A FIELD GUIDE TO THE GEOLOGY OF SINGAPORE

Grahame J. H. Oliver and **Avijit Gupta**

Lee Kong Chian Natural History Museum
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Grahame J. H. Oliver[1] and **Avijit Gupta**[2]
[1]Asian School of the Environment, College of Science, Nanyang Technological University
50 Nanyang Avenue, Singapore 639798, Republic of Singapore
[2]School of Earth and Environmental Sciences, University of Wollongong
Northfields Avenue, Wollongong NSW2522, Australia
Email: gjholiver@ntu.edu.sg (GJHO) and agupta@uow.edu.au (AG)

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Cover photograph of Little Guilin showing a fault and a white granite dyke cutting the strongly jointed dark gabbro © Grahame J. H. Oliver. The height of the quarry face is 45 m.

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CONTENTS

PART ONE

The aim of this guide is to introduce the reader to the geology of Singapore by way of field excursions to relevant sites of interest.

Plate tectonic Evolution of Singapore. — To understand the geology of Singapore, it is necessary to review the regional geology of the Malaysian Peninsula in terms of plate tectonic evolution. The following sections are summarised from Hutchison & Tan (2009), Lee & Zhou (2009), Metcalfe (2011), Oliver & Prave (2013), Oliver et al. (2014), and Ng et al. (2015a, b).

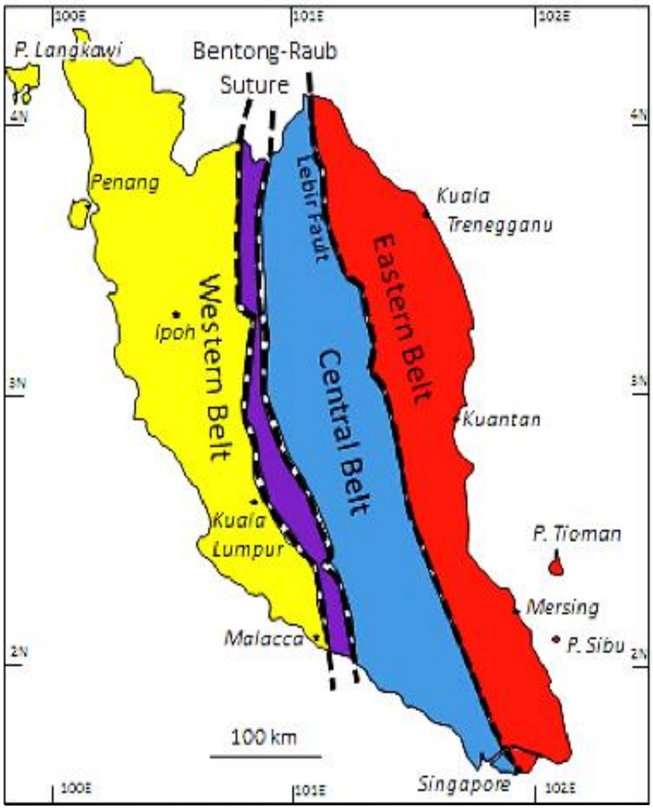

Fig. 1. Simplified geological subdivision of the Malaysian Peninsula and Singapore into Western, Central, Eastern Belts and the Bentong-Raub Suture. Modified from Hutchison & Tan (2009).

Linear belts of sedimentary and igneous rocks that run north northwest–south southeast down the Malaysian Peninsula can be divided into three belts, namely the Eastern, Central and Western Belts.

Fig. 1 is a simplified geological map of Peninsular Malaysia showing that the Eastern Belt is separated from the Central Belt by the Lebir Fault and the Central Belt is separated from the Western Belt by the Bentong-Raub Suture. Singapore lies at the southern tip of Peninsular Malaysia on the boundary between the Eastern and Central Belts.

The Eastern Belt. — In eastern Johor in southern Peninsular Malaysia, fossiliferous Permian conglomerates unconformably overlie metamorphosed sandstone (quartzite) and mudstone (biotite schist) of the Mersing Beds which are assumed to be Carboniferous in age (350–300 Ma[1]). Younger Permian (~300–250 Ma) shallow water marine sediments and Permian to Middle Triassic (285–240 Ma) andesitic volcanics and granites (with biotite and hornblende) are typical of those rocks found at modern active margins where subduction is occurring under volcanic arcs (e.g., as in the present day Andes or in the Sumatra–Java Volcanic Arc). The Eastern Belt is also called the Sukhothai Volcanic Arc which can be traced into Thailand and Cambodia. Permian fossil plants indicate equatorial affinities with Indochina. In Singapore, the boundary between the Central and Eastern Belts is marked by the Bukit Timah Fault (see Fig. 5).

The Central Belt. — The Central Belt contains thick sequences of fossiliferous shallow water marine Middle Permian to Middle Triassic (i.e., 275–240 Ma) mudstones and limestones and associated andesitic volcanic and Andean-type granites similar to (and therefore a younger continuation of) those in the Eastern Belt Sukhothai Volcanic Arc. The Central Belt is distinguished from the Eastern Belt by having Late Triassic (i.e., 230–200 Ma) continental red-bed deposits of sandstones and conglomerates.

[1]Ma = Million years before the present. “M” is the symbol for million, and “a” is the symbol of the *annus*, which stands for year before present, hence Ma.

The Western Belt. — The Western Belt has a Cambrian (~500 Ma) to Middle Triassic (~240 Ma) marine sedimentary sequence including low latitude Permo-Carboniferous glacial marine beds. There is a notable lack of Permian volcanic activity in the Western Belt generally and no record of Late Triassic sedimentation. Fossils indicate cold water Gondwana Permian fauna in contrast to the equatorial Indochinese Permian fauna of the Eastern Belt. The Western Belt is thought to represent the passive continental margin of Gondwanaland.

Granites in the Western Belt contain biotite and muscovite, similar to Himalayan continental collision granites and in contrast to the biotite-hornblende subduction zone granites in the Central and Eastern Belts. Western Belt granites are dated as Late Triassic (between 220–200 Ma) and are therefore younger than the Central Belt granites (280–220 Ma).

The Bentong-Raub Suture Zone. — The Bentong-Raub Suture Zone, which separates the Western and Central Belts, is a highly tectonized mixture of broken rocks of the former ocean floor such as serpentinite (formed by metamorphism of mantle peridotite) and amphibolite (formed by metamorphism of ocean crust basalt and gabbro). Limestone formed around submarine basalt volcanoes. Cherts represent accumulations of pelagic radiolaria micro-organisms and have Lower Devonian to Middle Triassic (i.e., ~410–240 Ma) ages which give the age of the sea floor. The tectonism and metamorphism that caused the deformation of the Palaeo-Tethys Ocean floor is thought to have occurred when the Western Belt collided with the Central Belt and the two were sutured together. The Bentong-Raub Suture Zone is overlain by conglomeratic continental red-beds, lavas, ash and felsic volcanics stitched through with Late Triassic (226 Ma) granites. On this evidence, the collision and suturing is dated at between 240 (the age of the youngest chert) and 226 million years ago (the age of the oldest stitching granite intrusions) in the Late Triassic.

Plate tectonic Model of the Malaysian Peninsula. — The Western Belt is part of a continental slice called **Sibumasu** (because it is found in **Si**am, **Bu**rma, **Ma**laysia, and **Su**matra) rifted off from glacial Gondwanaland. Sibumasu drifted across the Palaeo-Tethys Ocean to collide with the equatorial Sukhothai Arc along the Bentong-Raub Suture (Figs. 2, 3).

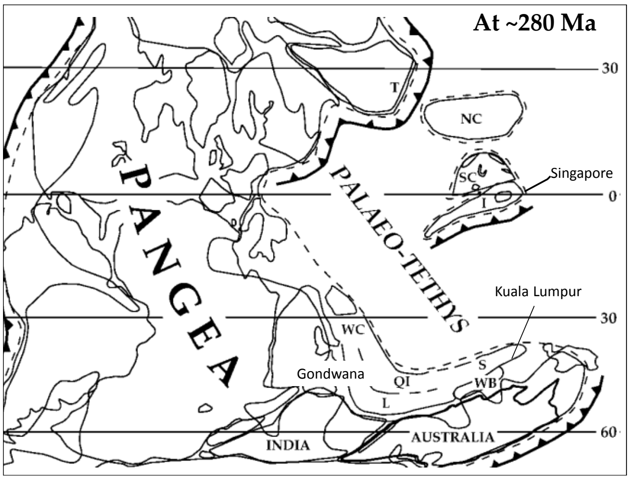

Fig. 2. Left: Palaeogeography of Pangea and Palaeo-Tethys at 280 Ma (after Metcalfe, 2011). Key: I = Indochina. L = Ladek. NC = North China. QI = Qiang-Tan. S = Sibumasu. SC = South China. T = Tibet. WB = West Borneo. WC = Western Cimmerian Continent. Note the location of Sibumasu (with the site of Kuala Lumpur) on the passive margin of Gondwana and the site of Singapore on the active margin of Indochina.

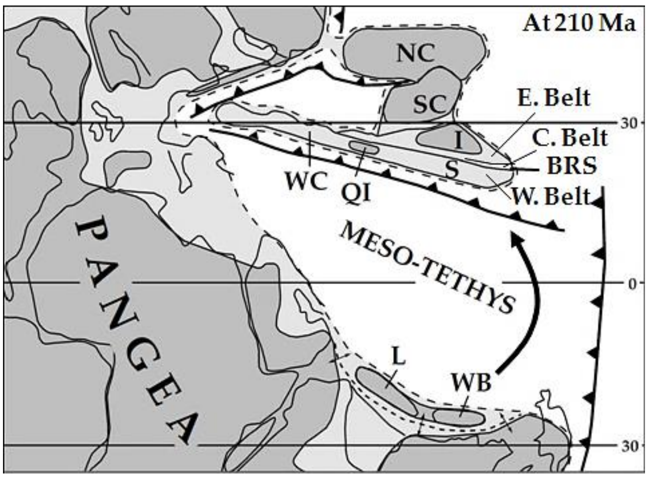

Fig. 3. Right: Palaeogeography at 210 Ma (after Metcalfe, 2011). Same key as Fig. 2: BRS = Bentong-Raub Suture. Note that Sibumasu (Western Belt) has drifted across the Palaeo-Tethys Ocean and has collided with Indochina (Central and Eastern Belts) along the BRS Zone. Figs. 2, 3 reproduced from Oliver et al. (2014), with permission from Elsevier.

The Sukhothai Volcanic Arc was initiated in the Early Permian (i.e., the age of the oldest volcanics). This is probably also the time when Sibumasu rifted away from Gondwana. The age of the beginning of the collision of Simumasu with Indochina (i.e., Western Belt against Central Belt in Malaysia) is dated by the age of the first Himalayan-type (muscovite) granites in the Western Belt: i.e., 226 Ma (Late Triassic). The end of collisional processes of crustal thickening and crustal melting is dated by the youngest Western Belt granite: i.e., 198 Ma (Earliest Jurassic). The ages 226–198 Ma coincide with the age of the Late Triassic continental red beds in Singapore.

Most hypotheses push the Western Belt *eastwards* under the Central Belt during the collision, thus doubling the continental crustal thickness and causing Himalayan-type lower crustal melting. These models would cause crustal melts to rise up and intrude into the Central Belt. This is not the case: Himalayan-type crustal melts intrude the Western Belt, not the Central Belt. Oliver et al. (2014) proposed that the Eastern Belt Sukhothai Arc was initiated in the Early Permian and the Central Belt was pushed *westwards* under Western Belt during a Late Triassic collision. This explains why Himalayan-type granites occur in the Western Belt and not in the Central Belt. This palaeogeography is illustrated in Fig. 4.

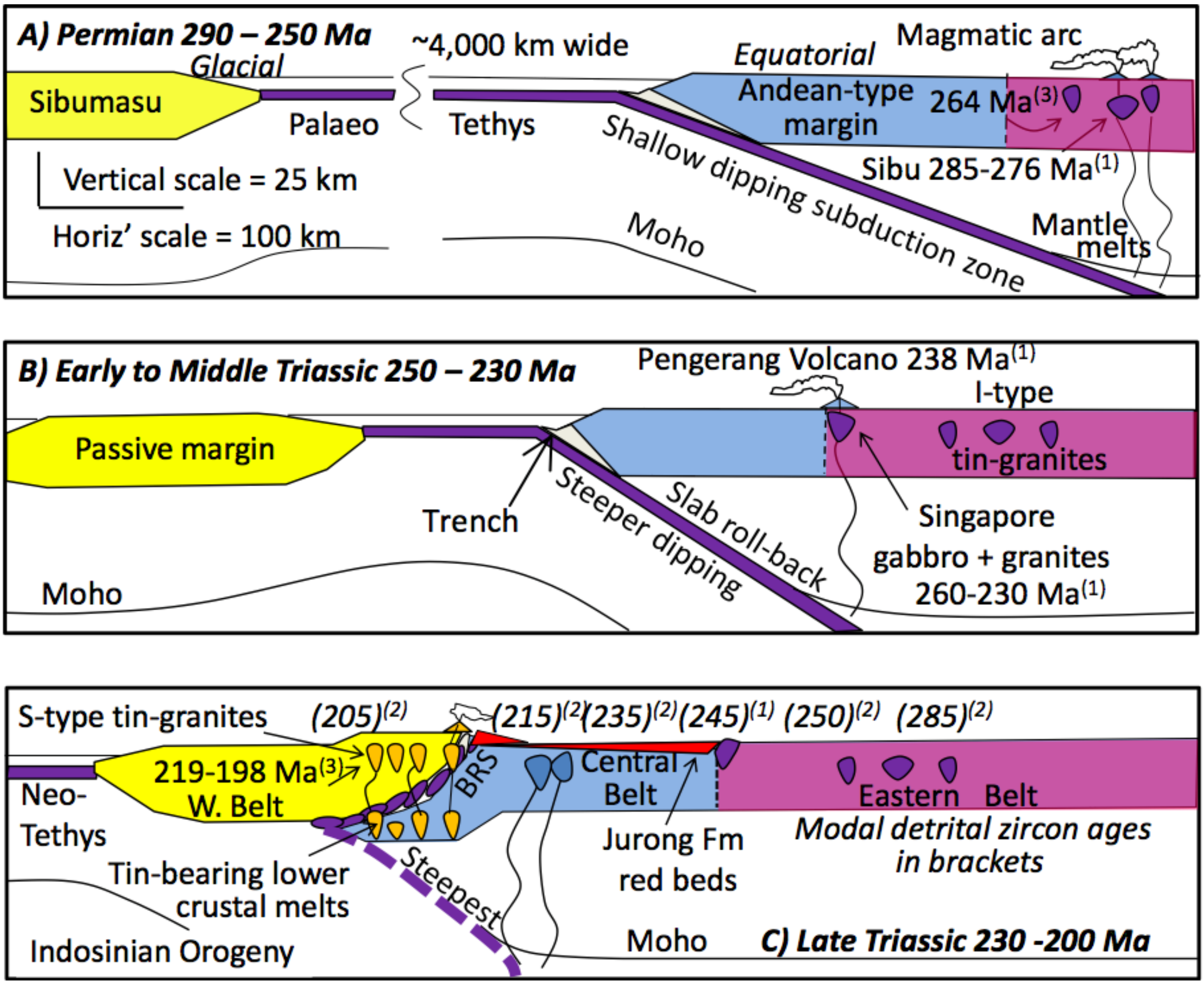

Fig. 4. Cartoon crustal cross-sections of the plate tectonic evolution of the Malaysian Peninsula between 290–200 Ma (from Oliver et al., 2013). Age dates (in millions of years) are from (1) Oliver et al. (2013), (2) Sevastjanova et al. (2011), (3) Liew and McCulloch (1985). BRS = Bentong-Raub Suture. The line of the section is orientated west-southwest to east-northeast from Kuala Lumpur to Kuantan as shown on Fig. 1. Reproduced from Oliver et al. (2014), with permission from Elsevier.

The Bentong-Raub Suture Zone therefore contains the relicts of the floor of a ~3,500 km wide Palaeo-Tethys Ocean that once separated Sibumasu (i.e., the Western Belt) from Indochina (i.e., the Central and Eastern Belts).

The Bentong-Raub Suture Zone and the Central and Eastern Belts are partly covered in continental red beds which are considered to be river, flood plain and lake deposits formed during the erosion of mountains thrown up when Sibumasu collided with Indochina. This period on mountain building in South East Asia is known as the Indosinian Orogeny which lasted from 226–200 Ma.

PART TWO

The Geology of Singapore. — The following text is a recent revision and reinterpretation of the geological history as presented by Lee & Zhou (2009), based on new mapping and new U-Pb zircon radiometric age dating by Oliver & Prave (2013) and Oliver et al. (2014).

The geology of Singapore can be represented on a map by eight units, namely the Sajahat Formation, Murai Slate, Gombak Gabbro, Singapore Granites, Pengerang Volcanics, Jurong Formation, Old Alluvium, and Kallang Formation (see Fig. 5).

Sajahat Formation. — Pulau Sajahat is an islet, located between Changi and Pulau Tekong, (Fig. 5) and is the type locality for the unfossiliferrous Sajahat Formation of so called argillites and quartzites. Lee & Zhou (2009) discussed two hypotheses for the age of deposition, i.e., *either* Lower

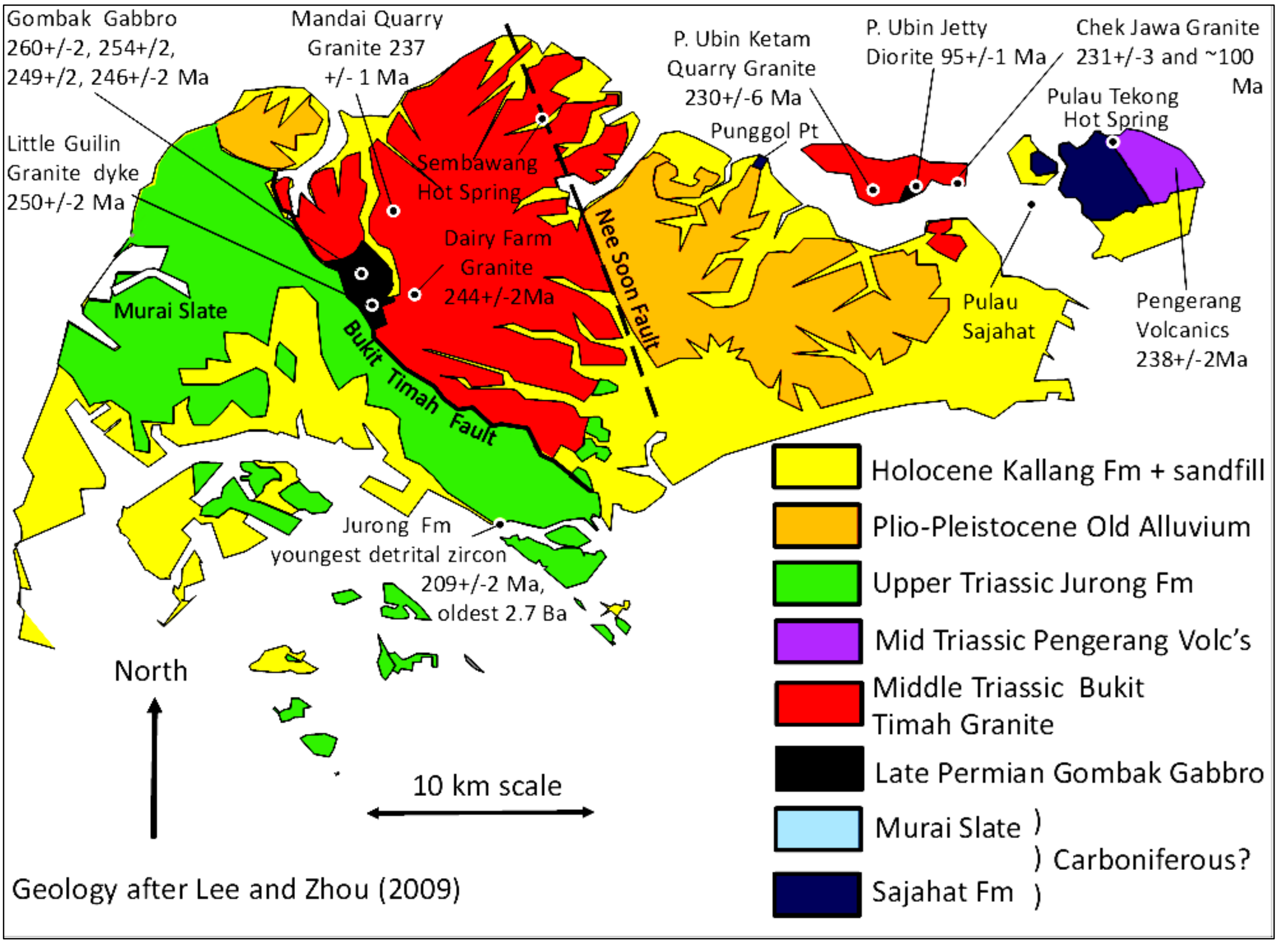

Fig. 5. Geological map of Singapore showing the results of U-Pb zircon age dating. Modified from Oliver et al. (2014) with permission from Elsevier.

Palaeozoic (and the oldest rocks in Singapore) *or* interdigitated with the Pengerang Volcanics in south Johor. The latter were formally considered to be Lower Palaeozoic but have since been U-Pb zircon dated at 238 ± 2 Ma, Middle Triassic (Oliver et al. 2014). Field work by GJHO revealed that the argillites (former mudstones) and interbedded quartzites (former sandstones) were deposited as turbidites, possibly in a deep sea fan.

The Pengerang Volcanics are not regionally metamorphosed, nor do they display the foliations and recumbent folding seen on Pulau Sajahat. Therefore the Sajahat Formation predates the Pengarang Volcanics and the unfoliated granites and gabbro (norite) of Singapore Island. The oldest gabbro is dated by Oliver et al. (2014) at 260 ± 2 Ma (Late Permian). The Sajahat Formation is therefore pre-Late Permian in age. The Sajahat Formation is very similar to the unfossiliferous, regionally metamorphosed, Mersing Formation described in eastern Johor and *assumed* to be Carboniferous in age because it is unconformably overlain by fossiliferous Permian conglomerates. Of course it could be older than Carboniferous.

Murai Slate. — Alexander (1950) recognised schists near Murai and postulated that they were the oldest rocks in Singapore. She did not report on the Sajahat Formation which has a more complicated (older?) structural history (see above). Lee & Zhou (2009) interpreted the Murai Schist (*sic*) as a zone of well-developed cleavage within the Jurong Formation. Actually, the present day outcrops in Murai Reservoir are purple slates, not schists, metamorphosed from mud. X-ray diffraction studies (Calder & Oliver, un-published) show that the clay in the slates is illite of epizone grade (i.e., regionally metamorphosed at 200–275^{o}C and depths of 8–10 km) whilst the neighbouring red and purple mudstones of the Jurong Formation fluvial facies have diagenetic grade kaolinite plus mix-layered smectite clay (i.e., buried less than 4 km with temperatures less than ~125^{o}C). The Murai Slate probably occurs in a faulted inlier within the outcrop of the Jurong Formation (see Fig. 5). The Gombak Gabbro is not cleaved so it can be assumed that the Murai Slate is older than the gabbro which is radiometrically dated as latest Permian (see below). The age of deposition and metamorphism is problematical since there are no fossils. Similar unfossiliferous slates on Batam, 20 km across the Singapore Straits are *assumed* to be Carboniferous.

Gombak Gabbro. — Gabbro occurs around the Gombak district in the centre of Singapore Island (Fig. 5). At Little Guilin, it contains 50% plagioclase, 35% orthopyroxene, 5% olivine, 5% brown hornblende and 5% opaques and is locally called the Gombak Norite. The zircon U-Pb dating ages vary from 260.3 ± 2.3 at Little Guilin (Late Permian) to 245.6 ± 2.3 million years old (Middle Triassic) on Butik Batok.

There is a prominent north-east/south-west trending ~3 m thick granite dyke in the middle of Little Guilin Quarry. It has an Early Triassic zircon U-Pb age of 249.9 ± 1.9 million years (Oliver et al., 2014). Significantly, the granite dyke does not have chilled margins, suggesting that the country rock gabbro was still hot during the dyke intrusion and that the gabbro and granite dyke are cogenetic.

