Jurong Formation strata. The Fort Canning Formation and Bedok Formation are ICS-compliant names for the Fort Canning Boulder Bed and Old Alluvium respectively (*cf.* DSTA, 2009). This new lithostratigraphical framework for Singapore is formalised in Dodd *et al*. (this volume).

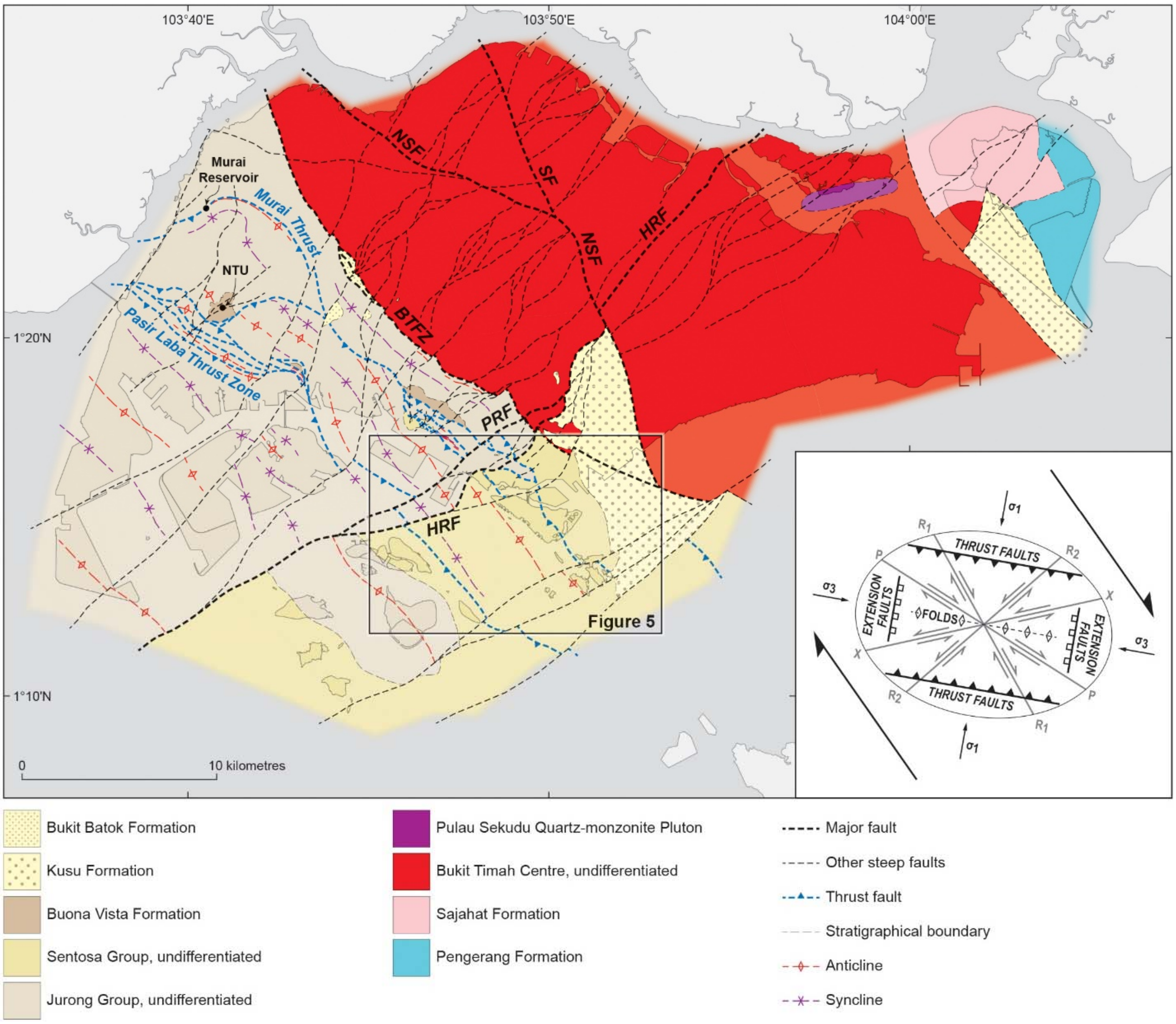


Figure 4

Revised but simplified geological map of Singapore derived from our interpretation of all available BCA data, including offshore bathymetrical data that provides some measure of constraint on fault patterns offshore. The map shows the principal geological units with the major fold, thrust, and fault structures superimposed. The Mesozoic Jurong and Sentosa group outcrops are shown undivided for clarity (*cf*. Figure 3). 'Murai Reservoir' is highlighted as a key exposure of the Murai Thrust in western Singapore; NTU – Nanyang Technological University campus (see text). Named brittle faults are labelled: HRF - Henderson Road Fault; PRF - Pepys Road Fault; NSF - Nee Soon Fault; SF – Seletar Fault; BTFZ - Bukit Timah Fault Zone. Boxed area is shown in more detail in Figure 5. The inset strain ellipse shows the array of fault orientations in Singapore in relation to a predicted maximum compressive stress direction, σ_1 (redrawn after McClay, 2013).