Bukit Timah Granite. — Granite occupies the central and eastern parts of Singapore (Fig.5). Around Bukit Timah, it typically contain 30% quartz, 30% plagioclase feldspar, 30 % potassium feldspar, and 5% biotite. Some varieties, particularly those from Pulau Ubin, contain 5–10% hornblende. Mineralogically and chemically they are typical of the Eastern Belt, Andean-type granites formed in the Sukhothai Volcanic Arc in Thailand and Eastern Malaysia (see Fig. 4). Singapore granites have been U-Pb zircon dated by Oliver et al. (2014) on the flanks of Bukit Timah at Dairy Farm Quarry (244 ± 1 million years), Mandai Quarry (237.0 ± 1.4 million years) and Ketam Quarry on Pulau Ubin (230.2 ± 5.9 million years). These age dates range from the Middle Triassic to the early part of the Late Triassic.

Pengerang Volcanics. — There are poor outcrops of andesitic tuff (lithified volcanic ash) and agglomerate tuff (volcanic ash with ejected lava bombs) on the east side of Pulau Tekong (see Fig. 5). Similar pink rhyolite lava associated with andesitic agglomerate from a coastal outcrop of the Pengerang Volcanics at Telkuma, southeastern Johor and gives a Middle Triassic, U-Pb zircon dating age of 238.4 ± 1.9 million years (Oliver et al. 2014) which is statistically the same age as the Mandai Quarry Granite (237.1 ± 1.4 Ma) and indicates that intrusion of magma chambers and extrusion of volcanoes were contemporaneous in the Singapore–Johor region. Based on the size of ejected bombs, Pulau Tekong was less than 3 km from the central crater of the Pengarang Volcano (Zainal, 1984). Boulders from Pengerang quarries can be seen at Punggol Point where they have been used for beach protection.

Jurong Formation. — The boundary between the Eastern and Central Belts can be drawn through Singapore along the Bukit Timah Fault which separates the Singapore Granites from the Jurong Formation (see Fig. 5). The Jurong Formation is a fossiliferous shallow marine (deltaic) sedimentary sequence occurring with interdigitated river and lake deposits. Figure 6 illustrates typical fossils from the Jurong Formation.

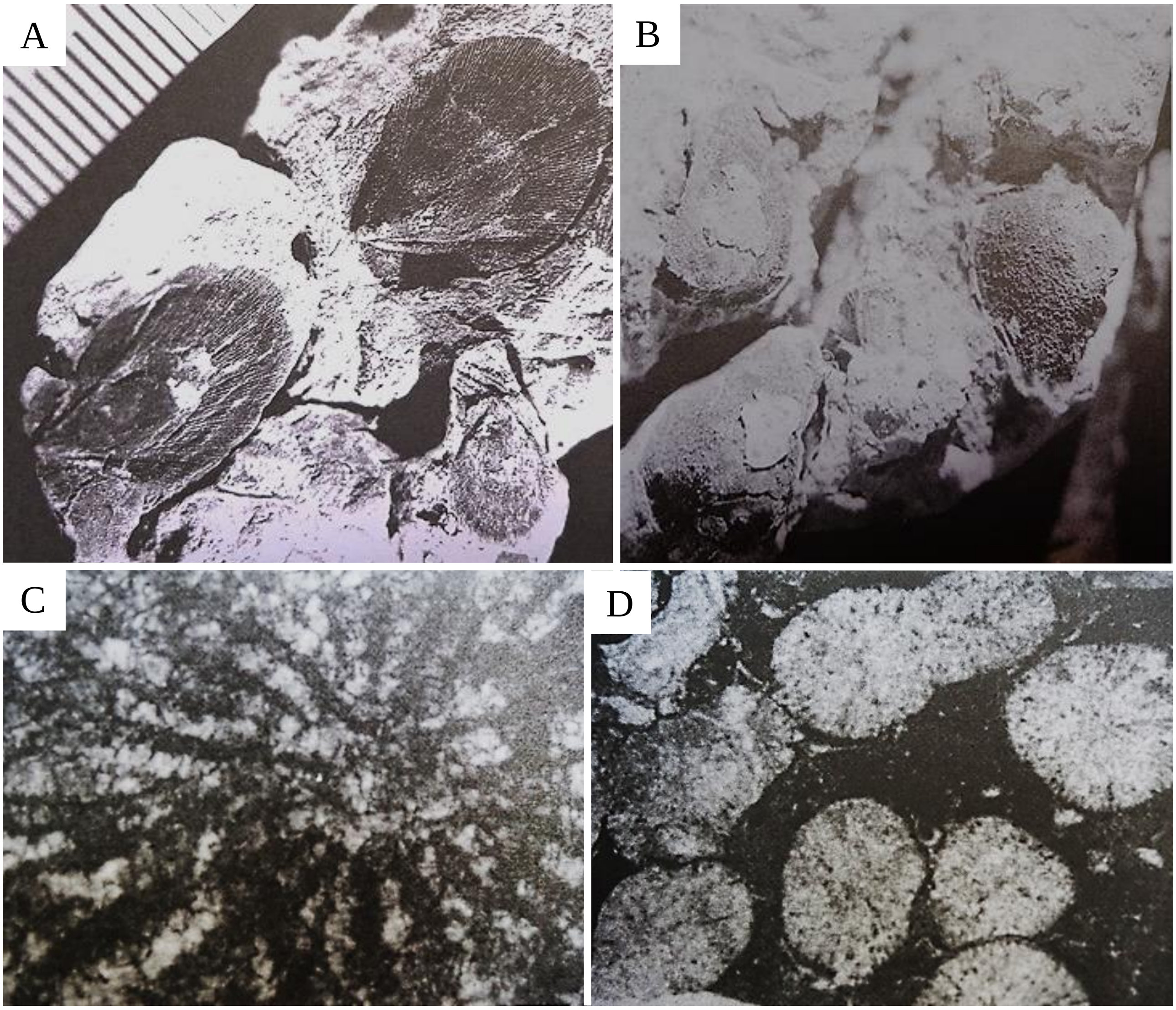

Fig. 6. Typical fossil scallops and corals from the marine facies of the Jurong Formation. (Photographs reproduced from Lee & Zhou [2009]). A. *Plicatula* cf. *carinata* (Healy) Upper Triassic. B. *Palaeonucula* sp. C and D. Coral species from the Padan Limestone. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

These fossils have been assigned to the Late Triassic (i.e., between 230–200 Ma). However, marine shells from Mount Guthrie (near Mt. Faber but now excavated away) are quite different from any Triassic fossils from Singapore or Malaysia and were suggested to be *probably* Early Jurassic. However, Early to Middle Jurassic fossils have never been found in Malaysia and the existence of Lower Jurassic strata in Singapore is unproved and doubtful.

A shore section of the Jurong Formation has been examined in detail by Oliver & Prave (2013) around Fort Siloso on Sentosa (Fig. 5). The lower part of the section is dominated by purple-red, massive to finely laminated mudstones containing thin, discontinuous lenses of fine sandstone with small ripples. One dinosaur-like foot print has been discovered in a loose block of red mudstone. It is concluded that these muds and silts were deposited in a shallow lake called Lake Sentosa. Lee & Zhou (2009) would call these continental red-beds the Queenstown Facies. Continental red-beds form today between the Tropics.

The upper part of the sequence consists of medium-grained sandstone and conglomerates (i.e., lithified gravel) alternating with purple-red mudstone with worm burrows. One possible dinosaur trackway in granule size conglomerate has been located. The conglomerates contain abundant pebble-sized clasts of quartz and lesser amounts local Singapore-type rocks such as granite, gabbro and slate. Lee & Zhou (2009) called these sediments the Remau Facies. Undercut channel banks and large-scale cross-bedding characterise the sandstone and conglomeratic beds as being deposited by flash river floods feeding into Lake Sentosa at a fresh water delta.

Individual zircon sand grains from the Jurong Formation conglomerates located in the Labrador Nature Park have U-Pb dating ages varying from 2,700 Ma to 209 ± 2 Ma (Oliver et al. 2014). Therefore this part of the Jurong Formation must be at least 209 million years old if this zircon grain was formed in a contemporaneous volcano, i.e., late part of the Late Triassic, which agrees with the fossil ages.

Palaegeography of Lake Sentosa. — It is notable that the Queeenstown Facies lake deposits have an elongate outcrop pattern orientated northwest/southeast adjacent to the gabbro/granites of central Singapore (see Fig. 7).

Furthermore, the Queenstown Facies lake beds are positioned so that they are in an apparent sharp and linear contact with and nestled against the older igneous rocks. This pattern fits the hypothesis that Lake Sentosa was formed in a northwest/southeast orientated faulted valley (i.e., a half graben) in which the granite/gabbro hinterland was up-faulted relative to the down-faulted valley with the latter forming a depositional basin for the rivers and lakes. In this way, the Singapore Granites and the Gomback Gabbro were exhumed along a fault scarp and the eroded sediment was deposited in rivers and lakes. Down-faulting may have been sufficient enough to place the valley below sea level at certain intervals to allow marine incursions. The boundary fault is called the Bukit Timah Fault. The amount of relief on the Bukit Timah Fault scarp at the time of the formation of Lake Sentosa may have been in the order of hundreds of meters considering the cm size of the pebbles and cobbles seen in the conglomerates. The occurrence of tuff (volcanic ash) and spilite (lava) in the Queenstown, Jong and Ayer Chawan Facies suggest volcanism concomitant with a regime of crustal rifting and down-faulting following the climax of the Indosinian Orogeny. A 30 cm-thick coal bed is evidence for forest and swamp conditions. Figure 8 is a schematic reconstruction of the palaeogeography of the Singapore region at the time of the continental red-bed deposition in and around Lake Sentosa.

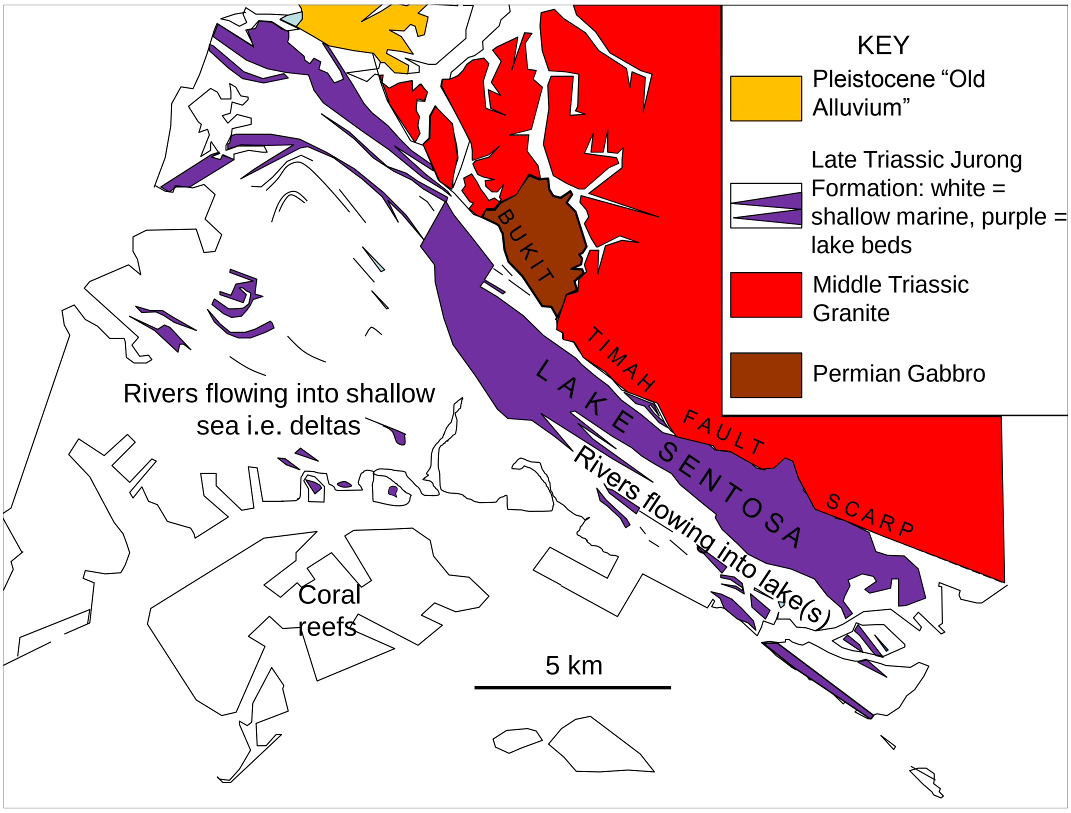

Fig. 7. Geology map of SW Singapore (after Lee & Zhou, 2009) showing the distribution of red-beds = lake beds of Lake Sentosa (Queenstown Facies), river deposits (Rimau Facies), shallow marine-deltas (Ayer Chawan Facies) and coral reef limestone (Pandan Facies). Modified by G.J.H. Oliver from Lee & Zhou, (2009) with permission from the Defence Science and Technology Agency, Singapore.

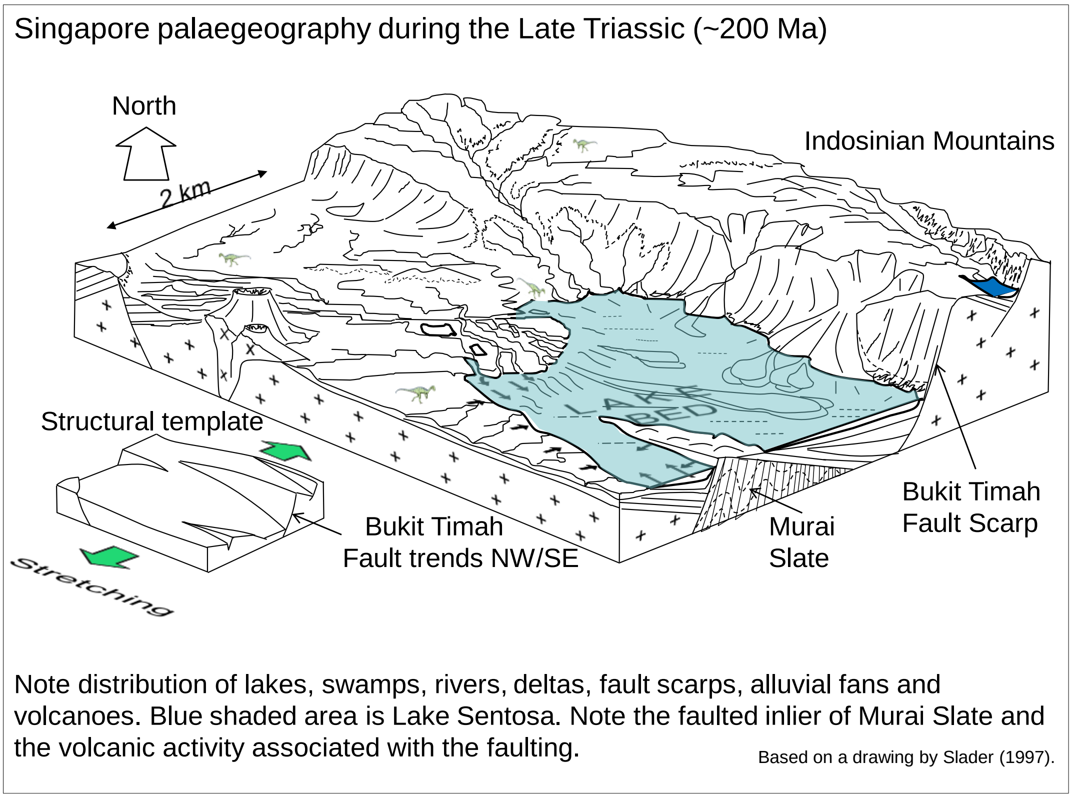

Fig. 8. A reconstruction of the geography of Singapore ~ 200 Ma. Modified from Oliver & Prave (2013) with permission of Elsevier.

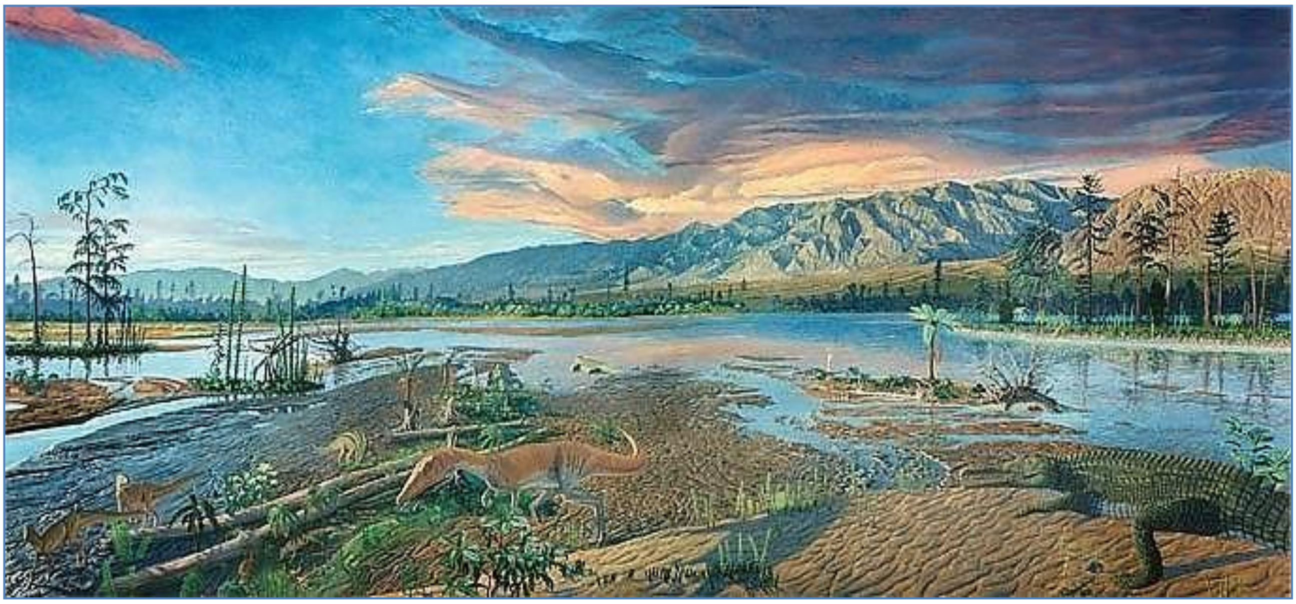

Fig. 9. Artist's impression of what Singapore might have looked like looking north from the vicinity of Sentosa in the Late Triassic Period (200 Ma) before the mountains were eroded away to the low hills of the present time. The Bukit Timah Fault scarp and the Bukit Timah Granite and Gomback Gabbro form the mountains in the distance. In the foreground braided rivers drain into Lake Sentosa. The dinosaur in the front centre is the predator *Coelophysis*. Painted by W. Sillins. Reproduced here with permission from http://www.willsillin.com/Natural%20History.html.

Figure 9 is an artist's impression of what Singapore might have looked like when rivers were flowing into Lake Sentosa.

Lee & Zhou (2009) comment that the Queenstown Facies (i.e., continental red-beds) is interdigitated with the marine facies, demonstrating alternating shallow marine and fresh water conditions. Probably the subsidence rate on the Bukit Timah Fault, rate of supply of gravel, sand and mud via rivers, and changing sea levels, all oscillated in a complex way.

The Jurong Formation continental red-beds are regionally important because they represent the change from deep marine conditions in the Palaeo-Tethys Ocean from the (Early Permian till the lower Late Triassic) to tropical continental conditions following the collision of Sibumasu and Indochina (in the middle Late Triassic) that caused the Indosinian Orogeny.

Pulau Ubin Jetty Diorite. — At Pulau Ubin Jetty, (Fig. 5) a dark, coarse-grained, equigranular, crystalline diorite (i.e., a darker version of granite but with quartz (30%), clear plagioclase (30%), clinopyroxene (15%), hornblende (10%) and weakly chloritised biotite (5%) has a U-Pb zircon Cretaceous age of 94.6 ± 0.8 million years (Oliver et al., 2014). It is characterised by spherical enclaves of mafic microgabbro. Similar diorite occurs as a dyke on Pulau Sajahat. The origin of these plutonic rocks is unknown as yet: they may be hot spot or subduction related or neither.

From the Cretaceous to the Plio-Pleistocene (95 million years ago till ~2.7 million years ago) there is no rock record in Singapore until the deposition of the Old Alluvium (see next section). This was presumably because Singapore was an internal part of the stable continental plate called Sundaland.

Old Alluvium. — The Old Alluvium is a semi-consolidated deposit, mainly of medium to coarse sand and fine pebbles, deposited on a basement of granitic and metamorphic rocks. It has been studied in quarry faces in the Tampines–Bedok–Changi area and in boreholes. A number of quarries were excavated in east Singapore for land reclamation. In such quarries, a variety of beds were seen in truncated conditions. The composition and structure of the beds identified the Old Alluvium as a river deposit. Compositionally, the beds can be grouped into four textural classes: (1) coarse sand mixed with fine pebbles, (2) medium and coarse sand, (3) pebble beds, and (4) clay with silt. Old Alluvium is essentially made of the first two classes. Structurally, pebbly longitudinal sandy river bars, transverse sandy river bars, thick flood-deposited channel fills, and upper flow regime plane beds are visible and can be recognised. Several flood channels also are evident. The Old Alluvium of Singapore therefore has been identified as sandy deposit of a braided river with seasonal regime and large floods (Gupta et al., 1987).

The mineralogy of pebbles, sand and clay suggests a mixed provenance of granite and low-grade metamorphic rocks. The source material for the Old Alluvium in Singapore could very well be the Bukit Timah Granite and nearby Sajahat Formation. The freshness and angularity of several feldspar grains suggest erosion of unweathered rock, rapid and brief transportation, and quick burial. In Singapore, age determination of the Old Alluvium is difficult because of the absence of fossils or organic material, apart from a clast of a charred partially silicified part of an angiosperm. A Pleistocene age has been attributed to the Old Alluvium from indirect observations.

The present top surface of the Old Alluvium is in reality located somewhere in the middle of this three-dimensional deposit. The part above it has been eroded and removed. As shown in boreholes, the Old Alluvium is at least well over 200 m thick in the subsurface. Though the top of the sediment has been eroded, it occurs at an elevation of 35 m up local hills, and the use of the undrained cohesive strength to the effective overburden pressure for some of the deformed clay beds indicates that about 60 m of overburden has been removed (Pitts, 1986). The entire thickness therefore is over 244 m. Any post-deposition deformation has hardly been noticed but the quarry faces are marked with stress-relief joints.

The reconstruction of the environment of Old Alluvium is difficult, but it can be identified as the headwater deposits of a braided river sediment. The river continued to flow across the Sunda Shelf when extensive stretches of the bed of the South China Sea was exposed. A number of glacial and non-glacial periods occurred in the Pleistocene associated with the rise and fall of the sea level. Plant debris, mottled sediment (indicating partial oxidation), and lateritic wash have been found in sea floor cores located in the middle of the present South China Sea (Biswas, 1973). Emmel & Curray (1982) working in the Malacca Strait area identified an old submerged river system and a sea level of at least 146 m below the present one. Several such extinct large drainage systems flowing over the lower stretches of the exposed sea floor during the glacial times and low sea levels have been suggested. Molengraff (1921) discussed a similar drowned river system, termed the North Sunda River, flowing north and collecting tributaries from the present Malay Peninsula to the west and the island of Borneo to the east. The present-day Singapore could have been about 300 km from the sea, draining south or southeast to this North Sunda River. The sediment was derived from severe erosion of granitic and low-grade metamorphic slopes. The climate was less wet than present day, seasonal, and with periodic large floods. The distal parts of the sediment are currently submerged under the shallow water of the South China Sea. Similar deposits occur regionally around the South China Sea and the Malacca Strait.

Incised channels on top of the Old Alluvium, infilled with unconsolidated alluvium, shallow marine sand, and clay, have been found from offshore seismic work (CCOP, 1980). The surface of the Old Alluvium has been exposed, eroded, and infilled with later sediments with the rise of sea level. Some of the infill, if investigated, probably would correlate with the post-Old Alluvium material on land.

Huat Choe, Tekong and Kallang Formations. — Of these three Holocene formations, the Huat Choe is extremely limited in extent, and probably no exposure of it currently exists. The Tekong

Formation normally occurs as coastal terraces in islands such as Pulau Tekong and Pulau Tekong Kechil. It is also seen as discontinuous patches along coasts and the lower parts of certain valleys inland. The Tekong Formation has been interpreted as beach and sand deposits related to a higher sea level early in the Holocene. It is, however, difficult to distinguish between the sediments of the Tekong and Kallang formations in many places.

The Kallang Formation is made of sand, pebble, peat and clay, deposited during the Middle or Late Holocene. It is found near coasts, beaches, and reefs and also extends along the major river valleys of Singapore Island. This is potentially an important formation as it underlies much of the coastal plain and valleys, and in general, coincides with densely built-up areas and valley-bottom arterial roads. It carries information regarding the changing sea level and geomorphic processes of the Holocene and of geotechnical importance. It is often exposed when foundations for buildings are dug in coastal areas.

Conclusions.— The geology of Singapore is intriguing but it is not easily visible or understood because most of it has been covered by the growth of a global city where one tends to see a paved surface more than rocks. This guide includes a series of excursions where the geology and geomorphology of Singapore can still be studied. The walks are almost entirely on Singapore's geological past but also includes two on the present: enhanced flooding mainly caused by anthropogenic developments. Singapore is a naturally flood-prone island given its physical features and intense rainfall, but the propensity to flood has increased owing to the rapid extension of impervious surfaces such as streets, parking lots, rooftops, and others simultaneously with concrete storm drains and sewers. The last two excursions illustrate the change and some of the steps taken to alleviate the problem. This has given rise to street scenes which are eminently Singaporean.

PART THREE

***Field Excursions.* —** Any field excursion should be carried out in a group led by a competent, field-trained leader, who MUST carry out a risk assessment prior to the excursion. The leader should hold a safety briefing at the beginning of each excursion.

As far as possible, each excursion follows the same format: each is located on the geological map of Singapore as well as a Google Earth Map. The localities, to be visited are located on small scale maps as Location 1, Location 2, etc. Each location has a field photograph.

Each excursion is accessible by public transport except those into the military training areas.

Pulau Sajahat Excursion. — The aim of this excursion is to examine the Sajahat Formation on Pulau Sajahat (Figs. 10–24). Pulau Sajahat is the type locality of the Sajahat Formation, situated 3 km northeast of Changi Village and is accessible via boat from Changi Village (Figs. 10–13). Entry is by permission of the Ministry of Defence (MINDEF). Allow a half day for this excursion. This once tiny islet has now been joined to Pulau Tekong by land reclamation.

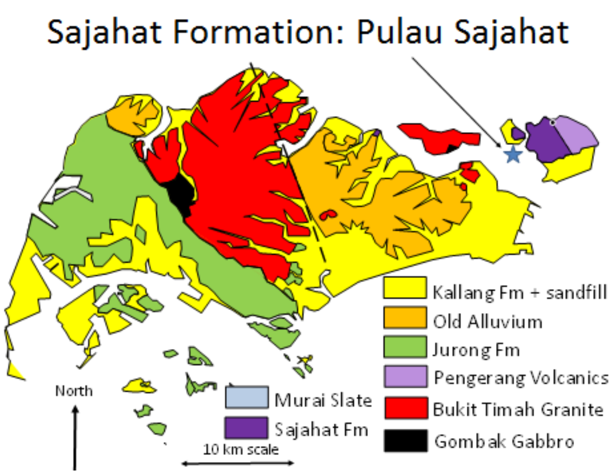

Fig. 10. Geological map of Singapore. Modified by GJH Oliver from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 11. Pulau Sajahat is 3 km northeast of Changi Village. Source Google Earth.

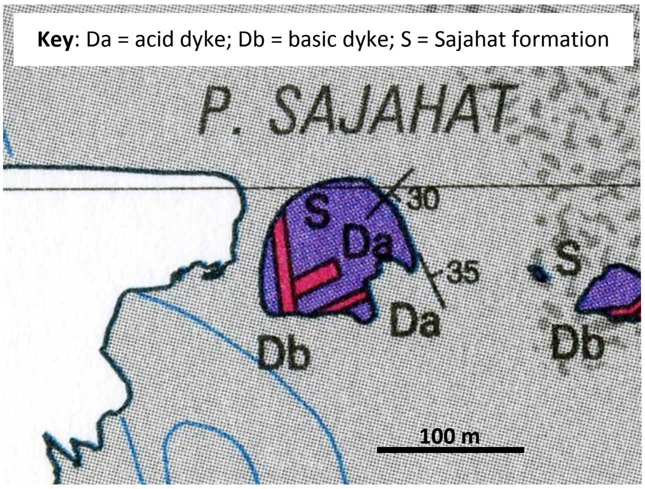

Fig. 12. Sajahat Formation type locality geology. From Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 13. Excursion localities of Pulau Sajahat. Source Google Earth.

Location 1 has Bouma-type graded bedding and cross-bedded lamination in quartzite turbidites. There is a low angle, regionally penetrative foliation lying sub-parallel to the flat-lying bedding and forming an axial plane foliation to tight recumbent folds. Quartz veins have been stretched and boudinaged in the plane of the foliation. This foliation was formed during regional metamorphism of the sediments up to the biotite zone of the greenschist facies. It would be more correct to describe the argillites as fine-grained schists.

There is a second upright spaced cleavage orientated at 150^{o} cross cutting the flat lying first foliation. Unfoliated granite veins cross cut both foliations. This biotite granite is texturally similar to the Middle Triassic granites of mainland Singapore, dated at 250 and 230 Ma (Oliver et al. 2014).

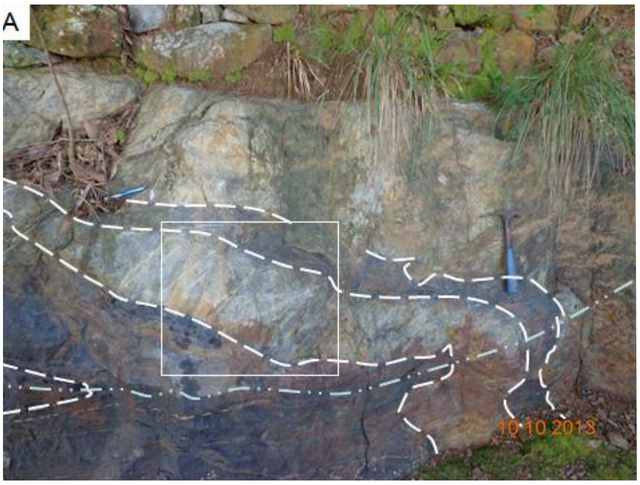

Fig. 14. Location 1: Folded quartzite and biotite schist. (Photograph by: G. J. H. Oliver).

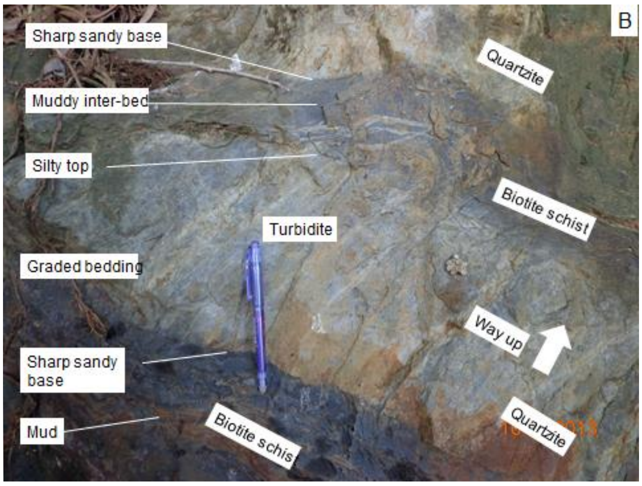

Fig. 15. Location 1: Close up of turbidite features. (Photograph by: G. J. H. Oliver).

Fig. 16. Location 1: Tight flat-lying fold and sheared quartz veins. (Photograph by: G. J. H. Oliver).

Fig. 17. Location 2: Folded and faulted granite vein. (Photograph by: G. J. H. Oliver).

Fig. 18. Location 3: There is circumstantial evidence for sheath-type folds, which if confirmed, would suggest that the Sajahat Formation is actually a tectonite in a shear zone. Tiny spots of cordierite in the schists could be related to contact metamorphism caused by either the Triassic or Cretaceous intrusions. (Photograph by: G. J. H. Oliver).

Fig. 19. Location 4. Recent erosion has exposed the sand-fill berm that surrounds Pulau Sajahat. (Photograph by: G. J. H. Oliver).

Fig. 20. Location 4: Note the several layers of sand-fill. (Photograph by: G. J. H. Oliver).

Fig. 21. Location 5: Shatter zone in thin bedded turbidites. (Photograph by: G. J. H. Oliver).

Fig. 22. Location 6: Sinistral and dextral shears in thin-bedded turbidites. (Photograph by: G. J. H. Oliver).

Fig. 23. Location 7: A dolerite (basic/mafic) intrusive dyke here may be related to the Pulau Ubin Jetty Diorite which has been dated by Oliver et al. (2014) as 95 Ma (Cretaceous). (Photograph by: G. J. H. Oliver).

Fig. 24. Location 7: Note the veined inclusions in the dolerite intrusive dyke of Fig. 23. (Photograph by: G. J. H. Oliver).

Western Catchment Area Excursion. — The aim of this excursion is to examine the Pasir Laba Fault (Thrust), the Jurong Formation, and the Murai Slate in the Western Catchment Area (Figs. 25–37). The Western Catchment is largely a military training area and permission to enter must be obtained from MINDEF. Allow for a day and a four-wheel drive vehicle is recommended.

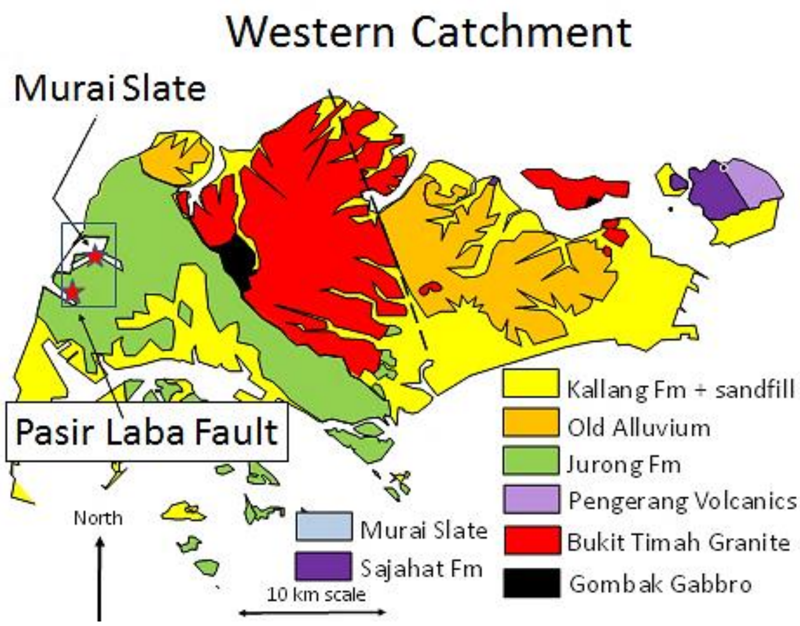

Fig. 25. Geological map of Singapore showing the location of the Pasir Laba Fault and the Murai Slates. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 26. Locations 1 to 5. Source: Google Earth.

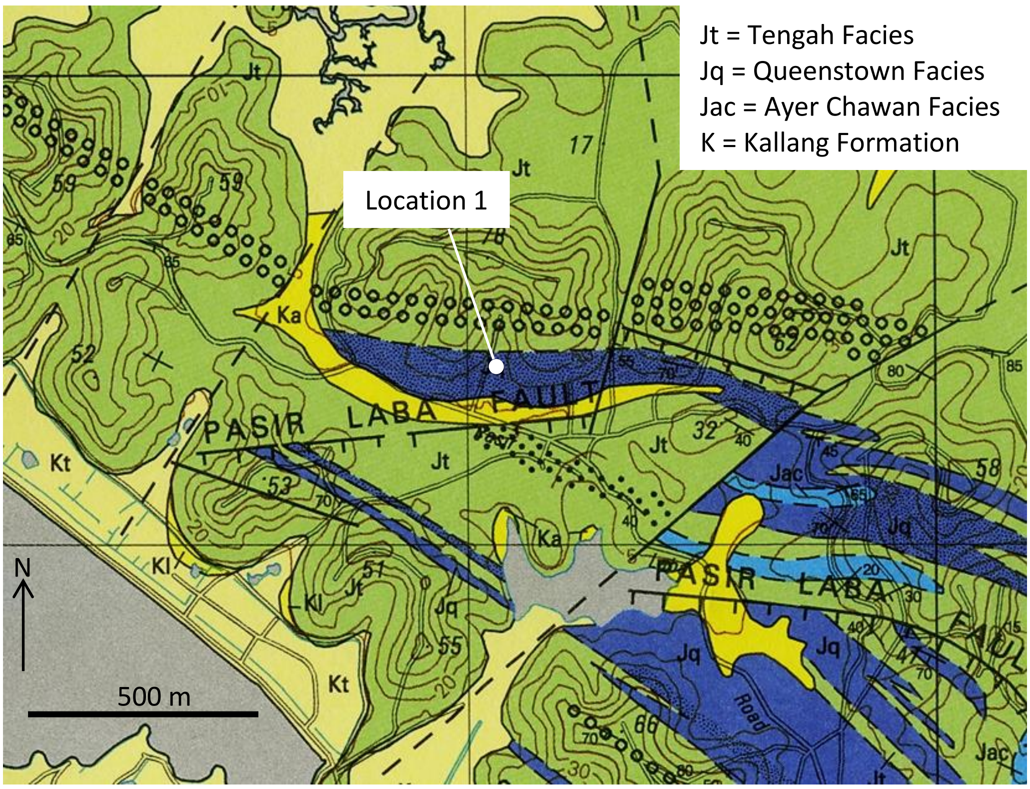

Fig. 27. Geological map of the Pasir Laba Fault at Junkyard. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

At Locality 1, a 150-m cutting, trending northeast to southwest, exposes fluvial sediments of the Queenstown Facies of the Jurong Formation which have been tectonically imbricated in the **Pasir Laba Fault** (Figs. 28–30). Strata strike 130^{o} and mostly dip towards the southwest but are tightly folded and faulted. The faults also strike at 130^{o} and dip 45^{o} to the southwest. Fold hinges plunge 10^{o} towards 300^{o}. A spaced fracture cleavage strikes at 280^{o} and dips 80^{o} N. The kaolinite rich mudstones here do not display a slaty cleavage

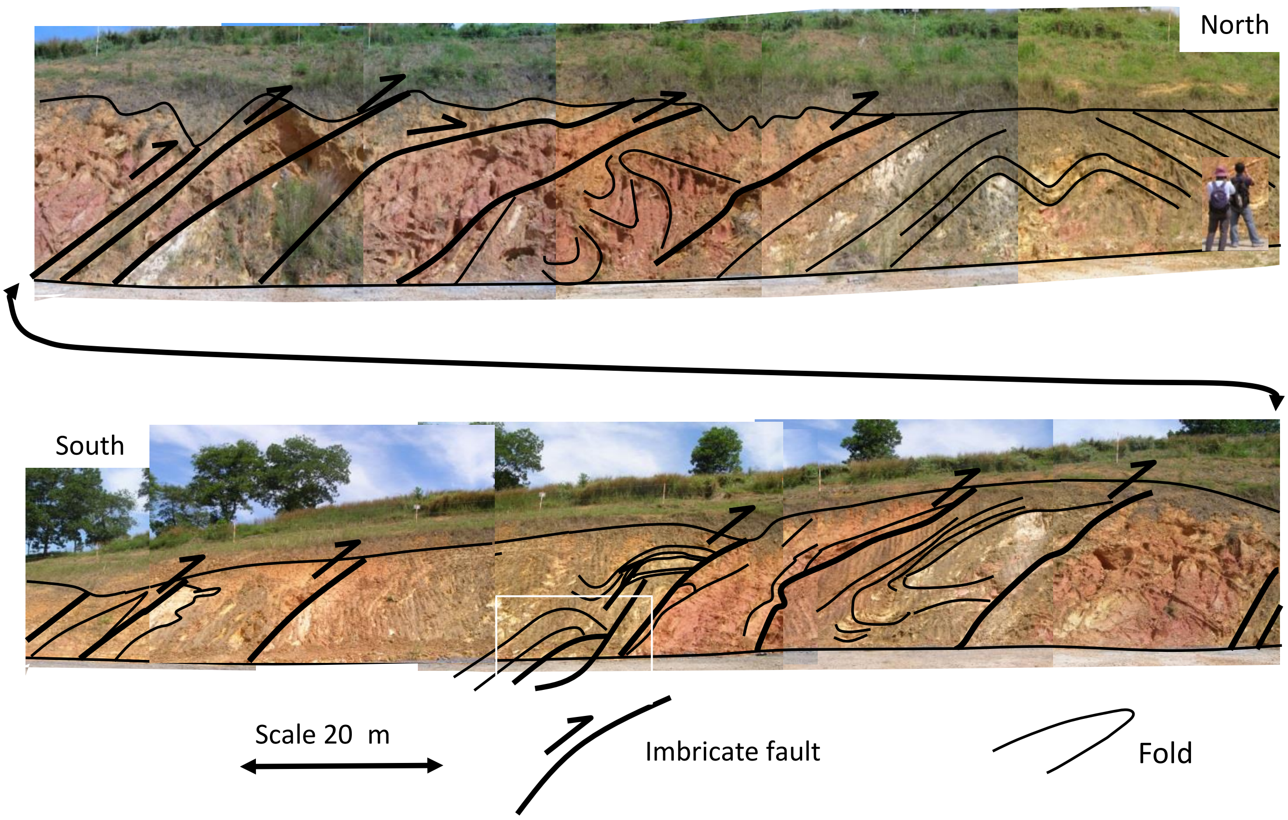

Fig. 28. Location 1. Pasir Laba Fault at Junkyard: Imbricate thrust zone within the Jurong Formation fluvial facies sandstone, siltstone and mudstone redbeds. White kaolinite mudstone is conspicuous. Thirteen faults can be counted. (Photographs by: G. J. H. Oliver).

Fig. 29. Location 1. Close-up of inset area above. Tape measure is 2 m long. (Photograph by: G. J. H. Oliver).

Fig. 30. Location 1. Interpretation: Drag folding caused by thrust faulting; top has moved towards the northeast. Tape measure is 2 m long. (Photograph by: G. J. H. Oliver).

Oliver & Prave (2013) proposed that the depositional basin for the Jurong Formation was formed in an extensional half-graben along the Bukit Timah Fault. The Pasir Laba Fault is clearly a later compressional fault zone, formed during the inversion of that basin. Imbricate thrusting is characteristic of thin-skinned tectonics. It may be that this outcrop is a small scale example of the large scale structure of the Jurong Formation. It is not known what caused this faulting: one possibility is collisional tectonics when the Wyola Volcanic Arc collided with Sundaland in the Late Cretaceous, about 80 million years ago.

There are numerous exposures in road cuttings between Poyan and Murai Reservoirs. At Locality 2, typical **Jurong Formation** (Figs. 31–34) cm thick bedded silty red beds strike at 80^{o} and dip 40^{o} S. Load casting suggests inversion. There is a lack of imbrication features seen at Locality 1. At Locality 3, Jurong Formation fluvial white sandstones strike 355^{o} and dip 50^{o} E. Load casts indicate right way up bedding. A dip slip fault stikes at 10 ^{o} and dips 50^{o} E parallel to bedding. Slickensides pitch down dip towards 34^{o}.

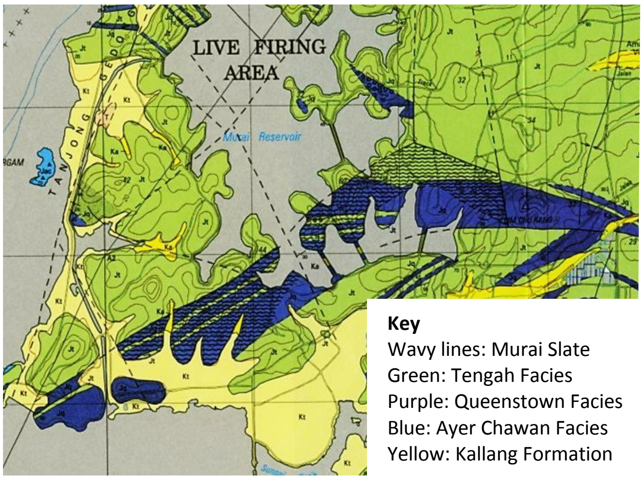

Fig. 31. Geological map between Poyan and Murai Reservoirs. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

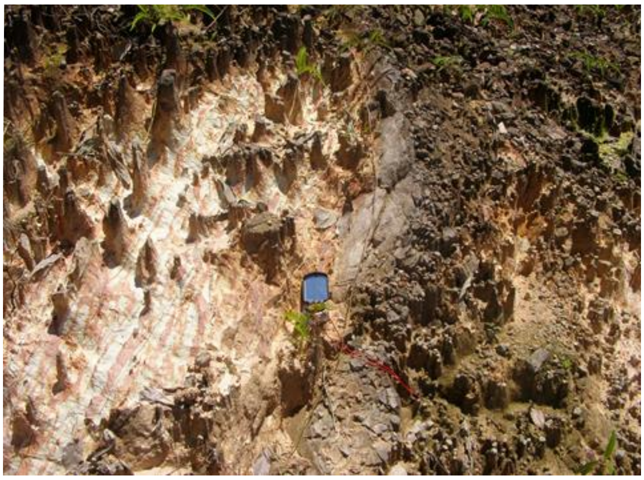

Fig. 32. Location 2: Typical fluvial siltstones of the Jurong Formation. (Photograph by: G. J. H. Oliver).

Fig. 33. Location 3: Fluvial sandstones of the Jurong Formation. The dark horizon is a fault dipping 50^{o} east. (Photograph by G. J. H. Oliver).

Fig. 34. Location 4. Spaced cleavage in Jurong Formation silty fluvials, possibly associated with the Murai Thrust. (Photograph by: G. J. H. Oliver).

At Locality 4, the Jurong Formation takes on a prominent vertical spaced cleavage, striking 50^{o} and bedding is difficult to identify. It could be that there is an important fault near here.

Murai Slate (Fig. 35–37). Four hundred metres to the northeast in Fig. 31, the Geology Map of Singapore (Lee & Zhou, 2009) shows an area of Murai *Schist* (sic) around Locality 5 at Murai Reservoir as described by Alexander (1950) and interprets them as “a zone of well-developed cleavage in rocks otherwise recognised as sediments of the Queenstown, Jong and Tengah Facies”. Actually, the rocks at Locality 5 are purple slates with a strong penetrative cleavage striking at 120^{o} and dipping 38^{o} towards the southwest. These slates are low grade metamorphosed mudstones whilst the Jurong sediments are unmetamorphosed at diagenetic grade and do not display a penetrative slaty cleavage. Thus the slates should be older than the sediments (as stated by Alexander, 1950). Contacts between the slates and the sediments have not been observed at Murai. On Batam, directly along strike on the south side of the Singapore Strait, the slates are faulted against the Jurong Formation and are assumed to be Carboniferous in age (van Bemmelen, 1949). It could be that the Murai Slates have been brought into contact with the Jurong Formation along the putative Murai Thrust, as imbricated thrust slices similar to that described at Junkyard, Locality 1. This theory can be tested by seismic reflection surveys.

Fig. 35. Location 5. Murai Slate from Murai Reservoir. The tape measure is 1 m long. (Photograph by: G. J. H. Oliver).

Fig. 36. Location 5. Specimen of typical Murai Slate showing penetrative slaty cleavage. (Photograph by: G. J. H. Oliver).

Fig. 37. Location 5: Slice of Murai Slate illustrating the near perfect slaty cleavage. There is a tectonic lineation running from top left to bottom right. Note the ~1 mm diameter spherical “spots” which may have been caused by thermal metamorphism from the Bukit Timah Granite or Gombak Gabbro. (Photograph by: G. J. H. Oliver).

Bukit Timah Excursion. — The aim of this excursion is to examine the Gombak Norite (Gabbro) and Bukit Timah Granite at Little Guilin, Dairy Farm Quarry, Singapore Quarry, Hindhoek Quarry, and Bukit Timah. Allow for half a day.