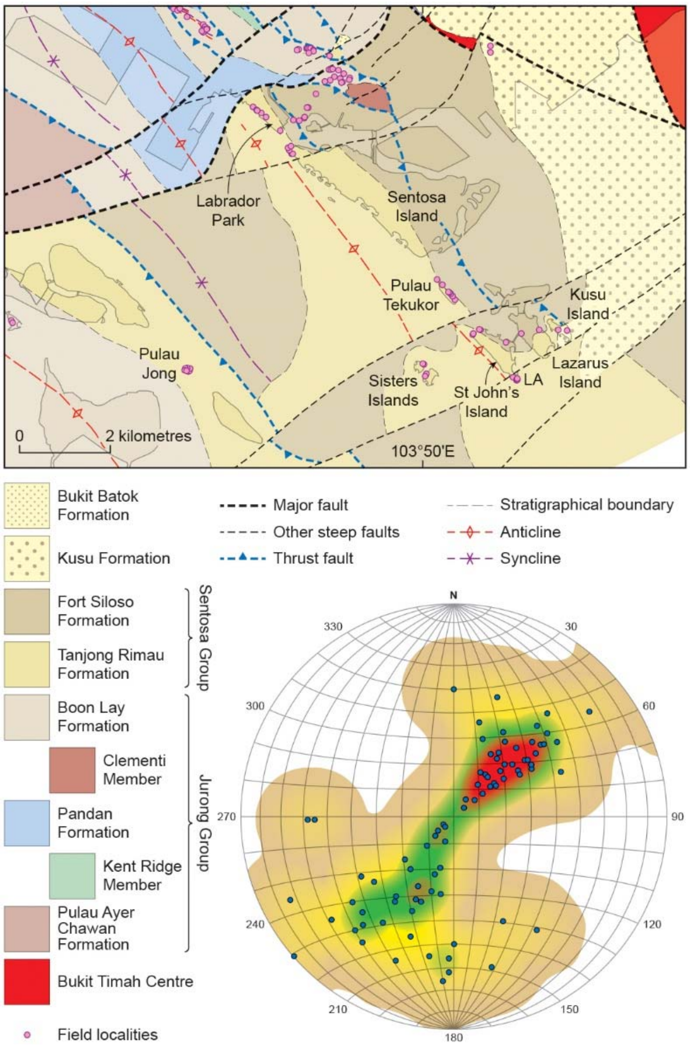


Figure 5

Bedrock geological map of southern Singapore, including the 'Southern Islands'; key field localities visited are superimposed on the formation level lithostratigraphy (*cf*. Fig. 3). LA – Lokos Anticline at Tanjong Lokos, St. John's Island. The stereonet shows bedding measurements in Sentosa Group strata from Sentosa Island and Labrador Park to St. John's and Lazarus Islands (equal area lower hemisphere projection, n = 81), NW–SE trending folding is clearly demonstrated.

Figure 6

A – Hinge area of a metre-scale anticline in sandstone and mudstone, northern shore of Pulau Jong. View to south-east, the hammer shaft is 35 cm long. (Locn. AGLE_156, [22769.9 22039.0]).

B – Well-developed discrete planar S1 foliation, in steeply NE-dipping planar laminated fine sandstone and mudstone, northern shore of St. John’s Island, Fort Siloso Formation. Profile view looking to the south-east. (Locn. KMGO_5, [29827.8 22611.9]).

C – Lazarus Island: Interbedded sandstone and siltstone, Fort Siloso Formation. S0 dips NE, and S1 is clearly seen in all lithologies (aligned parallel with compass-clinometer), and is clearly refracted across mudstone/sandstone layers. View to south-east. (Locn. KMGO_6, [30169.0 22806.0]).