Guilin in southern China is famous for its limestone karst and river gorge scenery. **Little Guilin** in Singapore is a flooded, gabbro quarry off Bukit Batok East Avenue 5, within easy walking distance of Gombak MRT station (Figs. 38–51). Allow at least 1 hour to investigate the quarry. Little Guilin is the type locality for the Gombak Gabbro. Lee & Zhou (2009) call this the Gombak Norite: norite is the specialist's name for a gabbro in which the pyroxene is an orthopyroxene called bronzite, rather than a clinopyroxene such as augite. We prefer the term Gombak Gabbro.

The geology map of the area shows that the Gombak Gabbro pluton is surrounded by Bukit Timah Granite on three sides and cut by the Bukit Timah Fault the other side. There are numerous acid and basic dykes cutting the gabbro.

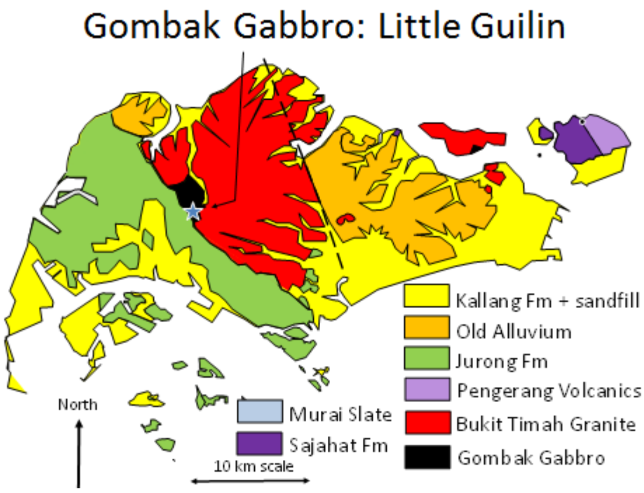

Fig. 38. Geology map of Singapore showing the location of Gombak Gabbro. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 39. Location of Little Guilin and other quarries. Source: Google Earth.

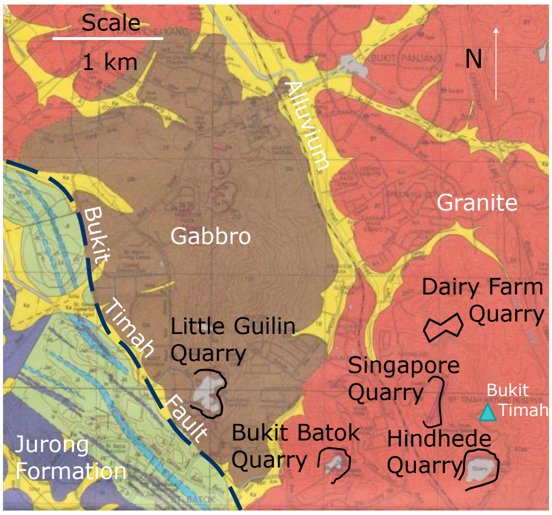

Fig. 40. Geology of the area around Little Guilin. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

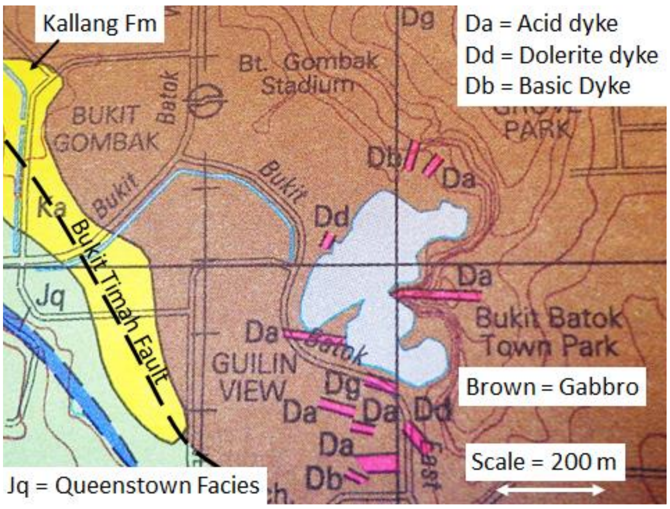

Fig. 41. Detailed geology map showing cross-cutting dyles. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Locality 1 is reached by walking up the steps from Gombak Avenue. Here coarse-grained and equigranular, bronze-coloured bronzite and white plagioclase can be examined. In thin section under the microscope, the mineral composition is 50% plagioclase, 35% orthopyroxene, 5% olivine, 5% brown hornblende, and 5% opaques. This is therefore an olivine gabbro. Zircons from this locality give an U-Pb age of 260 ± 2 million years (latest Permian) which is the oldest dated rock in Singapore so far.

Fig. 42. Localities to visit in Little Guilin. Source: Google Earth.

Fig. 43. View of strongly jointed gabbro from Location 1. A lack of 'tide marks' indicates that the gabbro is impermeable. (Photograph by: G. J. H. Oliver).

Fig. 44. Location 1: Gabbro consisting of white plagioclase and bronze-coloured bronzite. (Photograph by: G. J. H. Oliver).

The view looking east across the lake from Locality 2 shows a large quarry face with a fault zone and a ~3 m thick white leuco-granite dyke. At Locality 3, the leuco- granite dyke does not have chilled margins, suggesting that the country rock gabbro was still hot during the dyke intrusion and that the gabbro and leuco-granite might be cogenetic. The leuco-granite dyke margins are parallel to joints in the gabbro suggesting that the joints pre-date the leuco-granite dyke.

Fig. 45. Location 2: View of a fault and a white granite dyke cutting strongly jointed, dark gabbro. (Photograph by: G. J. H. Oliver).

Fig. 46. Location 3: Granite dyke cutting gabbro. Note the lack of chilled margins and gabbro inclusion. (Photograph by: G. J. H. Oliver).

Across the water from Locality 3, the leuco-granite dyke is beautifully exposed. Zircons from the granite at Locality 4 give an Early Triassic U-Pb age of 250 ± 2 million years, obviously younger than the gabbro. In fact, zircon from the gabbro from nearby Bukit Gambok give U-Pb ages as young as 246 ± 2 million years although contacts inside the gabbro have not been observed. Close examination of Locality 4 reveals that the leuco-granite dyke is cut by fine grained dolerite veins (of gabbro composition).

Therefore the gabbro pluton and leuco-granite dyke overlap in age. Behind the bus stop shelter at Locality 5, a large boulder displays cross cutting igneous contacts. The order of intrusion appears to be gabbro, granodiorite, granite, diorite, leuco-granite veins. The granodiorite contains an inclusion of ultramafic rock which may be a cumulate pyroxenite. Geochemical analyses might show that all these rock compositions are related to a fractionation series, starting with olivine gabbro and terminating with the leuco-granite.

Fig. 47. The granite dyke observed from Location 3. (Photograph by: G. J. H. Oliver).

Fig. 48. Location 4: The granite dyke is cut by a thin vein of dolerite. (Photograph by: G. J. H. Oliver).

Joint orientations at Locality 1 are dominated by north to south and east southeast to west northwest directions. Joint orientations at Locality 4 are dominated by north northwest to south southeast directions. These may be cooling joints.

Fig. 49. Location 4: Close up of dolerite vein (sill) cutting leuco-granite. (Photograph by: G. J. H. Oliver).

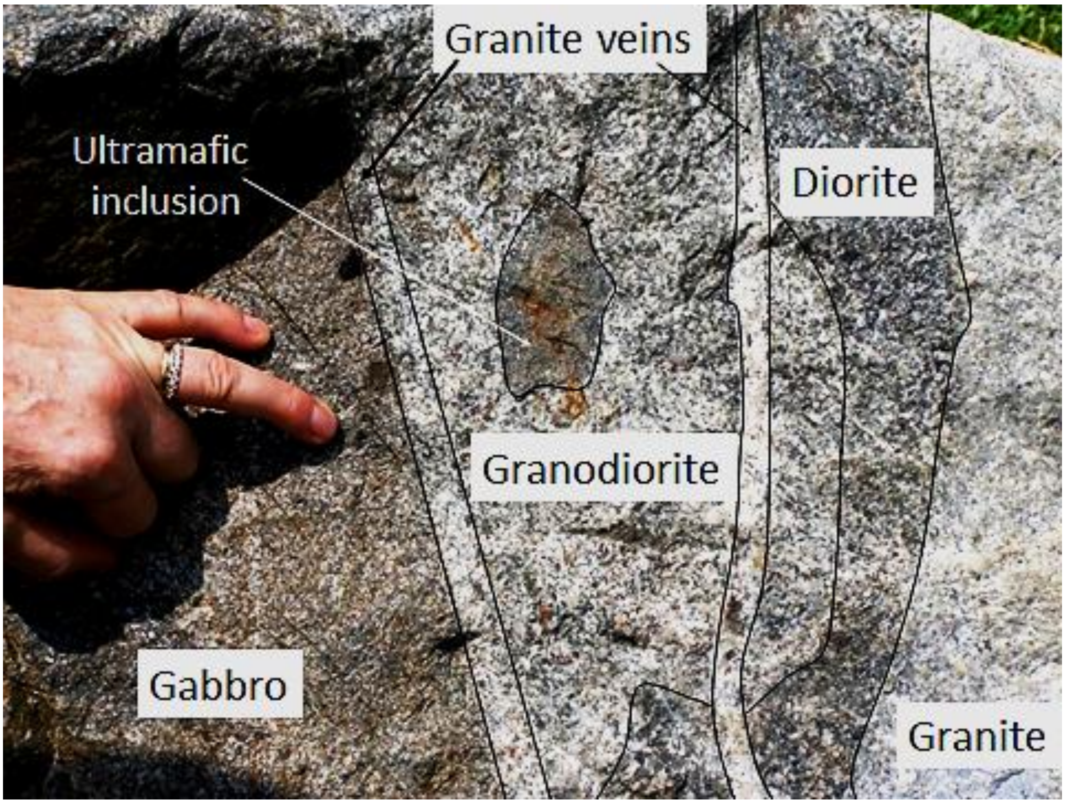

Fig. 50. Location 5: Multiple-phased intrusions. (Photograph by: G. J. H. Oliver).

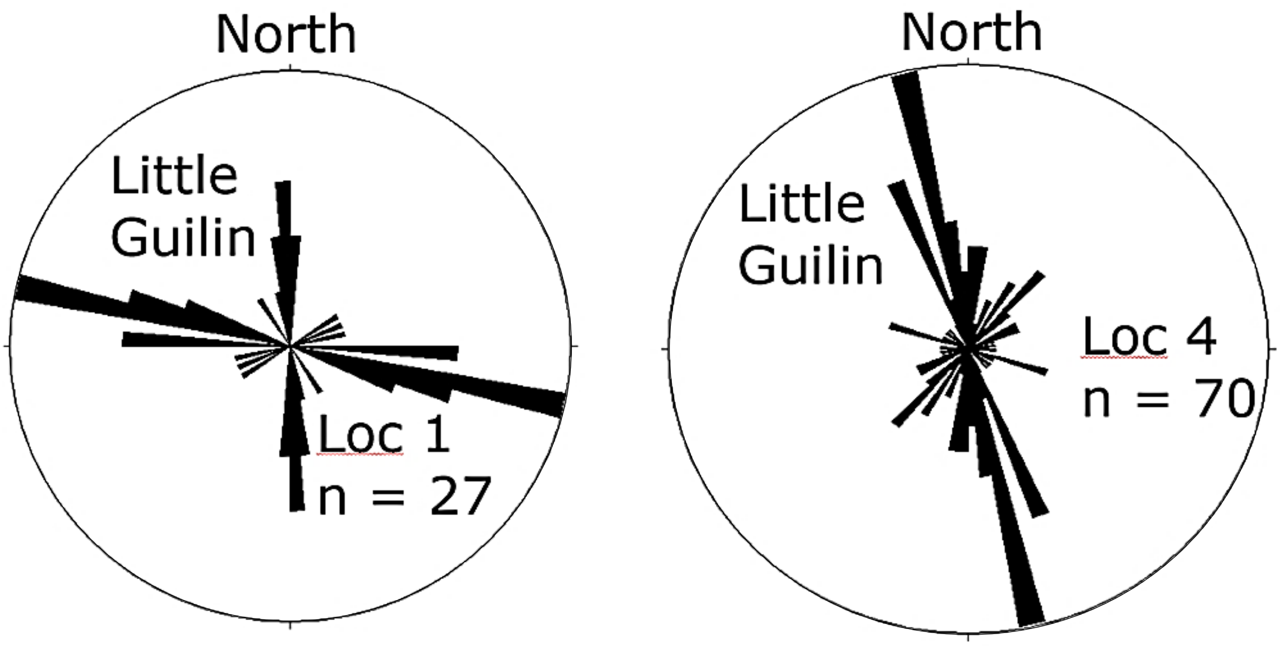

Fig. 51. Rose diagram of the joint orientations in the gabbro at Locations 1 and 4 at Little Guilin Quarry.

Dairy Farm Quarry (Figs. 52–63). There is a car park on the corner of Upper Bukit Timah Road and Dairy Farm Road. Walk up the track to the entrance to Dairy Farm Quarry. Allow for one hour.

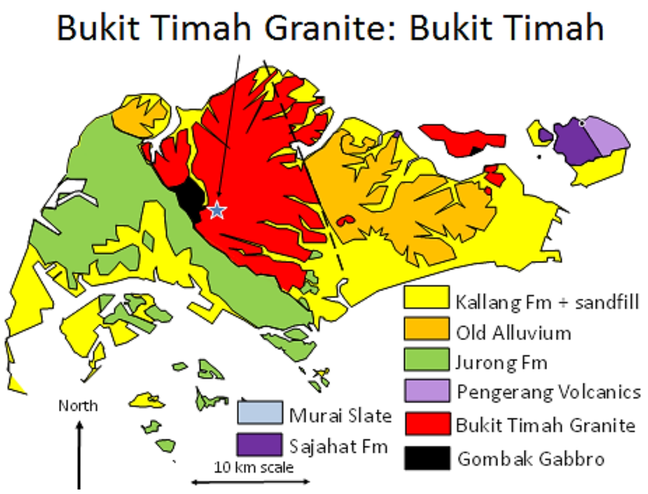

Fig. 52. Geological map with the location of Bukit Timah. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

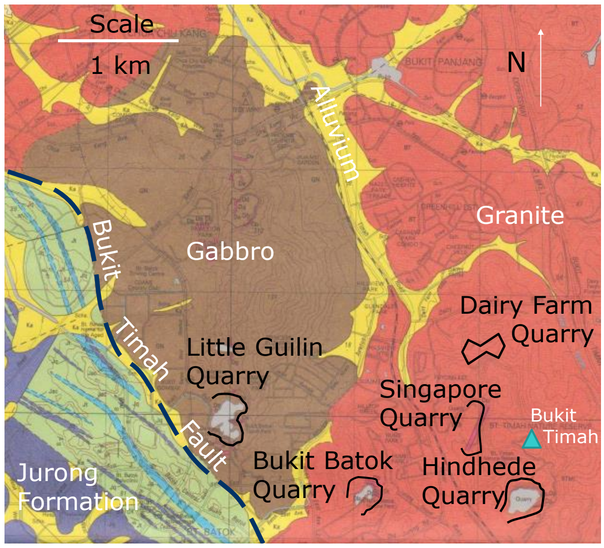

Fig. 53. Geological map with the locations of the quarries. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 54. Location of Dairy Farm Quarry. Source: Google Earth.

Fig. 55. Locations 1 to 4 within Dairy Farm Quarry. Source: Google Earth.

Fig. 56. View from Location 1 shows a 50-m high quarry face viewed towards the southwest. (Photograph by: G. J. H. Oliver).

Fig. 57. Location 2: North to south orientated fault zone within the granite. (Photograph by: G. J. H. Oliver).

From the entrance to Dairy Farm Quarry at Location 1, the view towards the southwest is of the main quarry face which displays joint surfaces in massive granite and a sharp contact with ~10 m of red/brown soil called oxisol.

Location 2 is under an overhang of the quarry wall. Beware of falling rocks and falling climbers! Here there is a N-S orientated (at 012 ^{o}) fault zone with both sub-horizontal and sub-vertical slickensides. Above head height, the fault planes in the zone are curved and anastomosing, indicating normal faulting with the hanging wall moving down to the east. A clean surface shows coarse equigranular granite with 30% glassy quartz, 30% creamy K-feldspar, 30% white plagioclase and 5 % black flaky biotite.

A sample of granite from Location 3 gave a Middle Triassic zircon U-Pb age of 244 ± 2 million years (Oliver et al., 2014). The granite here is strongly jointed with two vertical sets spaced at 0.5 m and a sub-horizontal set at ~1 m spacing. The vertical sets at 90^{o} are thought to be cooling joints. The horizontal joints are thought to be pressure release joints formed as the granite was exhumed to the surface. A smooth fault plane with slickensides pitching moderately northwards, cuts the joints.

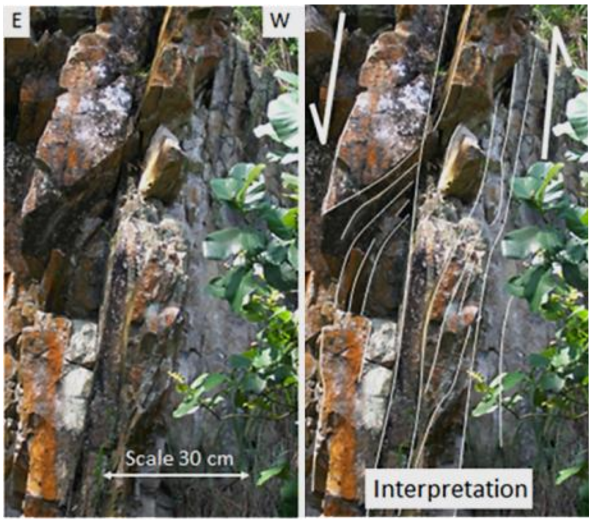

Fig. 58. Location 2: Normal fault showing down to the east movement. (Photograph by: G. J. H. Oliver).

Fig. 59. Location 2: Typical mineralogy and texture of the granite. (Photograph by: G. J. H. Oliver).

Fig. 60. Location 3: Vertical and sub-horizontal joint sets. (Photograph by: G. J. H. Oliver).

Fig. 61. Location 3: A smooth fault plane with slickensides. (Photograph by: G. J. H. Oliver).

Be careful at Location 4 which is overhung by unstable granite blocks! As at Location 3, two vertical joint sets are close to right angles to each other and have equal spacings of ~0.5 m, giving the effect of columns. These are also interpreted to be cooling joints. The orientations of the joints at Locations 2 and 4 are given below in a rose diagram.

It takes 20 minutes to follow the cycle track or old quarry road from Dairy Farm Quarry to the **Singapore Quarry** (Figs. 64–70). Access can also be made from the Rail Mall on Upper Bukit Timah Road. Rock from Singapore Quarry was transported by rail to form the Woodlands-Johor Causeway which was opened in 1923.

The quarry is now flooded. There is a viewing platform that looks eastwards towards a ~70 m high quarry face of massive Bukit Timah Granite overlain by a 10 m layer of soil. The quarry wall is smooth and lacks the columnar jointing seen in Dairy Farm Quarry. These smooth planes are fault planes running N–S which can be seen in profile in the northeast corner of the quarry. The fault planes are not cut by the (cooling) joints seen in Dairy Farm Quarry so they are younger than the joints.

Fig. 62. Two sets of vertical joints at ~90° give a column effect. (Photographs by: G. J. H. Oliver).

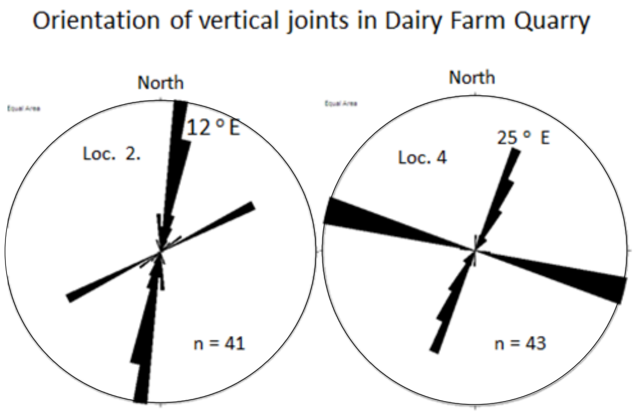

Fig. 63. Rose diagram of fault orientations from Locations 2 and 4.

Fig. 64. Access route to the Singapore Quarry. Source: Google Earth.

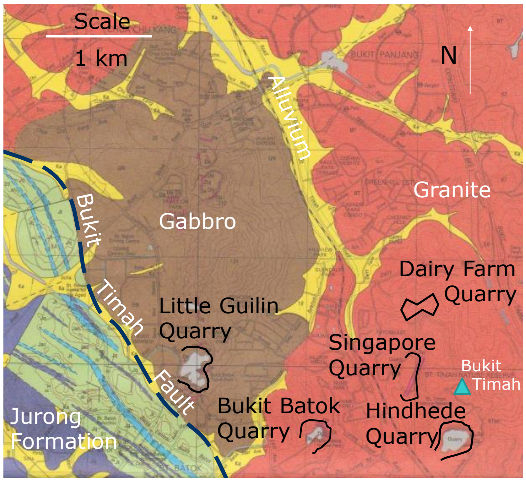

Fig. 65. Geological map of the Singapore Quarry. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

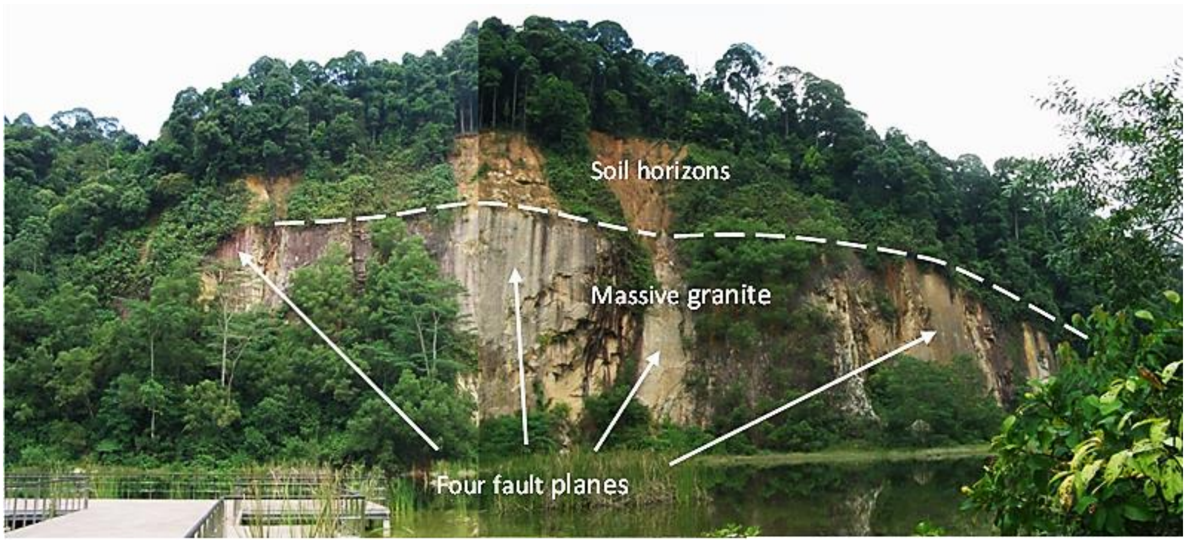

Fig. 66. View of the eastern face of the 70 m high Singapore Quarry with fault planes and soil horizons. (Photography by: G. J. H. Oliver).

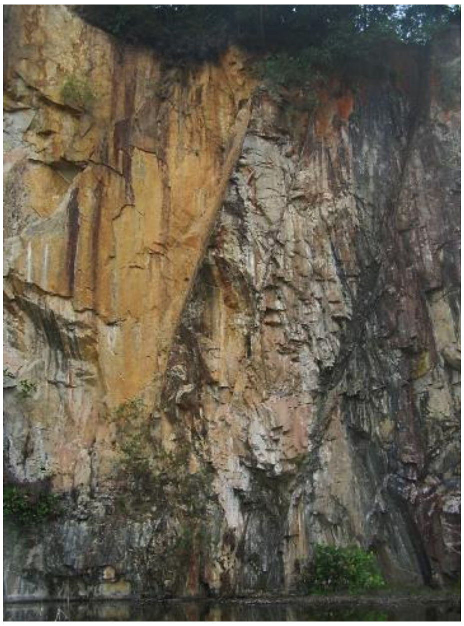

Fig. 67. Faulting in the northeast corner of Singapore Quarry. (Photograph by: G. J. H. Oliver).