D – Lokos Anticline in Tanjong Rimau Formation strata, St. John’s Island (Fig. 4). The fold is asymmetrical with a more steeply-dipping, and more intensely cleaved and rotated north-eastern limb to the right of the anticlinal hinge in this view. The S1 cleavage on the southwest limb dips steeply to the south-west and is north-east verging; an intense SW-dipping fracture cleavage occurs on the progressively rotated north-eastern limb of the fold. View to north-west, foreground figure is 1.8 m tall. (Locn. AGLe_140, [30070.8 21786.9]).

E – Intense south-west-dipping fracture cleavage, Lokos Anticline, St. John’s Island. This feature occurs on the progressively transposed and steepened north-eastern limb of the fold. Tanjong Rimau Formation sandstone. The hammer shaft is 35 cm long. (Locn. AGLe_140, [30070.8 21786.9]).

F – Intense, top-to-NE crushing/shearing in inner arc of Lokos Anticline, St. John’s Island. Gently north-east-dipping coarse-gravel fluvial sandstone, Tanjong Rimau Formation. View to north-west, hammer head is 15 cm long. (Locn. AGLe_140, [30070.8 21786.9]).

Figure 7

A – Fold closure in Pulau Ayer Chawan Formation sandstone and mudstone, BH2A12 [31439.2 08515.2]. The sharp basal boundary of the pale grey sandstone against darker grey mudstone is clearly folded across the core, locally becoming inverted. The scale bar is marked off in 10 cm intervals.

B – Core surface showing well-developed anastomosing S1 fabric, BH2A12. Note associated micro-offsets of the light grey sandstone/dark grey mudstone boundary indicating non-coaxial deformation.

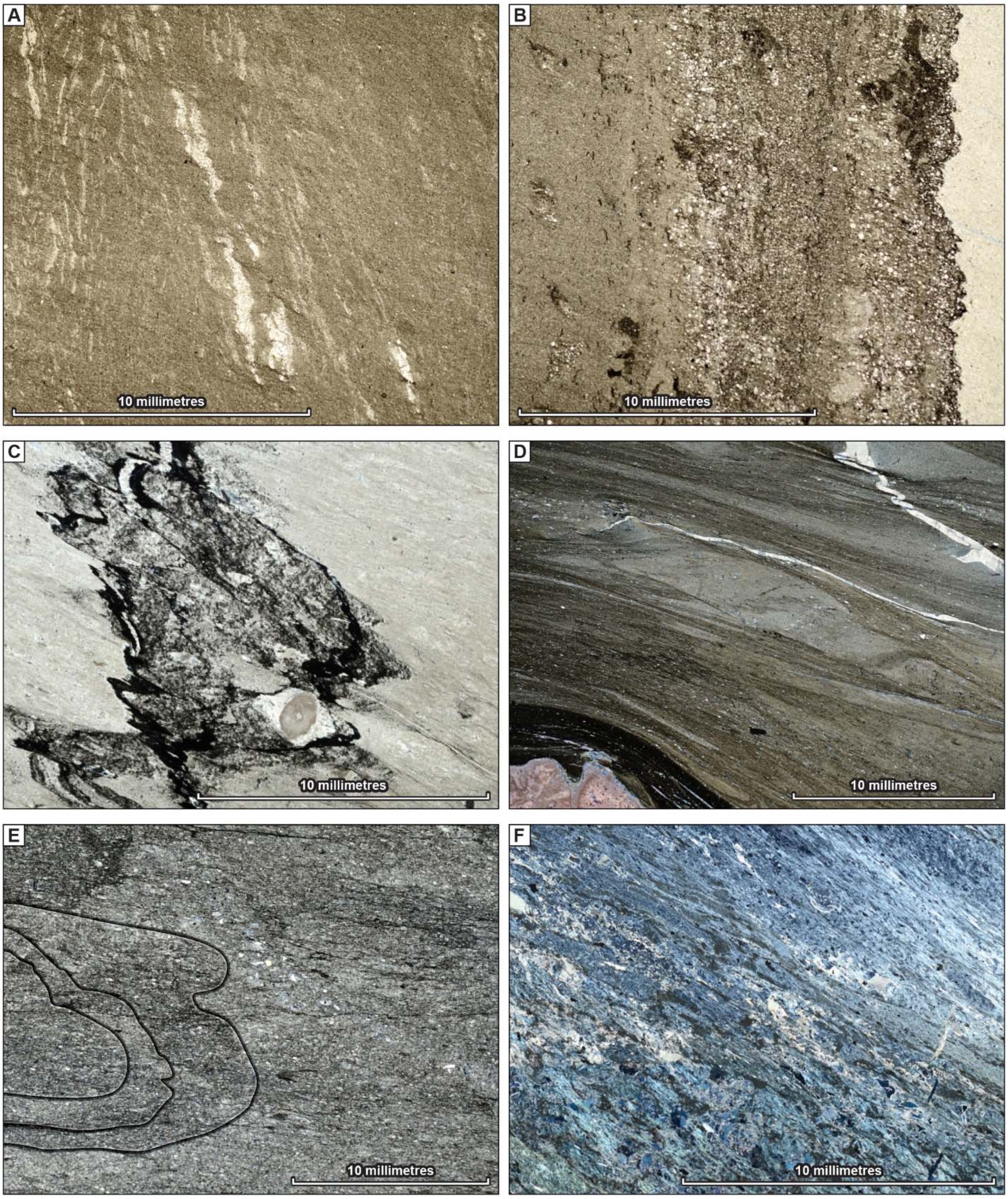


Figure 8

Photomicrographs illustrating the development of the S1 fabric in Jurong Group strata.

A – BH1A11, 156.9–157.0 m. Siltstone, Pulau Ayer Chawan Formation. Penetrative S1 fabric inclined left to right; dark iron-rich mineralisation on anastomosing pressure solution seams accentuate this fabric. S1 arranged at a high angle to the steep bedding lamination (S0) in this view. Note that micro-folding of S0 laminations is aligned on S1 as axial planer fabric. Plane-polarised light (PPL) image.

B – BH1A11, 117.5 117.86 m. Recrystallized, locally bioclastic, mudstone and siltstone, Pulau Ayer Chawan Formation, with conspicuous, pale coloured, fine-grained lithic-crystal-tuff horizon (to right) Well-developed, penetrative, pressure solution S1 fabric at a high angle to S0 laminations; non-coaxial simple shear fabric. Note micro-folding of S0 lamination at tuff/sandstone boundary. PPL image.

C – BH2A4, 127.8 - 128.0 m. Metalimestone. Pandan Formation. Intensely developed, anastomosing, S1 pressure solution fabric; axial planar close to tight folds of S0 lamination and black stylolitic seams (and of secondary calcite veins within those stylolite features). PPL image.

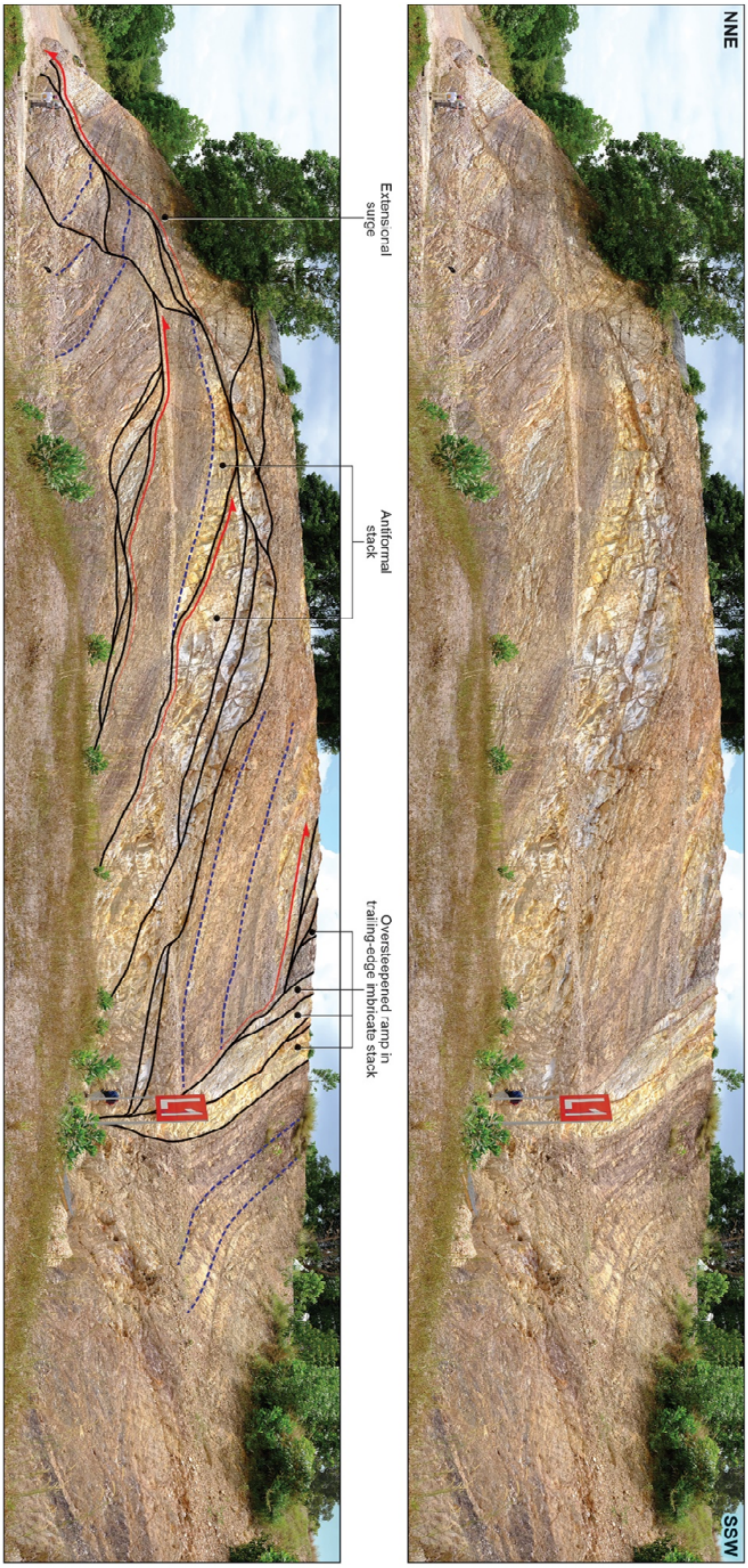
D – BH1A6, 161.2–161.40 m. Metamudstone, Pandan Formation. Very well-developed, intensely penetrative S1 anastomosing pressure solution fabric, with very tight folds of S0 lamination arranged around axial planar S1 fabric. Note cross-cutting (pressure solution) calcite vein is folded in that same S1 fabric. Note also that fabric deflects around little-modified macrofossil fragments. Chlorite grows on this S1 fabric confirming epizone-grade metamorphism. PPL image.