Fig. 68. ‘Tidal marks’ indicate filling and draining episodes showing that the granite is permeable. (Photograph by: G. J. H. Oliver).

Fig. 69. Ground water leaking from a joint in permeable granite. (Photograph by: G. J. H. Oliver).

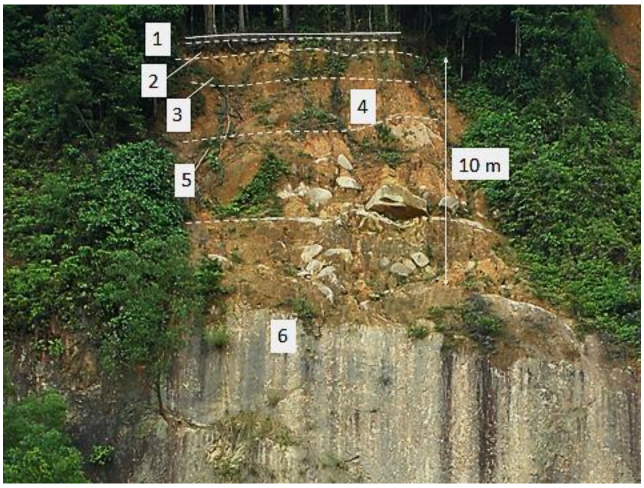

Fig. 70. Close up of the soil horizons in the Singapore Quarry. (Photograph by: G. J. H. Oliver).

In the northeast corner of the quarry, several parallel fault planes can be seen to strike at 007^{o} and dip 80^{o} to the west. These faults strike northwards into Dairy Farm Quarry where both strike-slip and dip-slip movements can be recognised by the orientations of slickensides. “Tide-marks” on the quarry walls indicate filling and draining episodes showing that the granite is permeable. Ground water can be seen leaking out of joints in the quarry walls. When the lake level is low, it is possible to walk around to the northeast corner of the quarry. Otherwise, binoculars are useful.

The soil formed on the granite is a typical oxisol formed in a wet tropical climate:

1. Layer 1 is the O horizon, made up of organic matter.
2. Layer 2 is the A horizon, made up of mineral soil mixed with humus.
3. Layer 3 is the E horizon, a zone of leaching of clay, Fe, and Al.
4. Layer 4 is the B horizon, a zone of accumulation of clay, Fe, and Al.

5. Layer 5 is the C horizon, a zone of relatively unweathered blocks which give rise to core stones
6. Layer 6 is bedrock (granite).

Hindhede Quarry and Bukit Timah. Allow three hours for this part of the excursion. The quarry is located behind the N Parks HQ for the Bukit Timah Nature Reserve which is a 30-minute walk from the Singapore Quarry along a cycle track in the forest. Alternatively, there are bus routes along Upper Bukit Timah Road with bus stops near Hindhede Drive which leads to the HQ. There is a path leading from the N Parks museum (which is very much worth a visit) to a viewing platform inside the quarry. The view to the east is of massive jointed granite, overlain by oxisols. The former entrance to the (now fenced off) quarry is cut into a dyke of fine grained leucogranite, trending 040 ^{o}, dipping 75^{o}NW. The quarry is flooded and the variation of water levels indicated by "tide marks" show that lake water is infiltrating the fractured granite.

It is worth walking from the Park HQ up to the top of Bukit Timah if only because it is the highest hill in Singapore. There are some weathered outcrops of granite in the road cuttings on the way up. Bukit Timah translates as "Tin Hill". Tin mineralisation in the form of cassiterite quartz veins has not been observed. The view at the top is blocked by the forest. The standing stone that marks the top is rounded and was probably a core-stone dug out of the local soil having suffered from exfoliation caused by deep chemical weathering when buried.

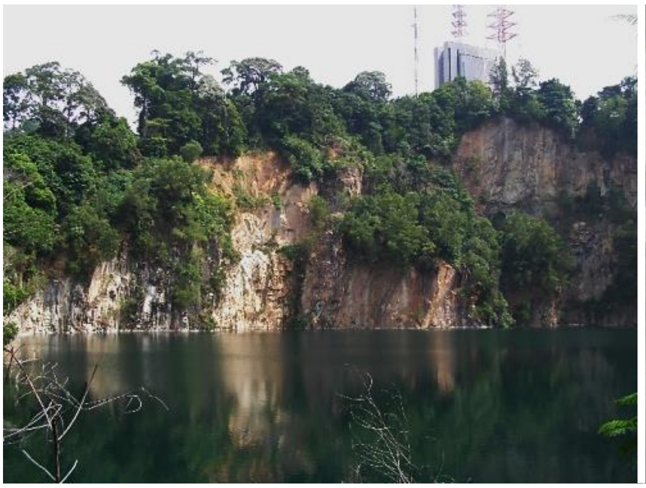

Fig. 71. General view of Hindhede Granite Quarry. (Photograph by: G. J. H. Oliver).

Fig. 72. 'Tide marks' indicate filling and draining episodes showing that the granite is permeable. (Photograph by: G. J. H. Oliver).

Fig. 73. Summit standing stone of Bukit Timah Granite. (Photograph by: G. J. H. Oliver).

Fig. 74. Edge on view of stone in Fig. 73 showing exfoliation. (Photograph by: G. J. H. Oliver).

Fig. 75. Close up of equigranular texture in summit granite boulder: rectangular crystals of orthoclase (white), in a matrix of plagioclase (very pale green), quartz (glassy) and biotite (black). (Photograph by: G. J. H. Oliver).

Fig. 76. The pavement slabs hereabouts are cut from andesitic lava with conspicuous pink orthoclase and black hornblende crystals set in a fine grained matrix: this has no comparison with any rock from Singapore and must have been imported. (Photograph by: G. J. H. Oliver).

Bukit Batok Quarry is a 2-km walk from Hindhede Quarry and is accessed from the car park at the junction between Bukit Batok East Avenues 2 and 6. Buses run along both. Allow for one hour. The northwest face of the quarry is unsafe and in places has collapsed into the quarry lake. An artificial peninsula in the lake allows the inspection of loose blocks of granite that are riddled with inclusions of angular blocks of dark grey dolerite (alternative name: micro-gabbro). It could be that the dolerite/micro-gabbro originated as part of the already crystallised Gombak Gabbro (age 260 Ma) and that the Bukit Timah Granite magma (age 244 Ma) later intruded it and broke it up into these blocks and carried them away. There are also some *very* large turtles in the lake!

Fig. 77. Bukit Batok Quarry face that is 30 m high. (Photograph by: G. J. H. Oliver).

Fig. 78. Bukit Timah granite with angular inclusions of dolerite. (Photograph by: G. J. H. Oliver).

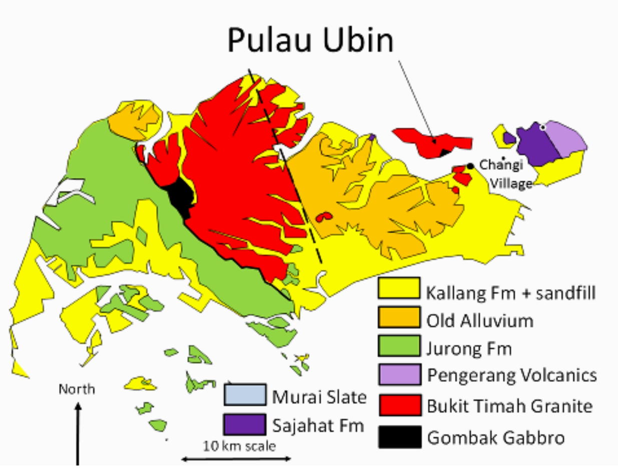

Fig. 79. Geological map showing the location of Pulau Ubin. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 80. View of Location 1 from the Jetty. (Photograph by: G. J. H. Oliver).

Pulau Ubin Excursion. — The aim of this excursion is to examine the plutonic rocks of Pulau Ubin. Pulau Ubin is accessed by inexpensive bumboats from Changi Village to Pulau Ubin Jetty that run from 6 am till 8 pm. Plan to spend the day on the island. Obtain a map of the island from the Information Kiosk next to the jetty. You can best get to Locations 1–7 by bicycle so hire a (cheap) bicycle near the jetty. Arrive at Location 1 an hour before low tide. You need permission from the Singapore Outward Bound School to visit Location 7 through a locked gate. You will need permission from the Republic Polytechnic to enter Pekan Quarry and borrow a canoe to view Locations 8–10. Location 11 needs to be viewed from an outboard-powered boat hired from Changi Village.

Pulau Ubin Jetty. Walk onto the rocks at Location 1 in front of the Information Kiosk at low water and find this spherical mafic inclusion of micro-gabbro within the Pulau Ubin Jetty diorite. Oliver et al. (2013) U-Pb zircon dated the diorite at 95 ± 1 Ma, i.e., Cretaceous. It contains plagioclase

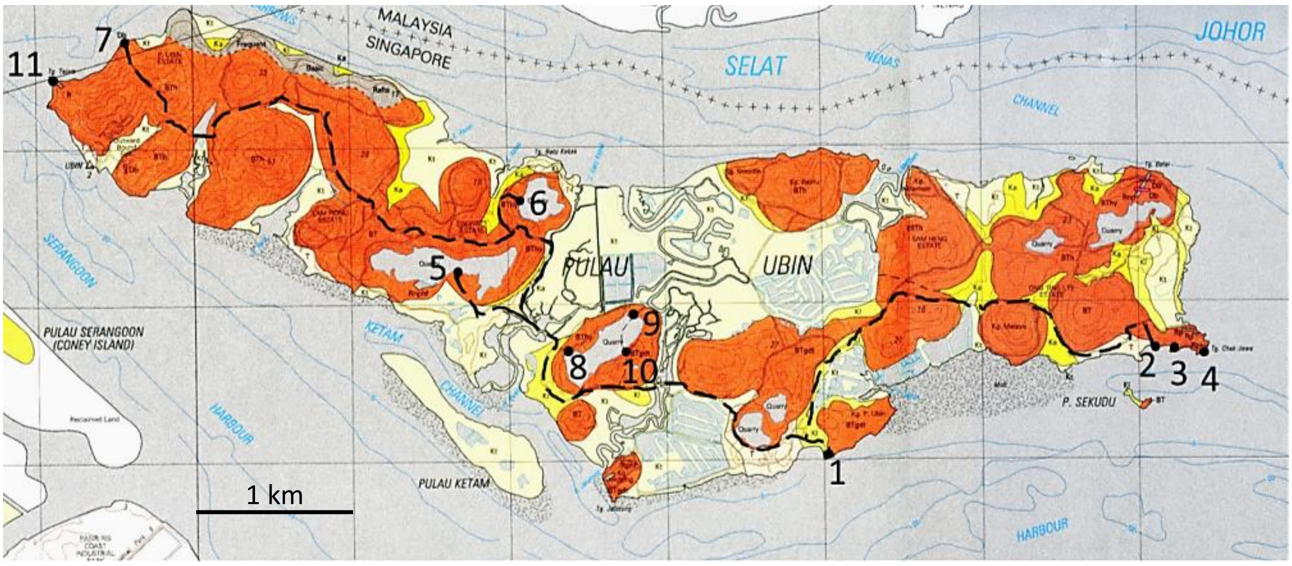

Fig. 81. Bicycle routes to Locations 1–11 on Pulau Ubin. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 82. Location 1: Mafic inclusion in Pulau Ubin Jetty Diorite. (Photograph by: G. J. H. Oliver).

(white) and hornblende, pyroxene and biotite (all black). Allow 25 minutes for a 3 km bike ride to Location 2 at Chek Jawa.

Chek Jawa. On the clean rocky fore-shore in front of the “Tudor” cottage and ~5 m east of the jetty, an intrusive complex can be examined. There are dark enclaves of fine grained diorite [1] enclosed in lighter medium grained granodiorite [2] which is surrounded and cut by medium grained pink granite [3]. Clearly, the pink granite is the youngest intrusion.

A sample of the pink granite analysed by Ng et al. (2015) yielded an imprecise Cretaceous zircon U-Pb age of ~100 Ma (i.e., close to the age of the 95 ± 1 Ma age of Pulau Ubin Jetty Diorite). The same sample also contains a significant population of inherited magmatic zircons with an Upper Triassic age of 231 ± 3 Ma. Light grey granite with an age of 230 ± 6 Ma was dated at nearby Ketam Quarry (see below).

Now follow the coastal path 100 m eastwards to Location 3 where a small rocky promontory of the pink granite [3] seen at Location 2 is cut by a medium grained grey granodiorite [4] dyke which is itself cut by another dyke of medium grained granodiorite [5]. Therefore, there are 5 igneous intrusive events at Chek Jawa that span 130 Ma from the Triassic to the Cretaceous.

Continue east and join the walkway and follow it to Location 3 where granite with closely spaced northeast/southwest trending joints and dyke-like intrusions of dark dolerite (micro-gabbro) can be seen on the rocky coast. The micro-gabbro could be the same as seen on Pulau Sajahat. Continue around the walkway and if the tide is out, observe the sea grass covered mudflats and mangrove wetlands.

Fig. 83. Location 2: Chek Jawa intrusive complex. (Photograph by: G. J. H. Oliver).

Fig. 84. Location 2: Interpretation of sequence of intrusions [1] to [3]. (Photograph by: G. J. H. Oliver).

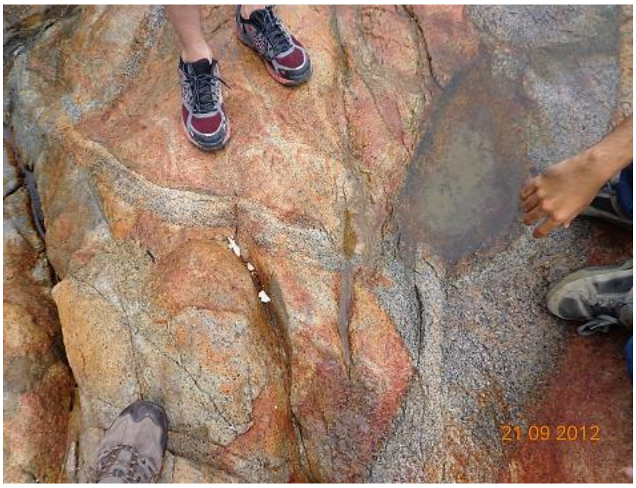

Fig. 85. Location 3: Chek Jawa: pink granite [3] is cut by 2 phases of grey granodiorite [4] and [5]. (Photograph by: G. J. H. Oliver).

Fig. 86. Location 3: Interpretation of Fig 85. (Photograph by: G. J. H. Oliver).

Fig. 87. Location 4: Chek Jawa—strongly jointed granite on the rocky shore. (Photograph by: G. J. H. Oliver).

Fig. 88. Location 4: Granite cut by dyke of micro-gabbro (Photograph by: G. J. H. Oliver).

Fig. 89. Location 5: Telescopic view of north side of Ketam Quarry showing light grey coloured granite cut by ~10 m thick darker grey (granodiorite?) dyke. (Photograph by: G. J. H. Oliver).

Fig. 90. Dyke in Fig. 89 highlighted. (Photograph by: G. J. H. Oliver).

Cycle back to the village for lunch and then cycle for a further 20 minutes onto **Ketam Quarry** (Figs. 89–93) and the view point at Location 5. From the view point it is possible to see light-coloured granite on the opposite side of the quarry cut by a ~10 m thick darker grey (granodiorite?) dyke.

If you have permission (and a key to the gate) from the National Parks Board, you can push westwards down the overgrown track from the view point to the lake side where fine grained white leucogranite, medium grained light grey granite and fine grained dark grey diorite contacts can be observed. Blocks of leucogranite are enclosed in grey granite and are interpreted to be inclusions of older country rock. Veins of finer grained diorite appear to intrude the grey granite and is therefore the youngest intrusion here. The light grey granite contains segregations of white quartz, pale green epidote and pink grossular garnet, thought to be metasomatic segregations formed by contact metamorphism caused by the heat of the diorite intrusion. The grey granite has been zircon U-Pb dated at 230 ± 5 Ma by Oliver et al. (2013); it might be that the diorite is Cretaceous in age, like the diorite at the Jetty.

Fig. 91. Location 5: Angular blocks of white granite inclusions (left side of photograph) in light-grey granite, itself cut by dark-grey diorite (see enlargement of inset below). (Photograph by: G. J. H. Oliver).

Fig. 92. Location 5: Medium-grained light grey granite and fine grained dark grey diorite contact from the previous photograph. Veins of younger diorite intrude the granite at the top of the photograph. (Photograph by: G. J. H. Oliver).

Fig. 93. Location 5: Segregation of quartz, epidote and grossular garnet in light grey granite caused by contact metamorphism of the granite by the diorite. (Photograph by: G. J. H. Oliver).

The west side of this flooded quarry at Location 6 is accessible by bicycle and is 15 minutes from **Ketam Quarry** (Figs. 94, 95). By the gate at the water's edge, medium-grained granodiorite is in sharp contact with finer grained granodiorite. Perhaps the finer grained granodiorite is the younger intrusion. Down near the water-level, there is a swirly mixture of darker dioritic material within the granodiorite which is suggestive of magma injection and mixing.

Fig. 94. Location 6: Sharp contact between medium and fine grained granodiorite. (Photograph by: G. J. H. Oliver).

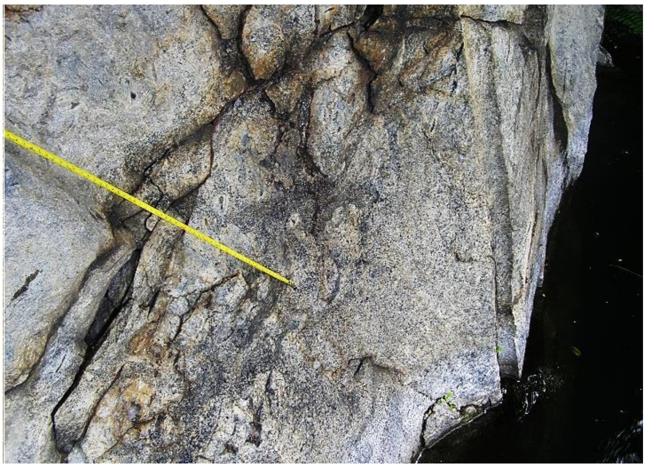

Fig. 95. Location 6: Swirly mixture of darker dioritic material in lighter granodiorite suggestive of magma injection and mixing. (Photograph by: G. J. H. Oliver).

At the **Singapore Outward Bound School** (Figs. 96–99) at the western end of Pulau Ubin, there is a track leading to a pier at Location 7. However, there is a locked gate and you will need to liaise with the School for permission to enter. On the south side of the steps to the pier, coarse-grained hornblende gabbro is cut first by narrow, coarse-grained granite sills and dykes. The gabbro and the granite are a cut by a thin dyke of fine-grained dolerite. On the north side of the steps, a ragged raft of fine- grained dolerite has been injected by the gabbro. The age of these three magmatic events is not known.

Fig. 96. Location 8: Hornblende gabbro cut by a granite sill and dyke. (Photograph by: G. J. H. Oliver).

Fig. 97. Location 8: Gabbro country rock and granite vein cut by black dolerite dyke. Photograph by: G. J. H. Oliver).

Fig. 98. Location 8: Hornblende gabbro with ragged raft of black, fine-grained dolerite. Height of outcrop is 2 m. Photograph by: G. J. H. Oliver).

Fig. 99. Location 8: Close up showing gabbro injected into the dolerite raft. Photograph by: G. J. H. Oliver).

You will have noticed the locked gate to the flooded **Ubin Quarry** (Figs. 100−105) on your way to Ketam Quarry. You need to ask the Republic Polytechnic for permission to enter and borrow a canoe. Take care, there are many loose blocks balanced on the quarry walls: wear a hard hat. At Location 8, red oxisol with a relict core stone of granite can be seen. This highly oxidised and leached soil is so enriched in aluminium that it was once mined as bauxite in neighbouring Johor. Around the lake at Location 9, cliffs of grey, well jointed, equigranular, granodiorite show enclaves of dark grey, fine grained, equigranular, diorite.

Under the dangerous big cliffs at Location 10, medium-grained, equigranular granite is in sharp contact with medium grained, equigranular diorite. Nearby, rounded masses of dark grey, fine grained, equigranular diorite inside grey medium grained, equigranular granodiorite suggest that globules of diorite magma were injected into molten granodiorite: presumeably, the two magmas have not mixed because of immiscibility. Finally, white granite veins have been intruded along the margins of the diorite globules. There is one example of a quartz-feldspar pegmatite at Location 10 that has black prisms of tourmaline and what might be cassiterite.

Fig. 100. Location 8: Bauxite oxysol with relict granite core stone. Photograph by: G. J. H. Oliver).

Fig. 101. Location 9: Well-jointed granodiorite. Photograph by: G. J. H. Oliver).

Fig. 102. Location 9: Enclave of dark grey diorite in grey granodiorite. Photograph by: G. J. H. Oliver).

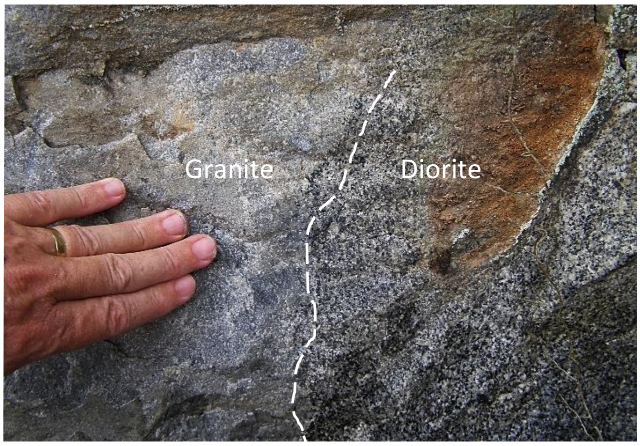

Fig. 103. Location 10: Sharp granite vs diorite contact. Photograph by: G. J. H. Oliver).

Fig. 104. Location 10: Evidence of magma immiscibility: globules of dark-grey diorite inside grey granodiorite injected by white-granite veins. Photograph by: G. J. H. Oliver).

Fig. 105. Location 10: Quartz-feldspar pegmatite vein with black tourmaline and brown cassiterite(?). Photograph by: G. J. H. Oliver).

Pulau Ubin has a variety of gabbro, dolerite, diorite, granodiorite and granite intrusions. In some places, gabbro appears to be the first intrusion, in others, granite is the first intrusion. U-Pb zircon dating has shown that there are two ages of magmatic activity: Upper Triassic and middle Cretaceous.

The aim of the next excursion is to examine the evidence for a Mid-Holocene high sea level stand in the Johor Strait by visiting the cliffs at **Tanjong Tajam** (Figs. 106, 107) at the western tip of Pulau Ubin. It is possible for a group of 4 people to negotiate with the fishermen located near the ferry terminal at Changi Village for a fast outboard motorboat to take them in 20 minutes to Tanjong Tajam at the western tip of Pulau Ubin. A larger group might consider chartering a bum boat from the ferry terminal. Arrange to arrive at low tide.

The granite cliffs at Tanjong Tajam show an obvious present-day high tide mark where granite, encrusted with dark coloured marine growth, changes to perfectly clean white medium grained, equigranular, biotite granite. The lowest extent of healthy vegetation on the neighbouring beaches coincides with this high tide mark. At 2.75 +/-0.1 m above this tide mark on the cliffs, there is another conspicuous marker, parallel with the first marker, where the clean white granite changes sharply to weathered brown stained granite. This second marker cannot be a recent high tide mark because a navigation beacon made out of bricks and cement has been erected on the clean white granite between the tide markers and does not display the higher marker. Clearly, no exceptional tides have washed the beacon away.