E – BH1A8, 172.05–172.15 m. Metacarbonate rock, Pandan Formation. Well-developed S1 fabric with axial planar relationship to close folds of S0 lamination (outlined). Pronounced grain-shape fabric in clastic quartz grains is aligned with S1. PPL image.

F – BH2A13, 160.15–160.35 m. Pyroclastic rock – ignimbrite, Pulau Ayer Chawan Formation. Strongly-developed S1 fabric (in sericite-chlorite trails), especially in upper left portion of view. Note that S1 is in an 'S/C' relationship with deformed fiamme and the earlier eutaxitic fabric in the ignimbritic groundmass (latter dominant in lower right of view). Cross-polarised image (XPL) image.

Figure 9

Murai Thrust: Western Water Catchment, SAFTI Live Firing Area. View centred on Locn. AGLe_22, [10906.3 42099.4]. The line interpretation (lower panel) of the panorama captured in the top panel shows the antiformal stacking of thrust imbricates in Jurong Group strata (Boon Lay Formation), and steepening of the trailing-edge imbricate stack, during top-to-NE tectonic transport (to the left in this image). View is to the south-east; the outcrop is some 18 to 20 m high.



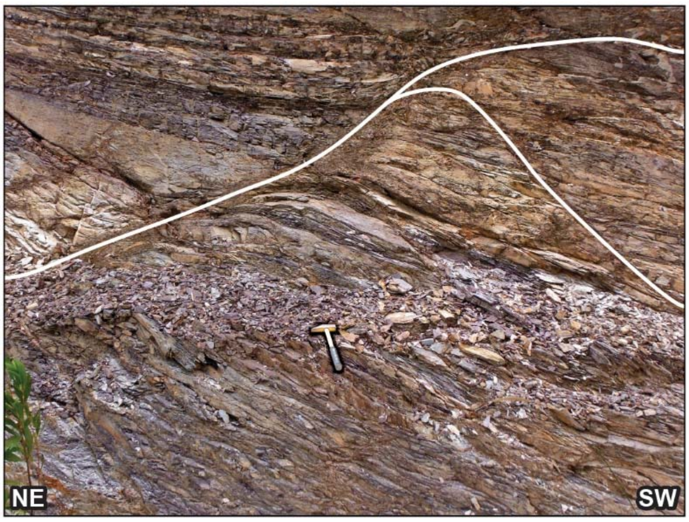


Figure 10

Murai Thrust: Locn. AGLe_22, [10906.3 42099.4]). Secondary shears (highlighted) cross-cutting and modifying anastomosing shear fabric in Jurong Group strata to produce top-to-NE antiformal stacking. View to south-east, the hammer shaft is 35 cm long.

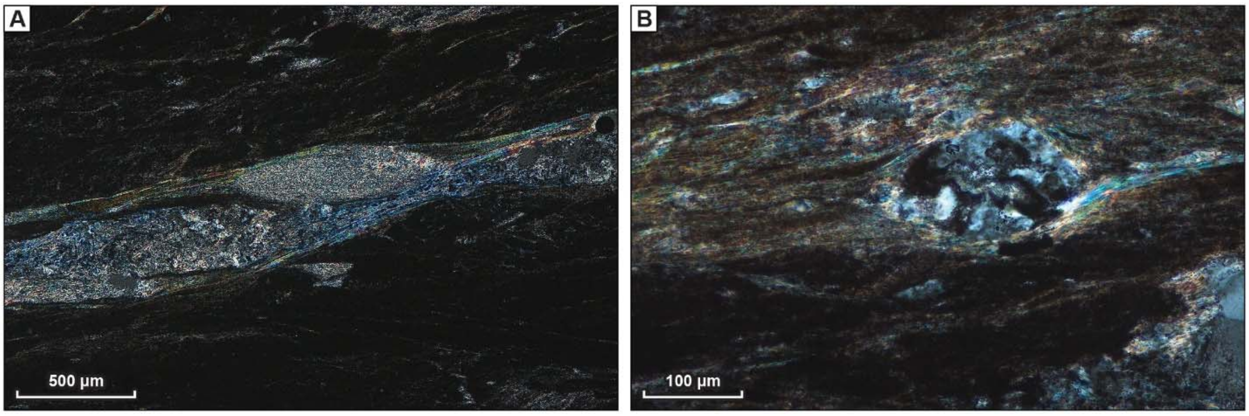


Figure 11

Murai Thrust: Locn. AGLe_22, [10906.3 42099.4]. Shear indicators in phyllonitic mudstone, Boon Lay Formation. A: elongate and stacked sericite 'mica fish' extending up to ~1.5 mm. B: sigma porphyroclast formed from recrystallised, 'cherty' quartz in phyllonitic argillised matrix. Quartz is only significantly recrystallized in these strata at these highest strains, indicating lowermost epizone metamorphic conditions. In both cases the sense of shear is sinistral as shown and top-to-the-NE in reality. XPL in both views.