Rain and soil-water solution grooves following vertical joints in the granite above the highest marker are deeper and closer-spaced than between the marker lines, whilst there are no grooves below the present-day high tide mark. This suggests that the granite above the higher marker has been exposed to acid rain and soil water for longer than the granite between the two markers. Bird et al. (2010) estimated on the basis of radio-carbon dating of shells and mangrove wood from an excavation under the Singapore Management University, that the sea level in the Singapore Strait was ~2.5 m higher than present ~6,000 years ago in the Mid-Holocene. The upper marker at Tanjong Tajam is therefore interpreted to be the high tide mark for the Mid-Holocene high stand. If this is correct, and Singapore and the Sunda Shelf have remained tectonically stable, then it can be concluded that relative sea level has dropped in the Singapore region by 2.75 +/- 0.10 m since the Mid-Holocene, presumably because of global climate cooling and the take up of ice. There is an estimated 0.10 m error on this number due to the unevenness of the tide marks. Global warming over the past 200 years of the Industrial Revolution has caused sea level to rise ~0.2 m: the banding in the marine growth just below the present-day high tide mark might be reflecting this.

Fig. 106. Locality 11, Tanjong Tajam, western tip of Pulau Ubin, looking northeast at low tide. Note high tide marks on granite cliffs for the present-day and the +2.75 m Mid-Holocene tide mark at ~6,000 years BP. The level of vegetation on the beach corresponds to the present-day high tide mark. (Photograph by: G. J. H. Oliver).

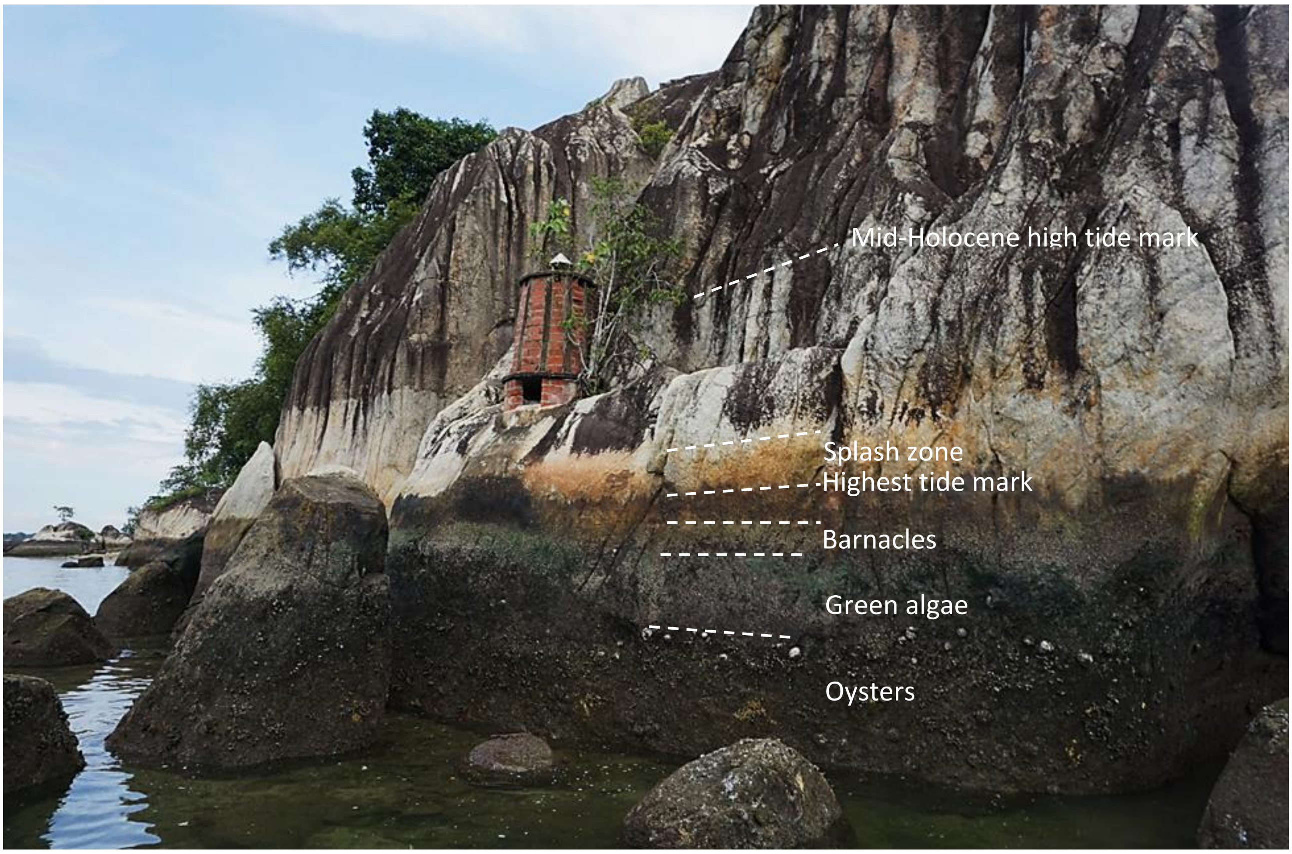

Fig. 107. Locality 11, Tanjong Tajam, western tip of Pulau Ubin, looking southeast at low tide. Top photograph—note i) the high tide marks on granite cliffs for the present-day and the + 2.75 m Mid-Holocene mark at ~6,000 yr BP; ii) that the solution grooves in the granite exposed above the Mid-Holocene high tide mark are deeper than those below this. Bottom photograph: Close up illustrating present-day tide marks and the +2.75 m Mid-Holocene high tide mark. Note i) the oyster, green algae and barnacle bands; ii) there is no tide mark on the red brick navigation beacon: it post-dates the Mid-Holocene high-stand. (Photographs by: G. J. H. Oliver).

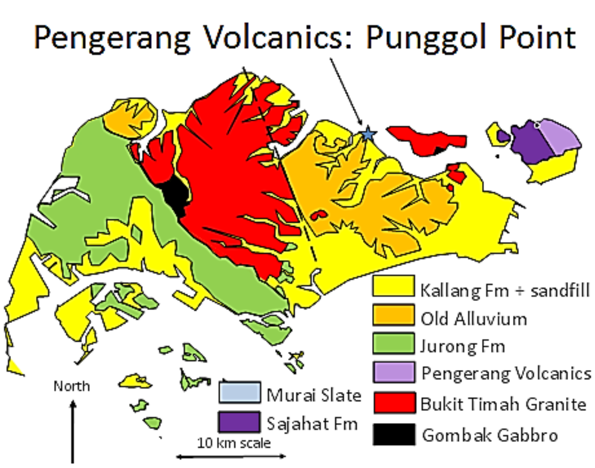

Fig. 108. Geological map showing the location of Punggol Point. Reproduced from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 109. Boulders of Pengerang Volcanics used for beach protection at Punggol Point. (Photograph by: G. J. H. Oliver).

Punggol Point Excursion. — The aim of this excursion is to examine the boulders protecting the beach at Punggol Point (Figs. 108–117). They are thought to be representative of the Pengerang Volcanics found in South Johore and on Pulau Tekong in Singapore. Allow one hour on the beach at low tide.

Punggol Point can be reached by bus or car. Walk westwards from under the pier along the beach and examine the boulders which were allegedly quarried from the Pengerang Volcanics, 20 km away in the east in Johor. Curiously, the boulders are quite rounded and look like they have been collected as river boulders rather than being blasted out of a quarry. Punggol Beach exhibits examples of boulders of andesite to rhyolite lava, tuff, and breccia. Some boulders show how falling volcanic bombs have impacted and deformed unconsolidated ash. The Pengerang Volcanics have been U-Pb zircon dated in Johor at 238 ± 5 Ma (Oliver et al., 2013) which is the same age as the Bukit Timah granite at Mandai Quarry (237 ± 1 Ma, Oliver et al., 2013). Boulders of rhyolite pumice have been washed up to the high-tide mark on the beach: throw one in the sea and watch it float! Rhyolite pumice was erupted in the South Sandwich Islands on 5 March 1962, and still circulates in the ocean currents. Incidentally, the geological map of Singapore for 2009 shows that Sajahat Formation argillites and quartzites are exposed at Punggol Point; however, at present, only deeply weathered granite can be seen.

Fig. 110. Layered rhyolite (white) and dacite (grey) tuffs with andesite bombs (brown). (Photograph by: G. J. H. Oliver).

Fig. 111. Andesite lava with dacite lava inclusions. (Photograph by: G. J. H. Oliver).


Fig. 112. Andesite tuff with sub-angular dacite blocks. (Photograph by: G. J. H. Oliver).


Fig. 113. Banded rhyolite with andesite block. (Photograph by: G. J. H. Oliver).


Fig. 114. Andesite tuff with rounded dacite blocks. (Photograph by: G. J. H. Oliver).


Fig. 115. Rhyolite tuff with angular andesite blocks. (Photograph by: G. J. H. Oliver).


Fig. 116. Flow banded rhyolite. (Photograph by: G. J. H. Oliver).


Fig. 117. Rhyolite pumice. (Photograph by: G. J. H. Oliver).

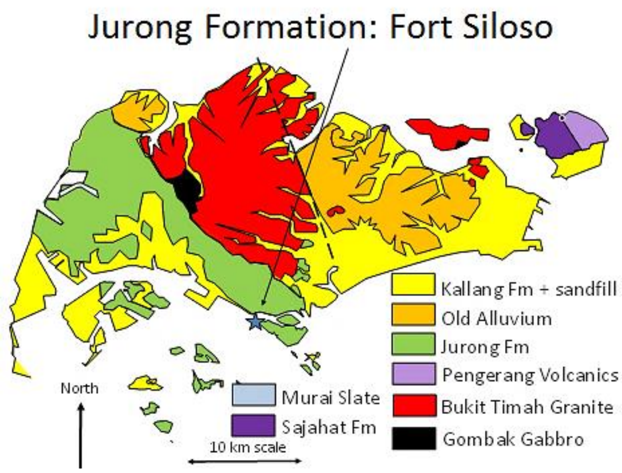

Fig. 118. Geological map showing the location of Fort Siloso. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 119. Start the Sentosa Excursion at the Underwater World car park. Source: Google Earth.

Sentosa Excursion. — The aim of this excursion is to examine the non-marine facies of the Jurong Formation around Siloso Fort, Sentosa (Figs. 118–135). Access is by car or by monorail from Vivo City to South Beach, Sentosa and thence by bus or cable car to Fort Siloso. Choose a tide of less than 1 m and start the excursion 1.5 hours before low water. Be prepared to get wet feet. Beware of falling rocks from the cliffs, especially during rain storms. Retreat to cover during lightning strikes. Beware of the wash from the fast ferries.

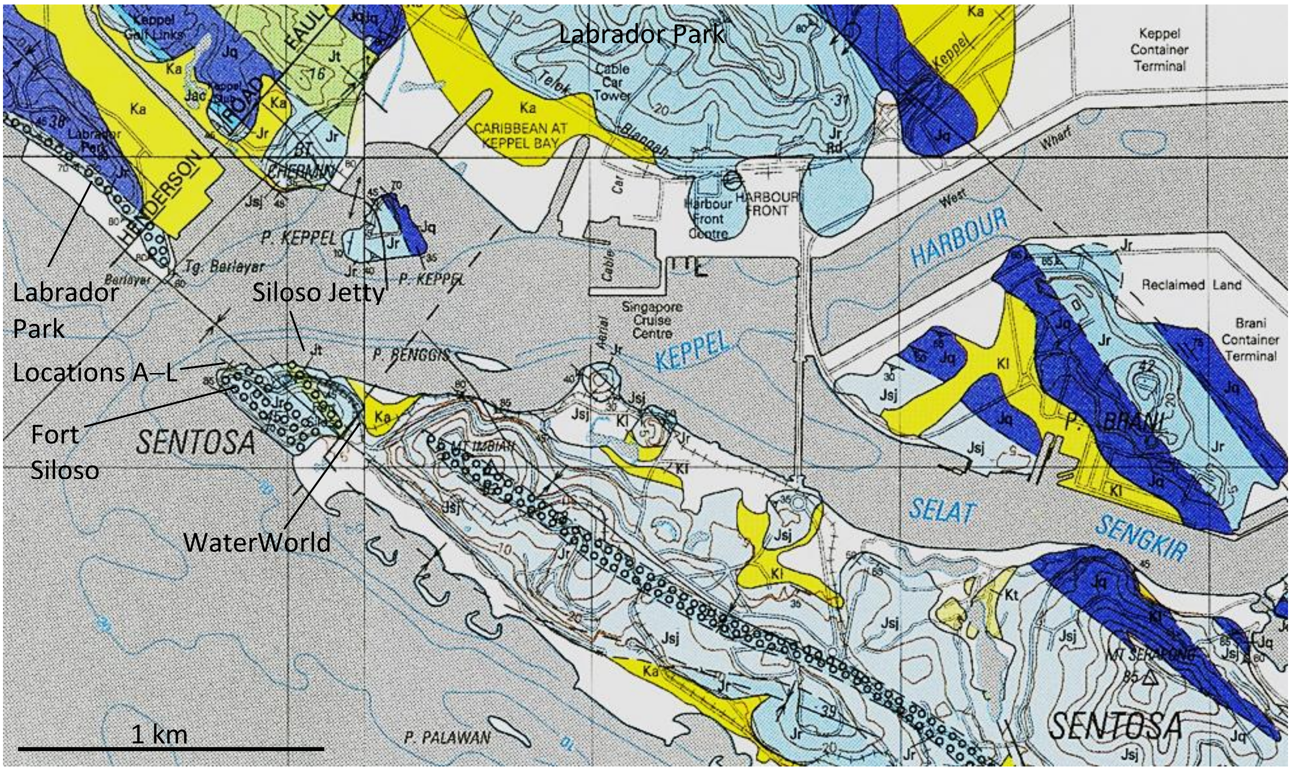

Fig. 120. Geology of Keppel Harbour. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

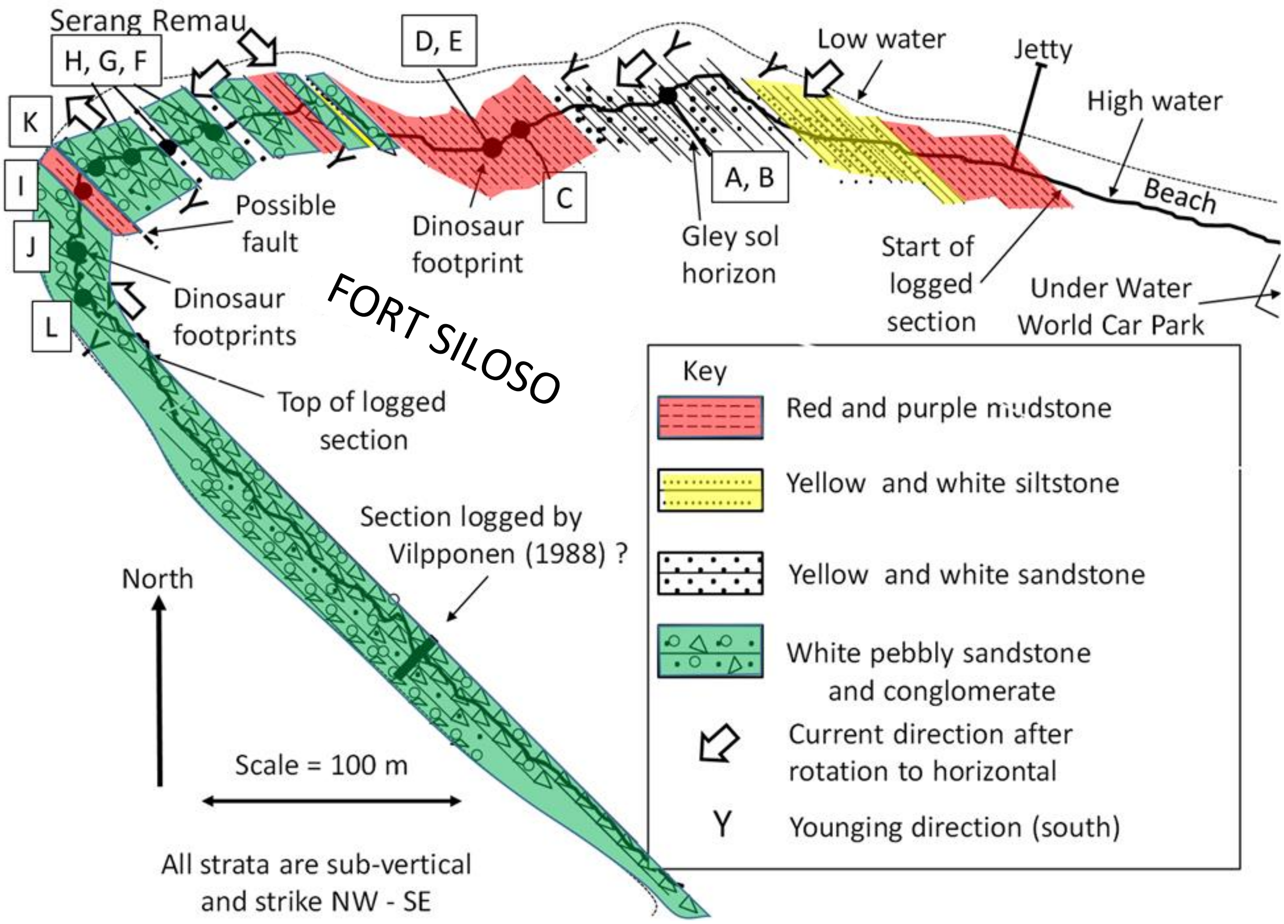

Fig. 121. Geological map of the northwest end of Sentosa with locations of outcrops A–L. Mapped and drawn by G. J. H. Oliver.

Figs. 122 to 135 are illustrations of outcrops A to L, respectively, in Fig. 121. They show the continental red-beds of the Jurong Formation along the forshore underneath Fort Siloso, Sentosa. According to Lee & Zhou (2009), Locations A to B are mapped as the St. John Facies, i.e., flycsh-like marine muddy fine sandstone with minor laminae of carbonaceous materials. By definition, flysch is a deep marine sediment: these chanellised sandstones are interpreted by Oliver & Prave (2013) to be fluvial deposits.

Fig. 122. Locality A. Channelised yellow sandstone interpreted as fluvial. The top of the photo is towards the southeast. The beds are younging from left to right, i.e., towards the southwest. (Photograph by: G. J. H. Oliver).

Fig. 123. Locality B. Thin bedded (fluvial?) sandstone overlain by white kaolin-rich mudstone formed by intense chemical weathering of local granites. The top of the photo is towards the northwest. The younging direction is from the right to left, i.e., towards the southwest.

Fig. 124. Locality C. This location is 25 m northwest of the location B of Fig. 123. The top of the photo is towards the southeast. These are upward thickening siltstone beds. (Figs. 124 and 125 photographs by: G. J. H. Oliver).

Localities of Figs. 125 to 127, are examples of red mudstone and siltstone which should be mapped as the Queenstown Facies but is not shown by Lee & Zhou (2009): Oliver & Prave (2013) interpret these as lacustrine muds and silts, deposited in Lake Sentosa. One loose boulder of red mudstone has an imprint of a claw-like feature, possibly a dinosaur footprint.

Fig. 125. Locality C. Alternating cohesive laminated grey, red, purple hematite-rich mudstone and white kaolin-rich laminated mudstones, interpreted as being deposited from turbidites in a tropical lake (called Lake Sentosa by Oliver & Prave, 2013). The top of the photo is to the northwest. Younging (indicated by the letter Y) is right to left towards the southwest. (Photograph by: G. J. H. Oliver).

Fig. 126. Locality D. Close up of earthy hematite-rich mudstone; note the tiny flakes of detrital, silvery muscovite, possibly eroded from granite or gneiss. (Photograph by: G. J. H. Oliver).

Fig. 127. Locality E. Possible dinosaur claw print in red mudstone indicated by the tip of the pen. Loose block. (Photograph by: G. J. H. Oliver).

Fig. 128. Locality E. Red and purple mudstones with yellow siltstone associated with possible claw print. The siltstone is cross bedded indicating younging towards the southwest. Plan view, top of photo is towards the southeast. Hammer for scale is 30 cm long. (Photograph by: G. J. H. Oliver).

Fig. 129. Locality F. Typical pebble conglomerate showing graded distribution of clasts including vein quartz, granite, gabbro, and slate. Bedding is younging (Y) left to right to the southwest. This is interpreted as flood channel fills on a delta top. (Photograph by: G. J. H. Oliver).

Fig. 130. Locality G. Graded pebble conglomerate in sharp contact with white siltstone; coarser 'armoured' bed tops are inferred to be water-winnowed lags. The top of photo is to the southeast, younging (Y) is left to right towards the southwest. (Photograph by: G. J. H. Oliver).

Localities illustrated by Figs. 129–135, F to L are from around **Serang Remau Point**, the type-section of the "transitional" Remau Facies of Lee & Zhou (2009). Oliver & Prave (2013) interpret these sands and gravels to have been deposited in river delta channels flowing into Lake Sentosa.

Fig. 131. Locality I. Vertical, mottled purple, lake bed silt and sandstone from Serang Remau, burrowed by worms. Note both purple silt filled- and white sand-filled, near vertical *Skolithos* burrows. Strata young towards the southwest from left to right. (Photograph by: G. J. H. Oliver).

Fig. 132. Locality H. Normal graded sandstone bed with abundant rip-up clasts of grey mudstone. The top of the photo is towards the southeast. Younging direction (Y) is left to right towards the southwest. (Photograph by: G. J. H. Oliver).

Fig. 133. Locality L. Planar cross-bedded medium-grained sandstone and granule to cobble fluvial channel conglomerates. Note GPS receiver for scale. The top of photo is towards the southeast. Younging is from left to right, towards the southwest. Palaeocurrent flowed towards the northwest. (Photograph by: G. J. H. Oliver).

Fig. 134. Locality J. Possible animal track way(s) on top of pebble conglomerate from Serang Remau. The tape measure is 1 m long. 10 m up vertical rock face, between the two concrete gun platforms, viewed towards the northeast. (Photograph by: G. J. H. Oliver).

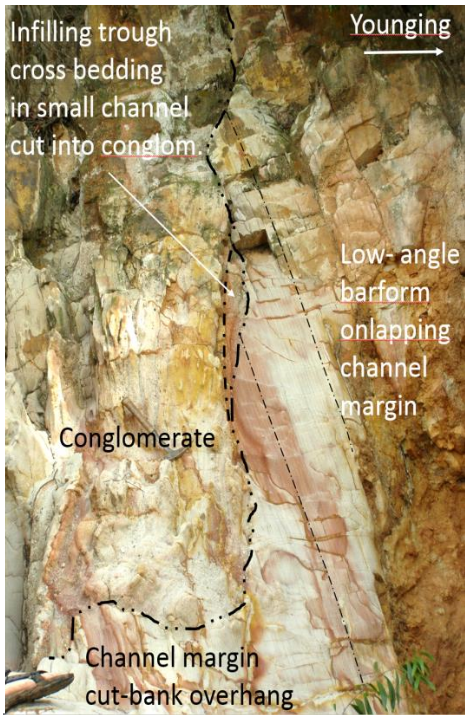

Fig. 135. Locality K. Channel margin cut bank overhang in fluvial channels. Outcrop view is 2.5 m across. Top of photo is towards the southeast. (Photograph by: G. J. H. Oliver).

Labrador Park Excursion. — The aims of the Labrador Park Excursion (Figs. 136–146) are to i) view present-day sedimentary processes in the delta of the Berlayer Creek; and ii) examine the sediments of the Jurong Formation. The park can be accessed directly by car or bus or from the Labrador Park MRT station followed by a 15-minute walk down the footpath that follows the tidal Berlayer Creek down to the sea onto the coastal walkway at Location 1. Go on a day when the tide is extra low (e.g., 0.1 m) so that the Berlayer Creek delta is exposed to show offshore sand bars and sand- and mud-flats cut by distributary channels.

Follow the path round to Location 3 at the entrance to Keppel Harbour where you can read that Chinese navigators were here in the 14^{th} Century! Vertical beds of conglomerate are boldly exposed and can be seen to be composed mostly of granules of white and grey angular quartz (and minor pink K-feldspar) together with sub-angular clasts of granite and gabbro which can be matched to the local Bukit Timah Granite and Gombak Gabbro. The black clasts are chert which is not found *in-situ* in Singapore and may have been derived from the Raub-Bentong Suture Zone somewhere off to the west of Singapore.