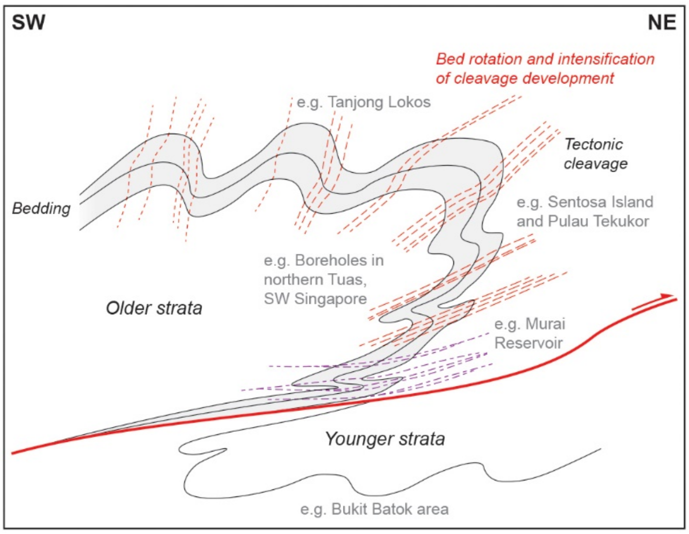
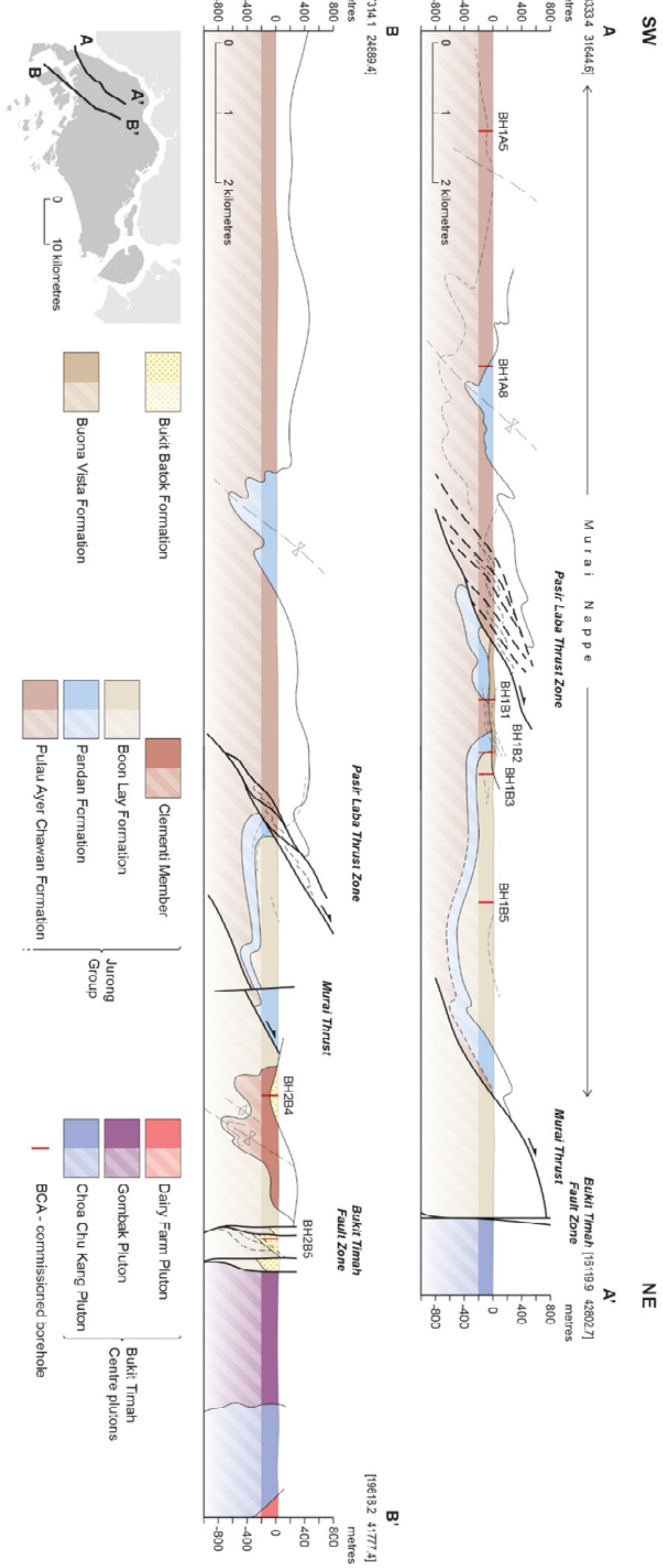


Figure 12

Composite cross-sectional schematic model for the ductile deformation of the Jurong and Sentosa group strata in southern and south-west Singapore. No specific structures are named in the model, see further discussion in text. The model is intended to be essentially scale-independent representing process.

Figure 13

Cross-sections constructed along the lines A–A’ and B–B’ in south-west Singapore – see inset map lower left. These sections are representative of the digital 3D National Geological Bedrock Model of Singapore created by BGS for BCA and are based upon the overall understanding of the structural architecture of the sedimentary rocks examined in boreholes and outcrop across south-west Singapore. Steep faults are omitted for clarity. The solid colour bar in these images, and the superimposed linework, reflects the volume occupied by the individual formations and their boundaries and structure in the new digital bedrock model. The diagonal shading and linework below represents the likely extension of the model units at depth; likewise, the model linework is projected above the present ground surface. The lithostratigraphy in this part Singapore is represented at formation level and thus provides a greater degree of resolution than in the Figure 4 map.