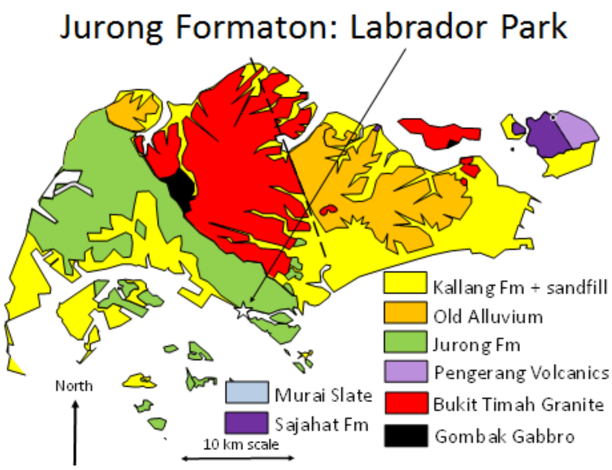

Fig. 136. Geological map showing the location of Labrador Park which is located in the Jurong Formation. Modified from Lee &Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Fig. 137. Locations 1 to 6 of the Labrador Park Excursion. Berlayer Creek forms a small delta in Keppel Harbour. Source: Google Earth.

Fig. 138. Loc. 1. Panoramic view (from east to west) across the delta mouth at very low tide (0.1 m): note sand bar (centre), distributary channels (left and right) and gravel bank (left). Mud flats lie behind. (Photograph by: G. J. H. Oliver).

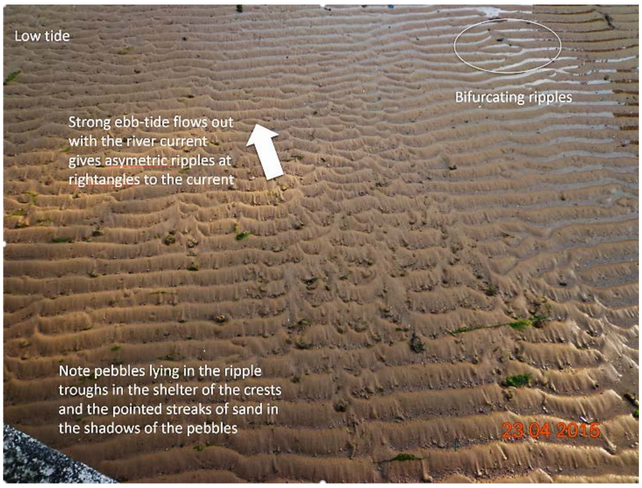

Fig. 139. Location 1: Details of tide generated sand ripples. (Photograph by: G. J. H. Oliver).

Fig. 140. Location 2: View looking east over the sand bars. (Photograph by: G. J. H. Oliver).

Fig. 141. Location 3: Vertically bedded conglomerates of the fluvial Remau Facies. Close-up photographs (middle and right) of the mixture of pebble and granule clasts of quartz (white and creamy), granite (pink), gabbro (dark grey) and chert (black). Note the rather good porosity in the sandy matrix of the conglomerate. (Photographs by: G. J. H. Oliver).

Now you can walk to the western end of the promenade to Location 4 where you can contemplate the rocky shore towards the northwest: Note the scars of several rock slides where steep slopes on steep beds of Jurong Formation conglomerates have collapsed into the sea. To access the beach at low tide at Locations 5 and 6, you need to obtain a key to the gate to the beach from the National Parks Board. Remau Facies, Jurong Formation, fluvial conglomerates and sandstones are the same as seen across Keppel Harbour on Sentosa at Remau Point. Here they dip moderately northeast and both normal and reverse grading and planar cross-bedded pebble beds can be seen.

Fig. 142. Location 5: Alternating Remau Facies fluvial sandstones and conglomerates from Labrador Park beach. (Photograph by: G. J. H. Oliver).

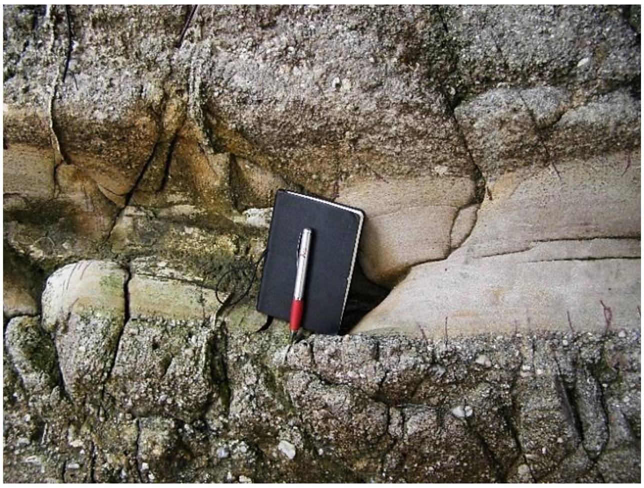

Fig. 143. Close-up of fluvial channel gravels seen in Fig. 142. (Photograph by: G. J. H. Oliver).

Oliver et al. (2014) reported the results of U-Pb dating individual detrital grains of zircon from the conglomerate from Location 6. Most of the zircon ages cluster around 245 Ma, exactly the same as the age as the Bukit Timah Granite which is only 5 km to the north (see above). So it is not surprising that pebbles of local granite are readily identified here. The oldest zircon was dated at 2,719 ± 25 Ma: this Archaean age is very old for Southeast Asia. Possibly this zircon has been through many cycles of erosion, deposition, burial, metamorphism, magmatism, uplift, and more erosion, starting in either Australia or China. Proterozoic zircons with ages ranging from 820–2260 Ma are also present. Nine analyses range from 320–370 Ma, i.e., Late Devonian–Middle Carboniferous, perhaps eroded from the Sajahat Formation. Thirty seven of the grains range between 274 ± 4 Ma and 209 ± 2 Ma (Early Permian to Late Triassic). The 274 ± 4 Ma age can be matched with volcanic rocks from offshore East Johor on Pulau Sibu (275 ± 5 Ma). The youngest zircon age (209 ± 2 Ma) is representative of Indosinian granite ages found in the Main Ranges of Peninsular Malaysia to the west of the Raub-Bentong Suture. Therefore, sand grains in the Remau Facies river deposits of the Jurong Formation have come from far and wide to reach Singapore.

Fig. 144. Location 6: Remau Facies fluvial conglomerates with quartz and granite clasts, planar cross-bedding. This outcrop (left) yielded the oldest mineral grain so far dated in Singapore (2,719 ± 25 Ma). A close-up is on the right. (Photographs by: G. J. H. Oliver).

Fig. 145. Location 6 displays meta-quartzite cobbles. (Photograph by: G. J. H. Oliver).

In addition to the same clasts as at Location 3, some large rounded metamorphosed quartzite cobbles of unknown provenance can be identified (Fig. 145). Channels eroded into underlying gravel beds clearly indicate that the beds are younging towards the north east (Fig. 146) which is the opposite to what is found at Remau Point along strike on neighbouring Sentosa. This might be explained by an anticlinal structure similar to the Lokos Anticline seen on St John’s Island (see next excursion).

Fig. 146. Location 6 displays channelised conglomerates indicating that the beds are the right way up and younging towards the north east. (Photograph by G. J. H. Oliver).

Southern Islands Excursion. **—** The aim of this excursion is to examine the geology of St. John's Island (Pulau Sakijang Bendera) and Kusu Island (Pulau Tembakul, Peak Island) which are basically an along-strike extension of the Jurong Formation seen on Sentosa, but with the advantage of better outcrops and the chance to observe a classic anticlinal fold structure.

St John's Island (Figs. 147–164). Access is by Singapore Island Cruise ferries which depart from South Marina Pier at 9 am weekends and returns via Kusu Island by 6.30 pm. Alternatively, private charters can be arranged from South Marina Pier. The trip to St John's Island takes ~30 minutes. Choose a day with a low spring tide at ~11.30 am or you will not be able to see the outcrops along the rocky shores. You will need a packed lunch and stout shoes to walk on the slippery rocks. You will likely get your feet wet.

If you are travelling on the ferry then you need to plan your itinerary and move quite fast because you will be restricted by the tides and by the departure time of the last ferry from St John's at ~4.30 pm.

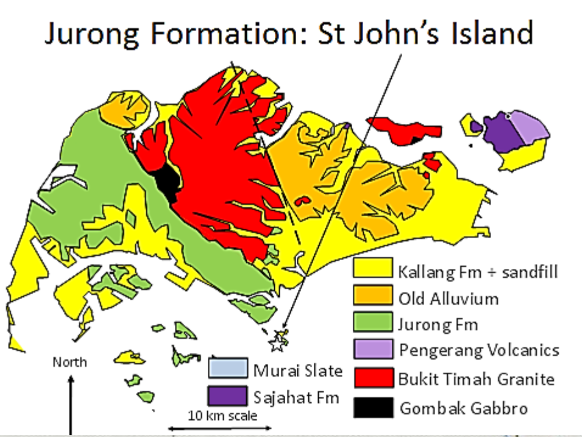

Fig. 147. Geological map showing the location of St. John's Island which is located in the Jurong Formation. Modified from Lee &Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

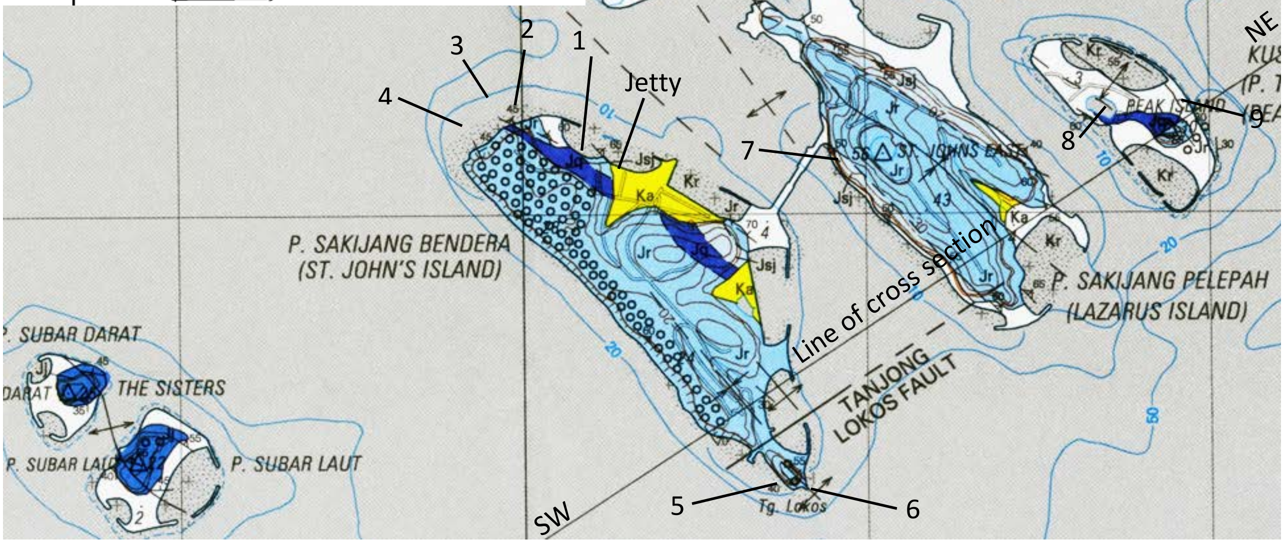

Fig. 148. Geological Map of St John's and neighbouring islands with locations 1–9. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

At the St John's Island jetty there are some interesting history boards to read. From here, starting 1.5 hours before high water, spend no more than 1 hour examining Locations 1 to 4. Walking northwest, note the striped red and light grey mudstones at Location 1 which Lee & Zhou (2009) call the St John (*sic*) Facies. However, these mudstones appear to be no different to those that Oliver & Prave (2013) called the Queenstown Facies, along strike on Sentosa.

Fig. 149. Location 2: Cross-bedded Remau Facies fluvial conglomerate. (Photograph by: G. J. H. Oliver).

Fig. 150. Location 3: Soft lacustrine Queenstown Facies red mudstone. (Photograph by: G. J. H. Oliver).

At Location 2, planar cross-bedded conglomerates are dominated by quartz and granite detritus just as at Remau Point on Sentosa, and are interpreted to be fluvial in origin. These are in sharp contact with red mudstones at Location 3 which might be lake (lacustrine) deposits. As you walk southwest you will see several features in the low cliffs that may be slumps in red mudstones that are now covered in “protective” concrete.

At the end of the section at Location 4 there are beautiful exposures of planar and trough cross-bedded conglomerates and sandstones with normal (and reverse) graded bedding indicating that the section is the right way up. One interpretation is that these are fluvial gravels and sands that were deposited in fresh water delta system that was filling up a lake (i.e., Lake Sentosa of Oliver & Prave, 2013).

Fig. 151. Locality 4. Cross-bedded fluvial conglomerates. (Photograph by: G. J. H. Oliver).

Fig. 152. Locality 4. Quartz pebbles in fluvial conglomerates. (Photograph by: G. J. H. Oliver).

Fig. 153. Locality 4. Cross-bedded fluvial conglomerates. (Photograph by: G. J. H. Oliver).

Fig. 154. Fluvial trough-cross bedding. (Photograph by: G. J. H. Oliver).

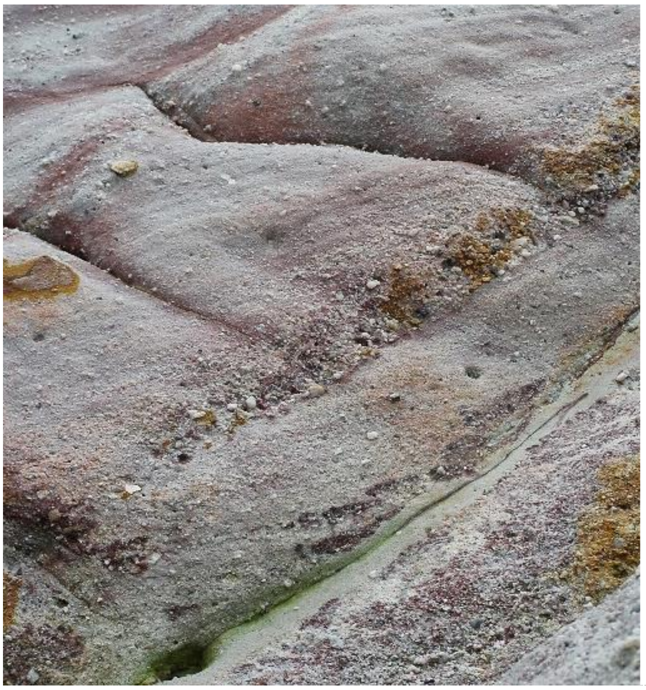

Fig. 155. Locality 4. Normal graded conglomerate. (Photograph by: G. J. H. Oliver).

Fig. 156. Locality 4: Reverse graded conglomerate. (Photograph by: G. J. H. Oliver).

Allow 20 minutes for a brisk walk to the southeast tip of the island. The coastal strip can be accessed on foot from the boat ramp, one hour each side of low tide. Ask for permission to enter from the Security Office in the National University of Singapore Marine Research Station. At Location 5, 1 m-thick quartz pebble conglomerate beds rest on sandstone with prominent load casts indicating that the beds are the right way up. There are two sets of near vertical joints orientated north to south and east-northeast to west-southwest, respectively. Quartz veins criss-cross each other forming a honey-comb effect because of differential weathering. Some veins show empty cavities with tooth-shaped quartz prisms growing inwards from the walls: these were once filled with silica-saturated hydrothermal fluid, perhaps derived by sand and gravel compaction and clay dehydration during burial.

Fig. 157. Locality 5: Quartz conglomerate beds with load and flame casts resting on sandstone. (Photograph by: G. J. H. Oliver).

Fig. 158. Close-up: load casts of gravel that have sunk into the underlying sand. (Photograph by: G. J. H. Oliver).

Fig. 159. Locality 5: Conglomerate with two joint sets. (Photograph by: G. J. H. Oliver).

Fig. 160. Close-up: conglomerate with pebbles of quartz (white and grey) and chert (black). (Photograph by: G. J. H. Oliver).

Fig. 161. Locality 5: Honey-combed sandstone caused by differential weathering of hard quartz veins and softer sandstone. (Photograph by: G. J. H. Oliver).

Fig. 162. Close-up: >4 vein filling episodes can be seen in this quartz vein. Note the open cavity with tooth-like quartz prisms. (Photograph by: G. J. H. Oliver).

Sandstone here has been recrystallized to quartzite: detrital quartz grains have been annealed, recrystallized and constricted to become elongated rods orientated along the hinge of the Lokos Anticline (see next Location 6 below). This is a sign of ductile deformation: quartz becomes ductile (or plastic) under hydrous conditions when it is strained at temperatures greater than ~200^{o}C.

Fig. 163. Location 5: Sandstone here has been recrystallized to become a quartzite. (Photograph by: G. J. H. Oliver).

At the southeast tip of the island (Location 6, Tanjong Lokos) the Lokos Anticline is exposed in the cliff below the radar station. Note how a spaced fracture cleavage radiates around the fold limbs such that it dips northeast on the southwest limb and southwest on the northeast limb as defined by the bedding. The axial plane dips steeply to the southwest. The fold crest is horizontal and trends northwest/southeast. Sandstone in the core of the fold at sea level shows brittle crushing: thus the fold as a whole has formed in the brittle-ductile transition since the limbs exhibit ductile deformation (e.g., at Location 5). Because the bedding is the right way up, structural geologists would say that the fold "faces up" (i.e., in the axial plane of the fold, the beds get younger upwards). This fold is not quite symmetric: it has an axial plane that dips steeply to the southwest and the northeast limb has a slightly shorter and steeper dip than the southwest limb.

Fig. 164. Location 6: Lokos Anticline, looking northwest. Note the cleavage bedding geometries and the brittle crushed sandstone in the core of the fold. (Photographs by: G. J. H. Oliver).

Lazarus Island (Figs. 165–168). After spending an hour at the Lokos outcrops, walk back towards the main jetty and across the causeway to Lazarus Island (Pulau Sakijang Pelepah) to Location 7. Here laminated mudstone, siltstone and sandstone is mapped as the St John Facies. Indeed, lamellae of carbonaceous material can easily be seen in the sandstones. Hummocky cross-bedding is indicative of breaking waves. In places, ~15 cm thick contorted coal seams can be seen. Since plant roots cannot be seen, it is assumed that this is plant material that has been carried in by currents. These are interpreted as lakeshore deposits.

Walk southeast for a few metres where clear bedding-cleavage relationships can be seen: the beds are the right way up and dip to the northeast, the cleavage faces upwards and refracts (i.e., changes orientation) through the sandstone and siltstone beds and dips to the southwest. Probably, the cleavage orientation in the Lokos Anticline (Location 6) is also refracted. Black staining on the outcrops is reminiscent of evaporated oil seeps seen on Labuan Island and at Miri, Sarawak.

Make sure you leave in time to catch the ferry to Kusu Island!

Fig. 165. Location 7: Laminated siltstones of St. John Facies. (Photograph by: G. J. H. Oliver).

Fig. 166. Location 7: Close up showing hummocky cross bedding. (Photograph by: G. J. H. Oliver).

Fig. 167. Location 7: Contorted coal seam within St. John Facies. (Photograph by: G. J. H. Oliver).

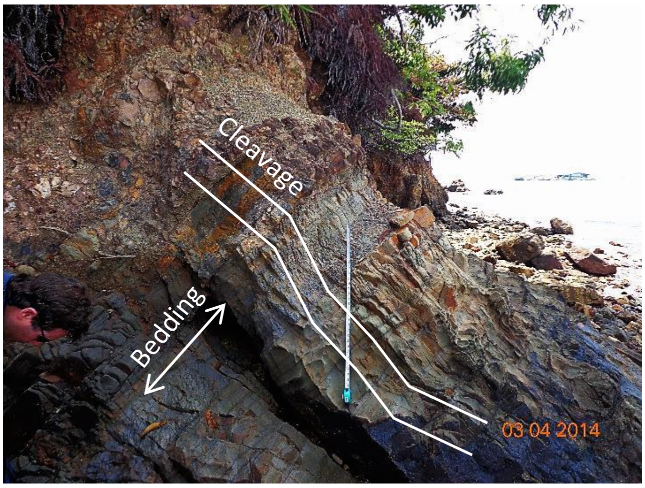

Fig. 168. Cleavage refracted through silt- and sand-stones. Note the black staining which is reminiscent of evaporated oil seeps. (Photograph by: G. J. H. Oliver).

Kusu Island. The trip from St John's to Kusu Island (Figs. 169–175) takes 15 minutes. Depending on the day, the ferry can wait for as little as 30 minutes before departing for Marina South. Kusu Island has temples and shrines that attract thousands of visitors in the 9th lunar month.

Location 8 is within the walls of the Taoist Da Bagong Temple next to the turtle pond. Remau Facies pebbly sandstone and conglomerate dip steeply to the southwest and contains rip-up clasts of siltstone: one example is 45 cm long. A hard to find cleavage strikes at 290 ^{o} and dips at 85 ^{o} to the northeast, very similar to the southwest limb of the Lokos Anticline at Location 6. If you go round the back of the temple and drop down onto the little beach, you can confirm that graded bedding and cross-bedding young towards the southwest. Thus the cleavage is upward facing.

Walk anticlockwise around the hill, noting the scars of landslides on the steep slopes, to the quarry at Location 9 where cross-bedding and load casts are the right way up in Remau Facies pebbly sandstones and conglomerates that dip at 30^{o} to the southeast and strike northeast/southwest at 220^{o}. This is a very unusual strike for the Jurong Formation along the normally northwest/southeast

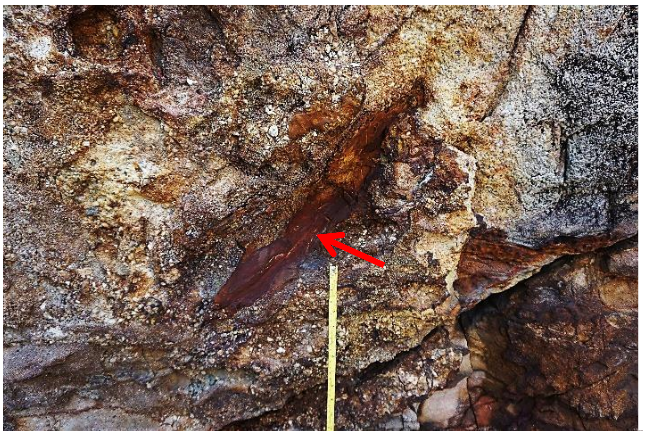

Fig. 169. Location 8: 45 cm-long rip-up siltstone (arrowed) clast in conglomerate. (Photograph by: G. J. H. Oliver).

Fig. 170. Location 8: Cleavage-bedding relationships. (Photograph by: G. J. H. Oliver).

Fig. 171. Location 8: Remau Facies dipping steeply southwest with graded and cross bedding younging towards the southwest (left). Close-up of grading (right). (Photographs by: G. J. H. Oliver).

Southern Isles/Mt. Faber/Kent Ridge trend. However, this northeast/southwest strike is common in the so called Jurong Formation found in the Pearl's Hill/Novena districts, north of the Bukit Timah Fault. Moreover, the upward facing spaced cleavage seen at Location 9 strikes at 305^{o} and dips at 85^{o} to the northeast, the same as at Locations 7 and 6 and so it could be concluded that the bedding and cleavage on St. John's, Lazarus, and Kusu Islands are structurally linked in a fold structure, possibly a southeast plunging anticline. Lee & Zhou (2009) have presented a southwest to northeast cross-section that shows an anticline and syncline on St. John's Island, a syncline on Lazarus Island, and a recumbent anticline on Kusu Island (Fig. 174), although inverted bedding was not observed by GJHO.

Fig. 172. Location 9: Cleavage bedding in Remau Facies. (Photograph by: G. J. H. Oliver).

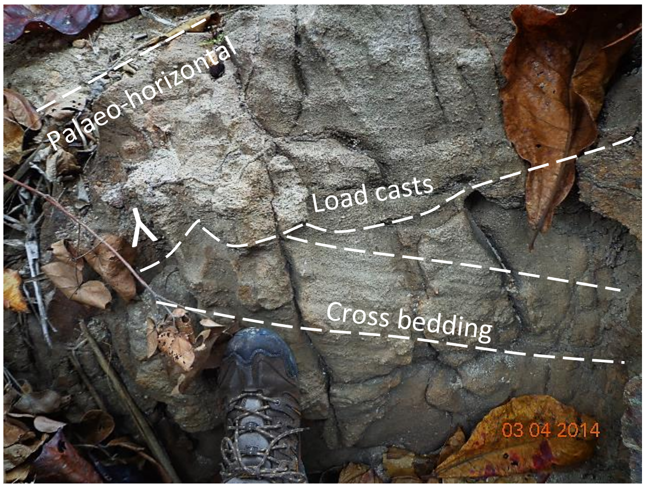

Fig. 173. Location 9: Cross bedding, load casts, and graded bedding. (Photograph by: G. J. H. Oliver).

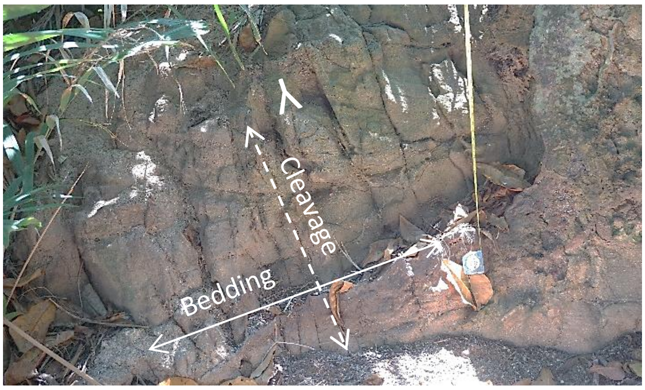

Fig. 174. Location 9: Right way up trough cross-bedded conglomerate with upward facing spaced cleavage. (Photograph by: G. J. H. Oliver).

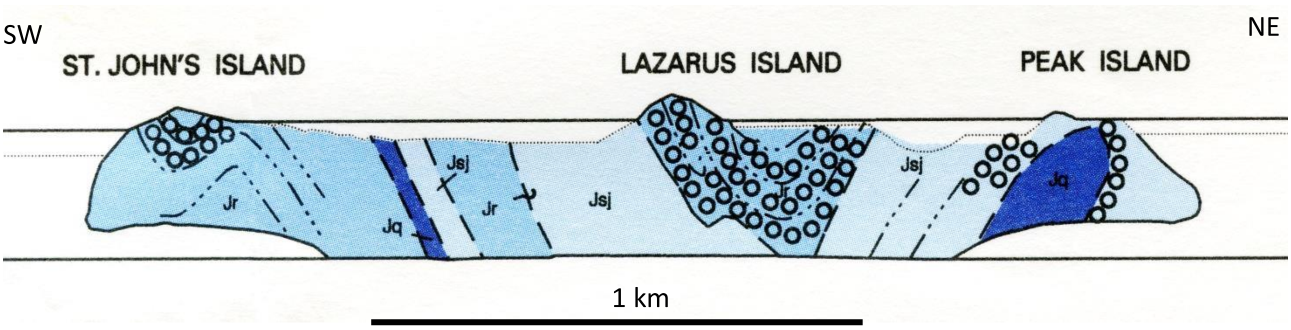

Fig. 175. Southwest to northeast cross section across St John's Island, Lazarus Island, and Kusu Island (named Peak Island here), illustrating folding. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

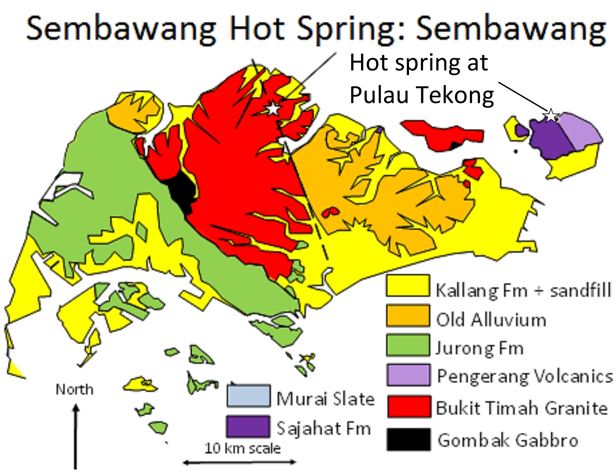

Fig. 176. Geological map showing the locations of the Sembawang and Pulau Tekong hot springs. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

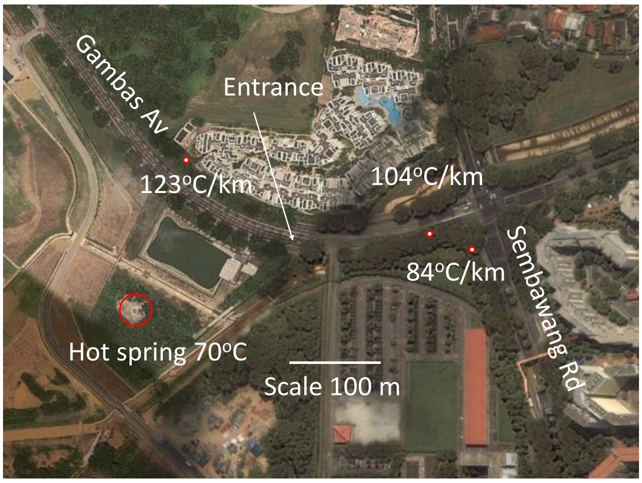

Fig. 177. The Sembawang hot spring is located on an extension of the Nee Soon Fault. The geothermal gradient is as high as 12°C/100 m in boreholes along Gambas Avenue. Source: Google Earth.

Sembawang Hot Spring Excursion. — The aim here is to visit the Sembawang Hot Spring and discuss its origin (Figs. 176–184). The hot spring is accessed by bus or car from Gambas Avenue or Sembawang Road. There are no carparks nearby. Sembawang Hot Spring is one of more than 60 thermal springs that extend northwest of Singapore into Malaysia, following the belt of heat generating, high-U/Th, granites which form the Western Belt of Malaysia and a world-class heat flow anomaly (Oliver et al., 2011a, b). There is a second hot spring in Singapore, on Pulau Tekong. Fifty metre-deep boreholes along Gambas Avenue show very high geothermal gradients of up to 12°C/100 m. Background geothermal gradients in the Singapore region are ~3.5°C/100 m. The spring is at a constant 70°C and will burn your skin. Steam has been reported to have seeped out of the ground on the nearby air base. The spring is possibly pressured by the 120 m high head of ground water on Bukit Timah, the highest point in Singapore. Rain water will sink into the “hot” granite and be heated and under the head of water on Bukit Timah, be pushed northeast along the preferred orientation of lineaments (faults and joints in Singapore) until it meets the Nee Soon Fault and comes to the surface as a 70°C hot spring. Fig. 180 shows four geothermal plays for Singapore.

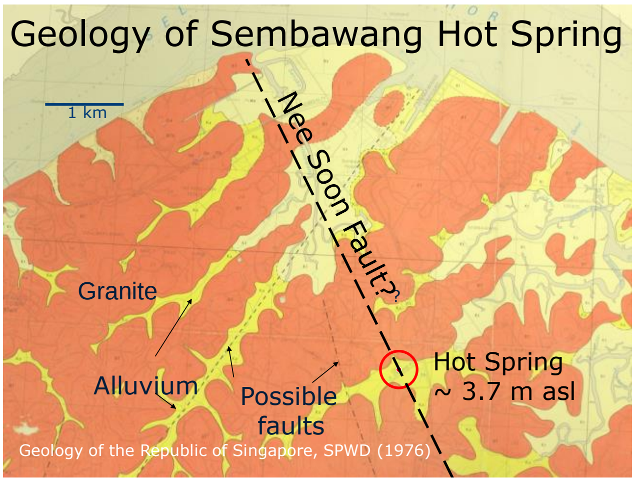

Fig. 178. Location of the Sembawang Hot Spring on the Nee Soon Fault. Modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

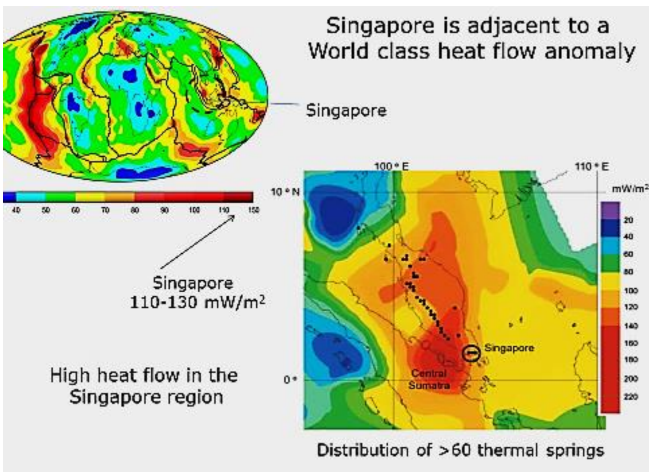

Fig. 179. Distribution of heat flow and thermal springs around Singapore. Modified by G.J.H. Oliver from Hamaza (2007) with permission.

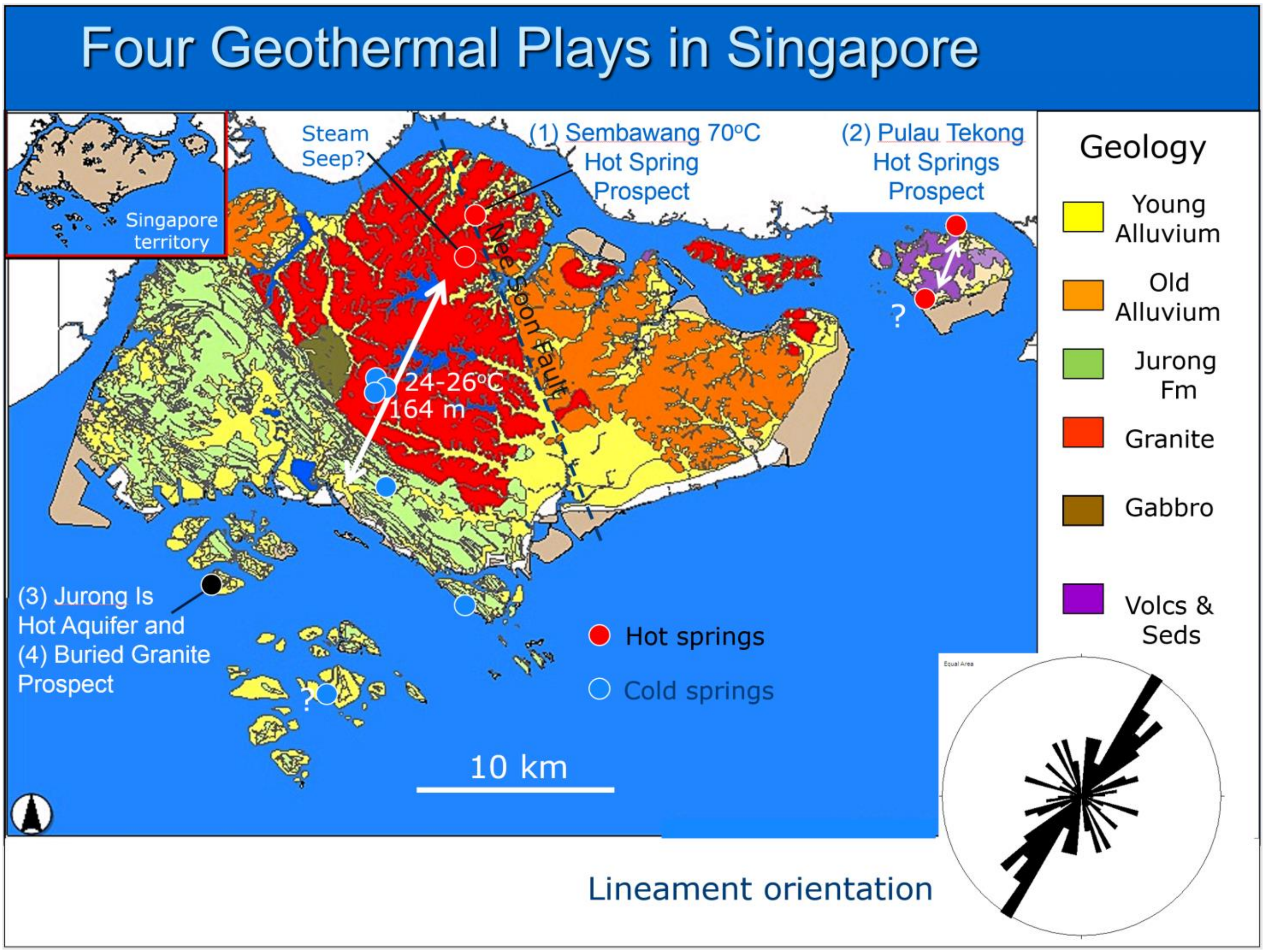

Fig. 180. Model for four geothermal plays in Singapore (Oliver et al. 2011a). Geology modified from Lee & Zhou (2009) with permission from the Defence Science and Technology Agency, Singapore.

Tjiawi (et al., 2012) constructed computer models of the Singapore geothermal system and showed that geothermal water at 2 km depth below the Sembawang Hot Spring could be 150°C. Geochemical analysis of K^+, Na^+ and Ca^{2+} dissolved in the spring water suggests that the reservoir temperature is 160°C. Calcite is precipitating on the standpipes and taps where the hot spring water is evaporating.

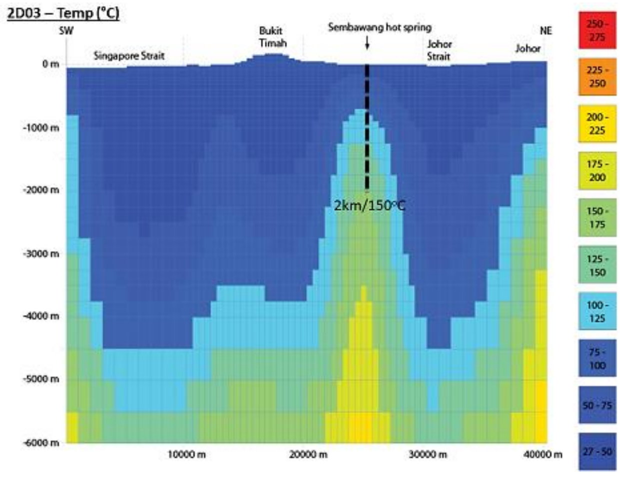

Fig. 181. Results of a computer model: 150°C water is 2 km below the Sembawang Hot Spring. Source: Tjiawi (2013).

Fig. 182. Calcite is precipitating on the taps at Sembawang Hot Spring. (Photograph by: H. Tjiawi).

Fig. 183. Thermophilic cyanobacteria (blue-green algae) grow in the hot water from the spring. (Photograph by: G. J. H. Oliver).

Fig. 184. Life may have originated in hot springs like this whose water is hot enough to cook an egg. (Photograph by: G. J. H. Oliver).

A faint smell of hydrogen sulphide can be detected in the air although the spring pH is neutral. The water was once bottled and sold as mineral water but be aware of the high fluorine content. Thermophilic cyanobacteria (blue-green algae) grow in the overflowing hot water which is hot enough to cook an egg. Life may have originated 3.5 million years ago in hot springs like this.

Oliver et al., (2011, a and b) discussed how this hot spring could be utilised for electricity generation, district cooling or desalination.

Orchard Road Excursion. — Many roads in Singapore follow natural river valleys that connect the coast with the higher interior. One of these is Orchard Road—perhaps Singapore's most famous street.

An hour's walk down Orchard Road reveals both its earlier natural form and flood-prone character. The flood-prone nature lies partly in the transformation of the present street from an ordinary river valley to a city street with high-rise buildings, glittering shops, and large hotels.

Orchard Road has a history of periodic flooding from intense storm showers, the rainwater accumulating swiftly in the lower part of the valley. It has always required good drainage. In his *An Anecdotal History of Old Times in Singapore, 1819–1867*, Buckley (1965) mentioned a flood when 235 mm of rain fell in four hours to inundate Orchard Road. He described an individual swimming with a three-foot ruler, measuring the depth of water. Flooding rarely happens these days, but a walk down the road with a few stops explains its transformation, and gives us an understanding of the amount of work city managers had to put in to create this glittering modern street.

Location 1. Junction of Orchard Road with Tanglin Road and Orange Grove Road. This is the head of the valley which continues along Orchard Road. Rain water starts to collect here, but the original headwaters are now replaced by efficient concrete drains hidden underneath the street pavement below your feet. Nearby Tomlinson Road, further up Tanglin Road, is another valley, which is very similar.

It is a 5-minute walk from Locations 1 to 2. The timings given here and below are approximate and designed for a slow walker who is sightseeing.

Location 2. Crossing of Orchard Road with Scotts Road and Paterson Road. This is probably the point at which tributaries of reasonable size first joined the stream flowing down the Orchard Valley. It is a 10-minute walk from Locations 2 to 3.

Location 3. Northeast corner of Lucky Plaza. Walk up Nutmeg Road to the junction with Mount Elizabeth. Turn and look back towards Orchard Road. You will find yourself on slightly raised ground, which probably was a terrace or an alluvial fan. Imagine a stream in the middle of Orchard Road. There would have been a floodplain between you and the imagined stream. The floodplain would have stored water immediately after a rainstorm and slowly released it to the channel. Today a progressively enlarged drainage system under the Orchard Road pavement carries all the water. The flat pavements you have been walking on cover the natural floodplain. It is a 15-minute walk from Locations 3 to 4.

Location 4. Next to the Killiney Road Post Office. Continue down Orchard Road for a while. Cross the road at the lights and walk up Killiney Road until you see an open stretch of the concrete canal to your left. This is an exposed part of Orchard Road drainage and observe how large it needed to be. You have walked only a short distance from the source! The surprising enlargement is due to urbanisation. If you look at the channel carefully, you will notice arrangements for hydrological measurement on its walls by the solar panel-powered instruments (Fig. 185). The canal bends left and crosses underneath Orchard Road. It is a 15-minute walk from Locations 4 to 5.

Location 5. Canal at Oldham Lane near Dhoby Ghaut MRT Station. Walk further east along Orchard Road. You need to be on the other side. Turn into Oldham Lane, which is immediately after the entrance to Dhoby Ghaut MRT Station. You will see another exposed view of the canal. Notice that it has become even larger, and people are warned not to swim in it. You will probably see hydrological instruments powered by their solar panel in the canal (Fig. 186). It is a 20-minute walk from Locations 5 to 6.

Fig. 185. Canal behind the Killiney Road Post Office looking downstream. Note its dimensions. All that space is required to drain rainwater after a large rainstorm. There is an inner channel for efficient draining of low water. The solar panel and the instruments are seen on the left bank. (Photograph by: A. Gupta).

Fig. 186. Another exposed part of the canal at Oldham Lane. Note the warning against swimming in the canal and the abandoned shopping trolley. (Photograph by: A. Gupta).

Fig. 187. Bras Basah Road (in front of the Rendezvous Grand Hotel) occupies the flood plain of a river that was once here. Orchard Road which continues into Bras Basah Road is also built on the same flood plain. (Photograph by: A. Gupta).

Walk back to Orchard Road and look upwards. You will see that low hills on both sides restrict the extent of the floodplain. This explains the story of exposed rocks which the washermen once used in the channel, giving it the name of Dhoby Ghaut which is derived from the “Bengali and Madrasi dhobies (laundrymen) who used to wash the clothes of local residents in Sungei Bras Basah, now Stamford Canal, and dry them on the land now occupied by the YMCA Building. Ghaut is Hindi for “landing place or flight of steps leading to a riverbank”—Dunlop (2000).

Location 6. Junction with Victoria Street. Orchard Road connects to Bras Basah Road. Walk further east on this road to its junction with Victoria Street but you will not see the canal as it is under decorated pavements and gardens. But notice the wide flat surface (Fig. 187). This is the extended plain of the river near its end. This probably explains why this was once chosen for drying wet rice giving it the name of ‘Bras Basah’ which means wet rice in Malay.

It is intriguing to try to follow the valley after this point, until it merges with the old coast, which was near Beach Road. Coastal reclamation work has modified the landscape so the coast has moved further south.

Do note how the size of the canal had to increase to cope with the urbanised drainage and how a small valley has been transformed into a modern road system.

Excursion on Flood-Prevention along the Bukit Timah Valley. **—** This is a longer walk than the one along Orchard Road and difficult to do it entirely on foot, especially on a sunny day. It is easier done in a car or by taking a sequence of buses along Dunearn Road, and observing the features described from various pedestrian bridges over Bukit Timah Canal. The walk is an excellent illustration of how flood propensity rises with urbanisation.

Location 1. Start near the railway bridge, east of the junction of Clementi Road with Bukit Timah and Dunearn Roads. The canal used to be a small stream between low granitic hills on either side of the valley. The area is still not densely built, small areas of secondary vegetation are common, and the canal is lined but not wide. The stream was first straightened as an alluvial canal, but later the channel needed to be lined for rapidly draining the floodwater after rainstorms (Fig. 188). The two arterial roads on either side of the canal occupy the old flat floodplain under vegetation that used to hold floodwater and slowly release it to the stream. Similar situations can still be found in south Johor in Peninsular Malaysia.

Continue along Dunearn Road to the junction with Swiss Club Road. If possible, walk the stretch between Swiss Club Road and Sixth Avenue and check the canal from various pedestrian bridges (Fig. 189). Notice the disappearance of natural vegetation and increase in urbanisation with denser residential population and larger amount of impervious area. The hills continue on both sides of the valley. The size of the canal becomes bigger as it has to transport larger volumes of water after rainstorms because of the changes in land use.

Fig. 188. The concrete-lined upper Bukit Timah Canal as seen from the new bridge near the Albert Park MRT station. Note the shape of the entire canal and the low-flow channel in the bottom. Storm drainage from side valleys reach the canal rapidly after a rainstorm. The arterial roads of Bukit Timah and Dunearn occur on floodplains on either side of the canal. (Photograph by: A. Gupta).

Fig. 189. The canal between Fig. A and Swiss Club Road. The size of the canal is bigger. (Photograph by: A. Gupta).

Location 2. — Sixth Avenue. The runoff following rainstorms became too large for the old canal to rapidly transport floodwater and prevent inundation of the two arterial roads running on former floodplain (Fig. 190). A diversion towards the southwest now takes excessive water through an engineered channel to the Sungei Ulu Pandan, the next basin to the south. This is the first diversion after the rapid and intense urbanisation of the Bukit Timah Basin. The diversion is located between Maple Avenue and Anamalai Avenue. Also note that the channel is trapezium-shaped with a low-flow channel in the middle. Hydrological instruments and solar panels are visible on this stretch of the canal.

Continue along Dunearn Road. This is a section of the basin which demonstrates intense urbanisation. It you have transport, go for a drive along Second, Third (Fig. 191) or Fourth Avenues off Bukit Timah Road, or Watten Estate off Dunearn Road. You will notice impervious surfaces built on steep granitic hills. You will have no problem imagining a very high percentage of the rainwater running on the surface, and quickly draining into the Bukit Timah Canal in large volume. Notice the efficient drainage system for the side slopes. The canal has to find space for all the water to prevent flooding of streets, shops, and residences in the area.

Location 3. — Look at the canal from the overhead pedestrian bridge near Shelford Road (Fig. 192). Look for (1) intense urbanisation in the valley, (2) the busy traffic on the floodplain roads, and (3) the enlarged size of the canal to carry the excess floodwater. A lot of effort is needed to keep the city going.

Fig. 190. The canal near Sixth Avenue designed to carry large volumes of floodwater even after diversion. To beautify them, the canal sides are landscaped with ornamental plants such as the butterfly palms (*Dypsis lutescens*; left background and right foreground) and turf as seen here. (Photograph by: A. Gupta).

Fig. 191. View up Third Avenue. Steep slope of the granite hills contacts sharply with the flatter floodplain. The contact approximately follows the line of shadow across the road. Note increased impervious area. The area is almost entirely built-up with miniscule open space. (Photograph by: A. Gupta).

Fig. 192. Note the expansion needed after the canal was originally constructed to cope with increased volume of water due to rapid urbanisation of the steep valley sides. (Photograph by: A. Gupta).

Location 4. — View the canal from the pedestrian bridge between Robin Road and Swiss Cottage Estate (Fig. 193). You will notice a much bigger canal and a required second diversion of floodwater to another neighbouring basin to the other side. All these changes are essentially due to enhanced urbanisation. This is the suggested end point of the trip. It is possible to follow the passage of floodwater to an estuary and to the coast, but it is not as easy to follow as along the Upper Bukit Timah Canal.

Fig. 193. The enlarged Bukit Timah Canal from the mentioned bridge. Compare the size of the canal with the canal in Fig. 188. A big change has occurred over a small distance. The second diversion also is visible. (Photograph by: A. Gupta).

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