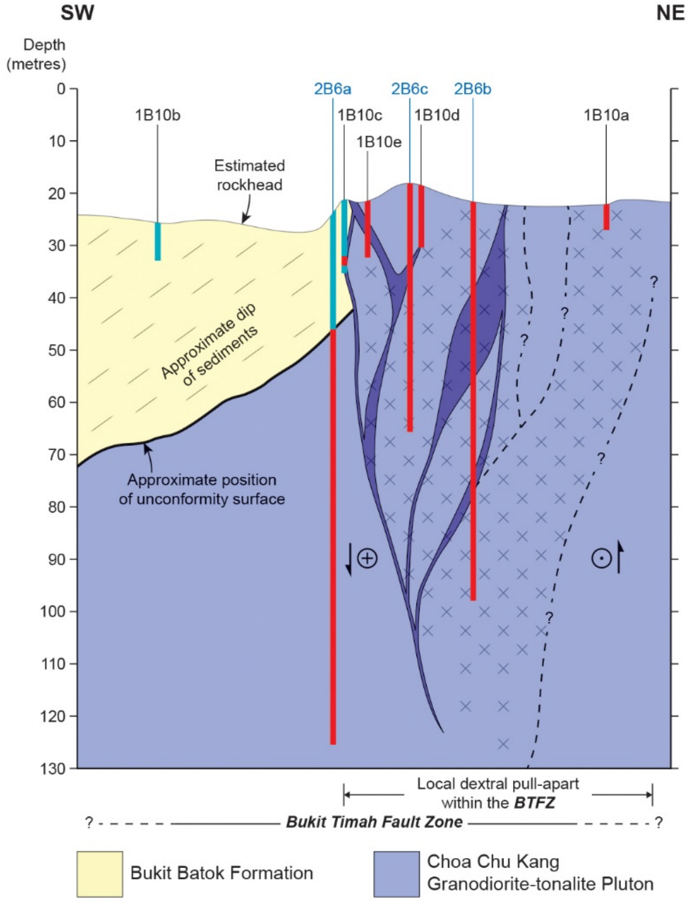


Figure 14

Interpretation of the geology of the Bukit Timah Fault Zone from profiles of the BH1B10 and BH2B6 series boreholes (Figs. 1B and 2). Vertical and horizontal scales are identical. Vertical bars below rockhead represent cores; blue fill denotes sedimentary rocks in core, red fill denotes igneous rocks in core. Borehole identifiers are abbreviated (e.g., '1B10b' is an abbreviation of BH1B10b). 'X's denote areas where intervals or occurrences of fault-rock are observed and/or inferred. Dark blue = inferred position of fault strands. Half-arrows indicate the sense of the vertical component of displacement; '+' and '•' the horizontal component. See text for details of geological interpretation.

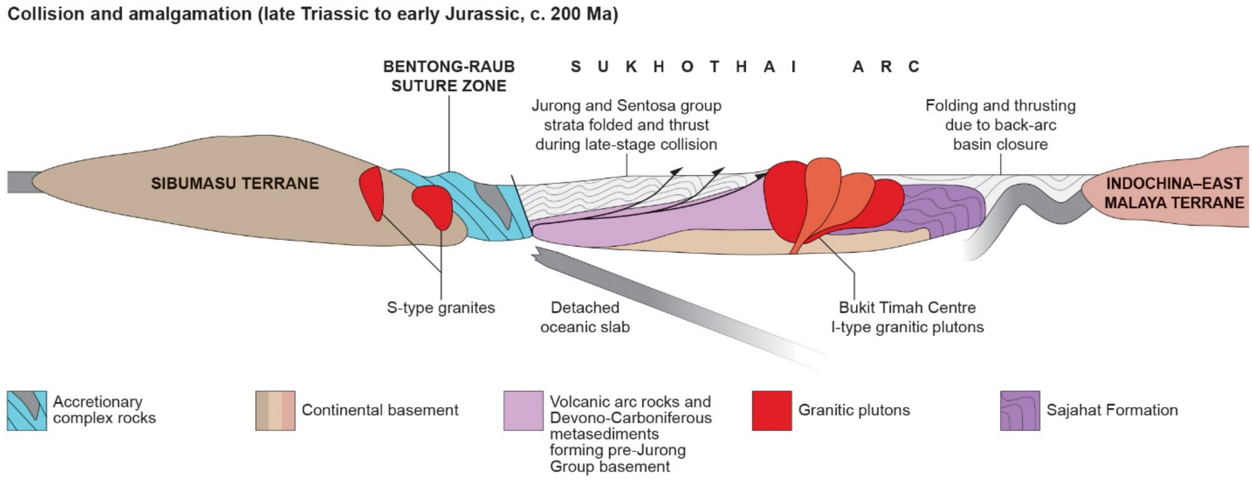


Figure 15

Cartoon showing the tectonic evolution of the Singapore crustal region during late Triassic to earliest Jurassic times, and as it 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; Ng *et al*. 2015a, b; Metcalfe, 2017; Dodd *et al*., this volume; Gillespie *et al*., this volume). The Sibumasu and Indochina-East Malaya terranes are shown in highly simplified form but see also Metcalfe (2017) for details of these elements.