Geology of Singapore

Geotechnical Engineering Appreciation Course

(Jointly organised by IES Academy and GeoSS)

Dr Cai Jun Gang
Tritech Consultants Pte Ltd

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Topics

1. Some Concepts in Geology & Significance of Geology in Civil Engineering
2. Recent Geological & Deep Rock Investigations
3. Singapore & Adjacent Geology
4. Geological Setting of Singapore
5. Features of Singapore's Geological Formations
6. Description of Singapore's Rocks & Soils for Civil Engineering Practice in Singapore
7. Weathering Classification of Singapore's Rocks for Civil Engineering Practice in Singapore
8. Updated Geological Maps & Report - 2nd Edition, DSTA (2009)

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Some Concepts in Geology

Some Concepts in Geology

- **Earth** is an active planet in a constant state of change.
- **Earth movements** are vital to the cycles. Without them the land would be eroded down to just below sea level.
- **Plate tectonics** provide the mechanisms for all earth movements. The hot interior of the earth is the ultimate energy engine driving all geologic processes.
- **Geologic processes** modify the earth's surface, destroy old rocks, create new rocks, and add complexity to ground conditions.
- **Geologic times** are in millions of years. The earth is 4,500 million years old.
- **Most rocks** encountered by civil engineers are 10 - 500 million years old. They have often been deformed, faulted, weathered, and eroded over many millions of years.
- **Most surface landforms** visible today have been carved out by erosion within the last few million years.

- **Sediments** – from rock destruction, weathering, and decomposition
- **Rivers** – major highways transporting new sediments
- **Seabed** – where much new sediments are deposited
- **Earth's crust** – where rocks are created and deformed.

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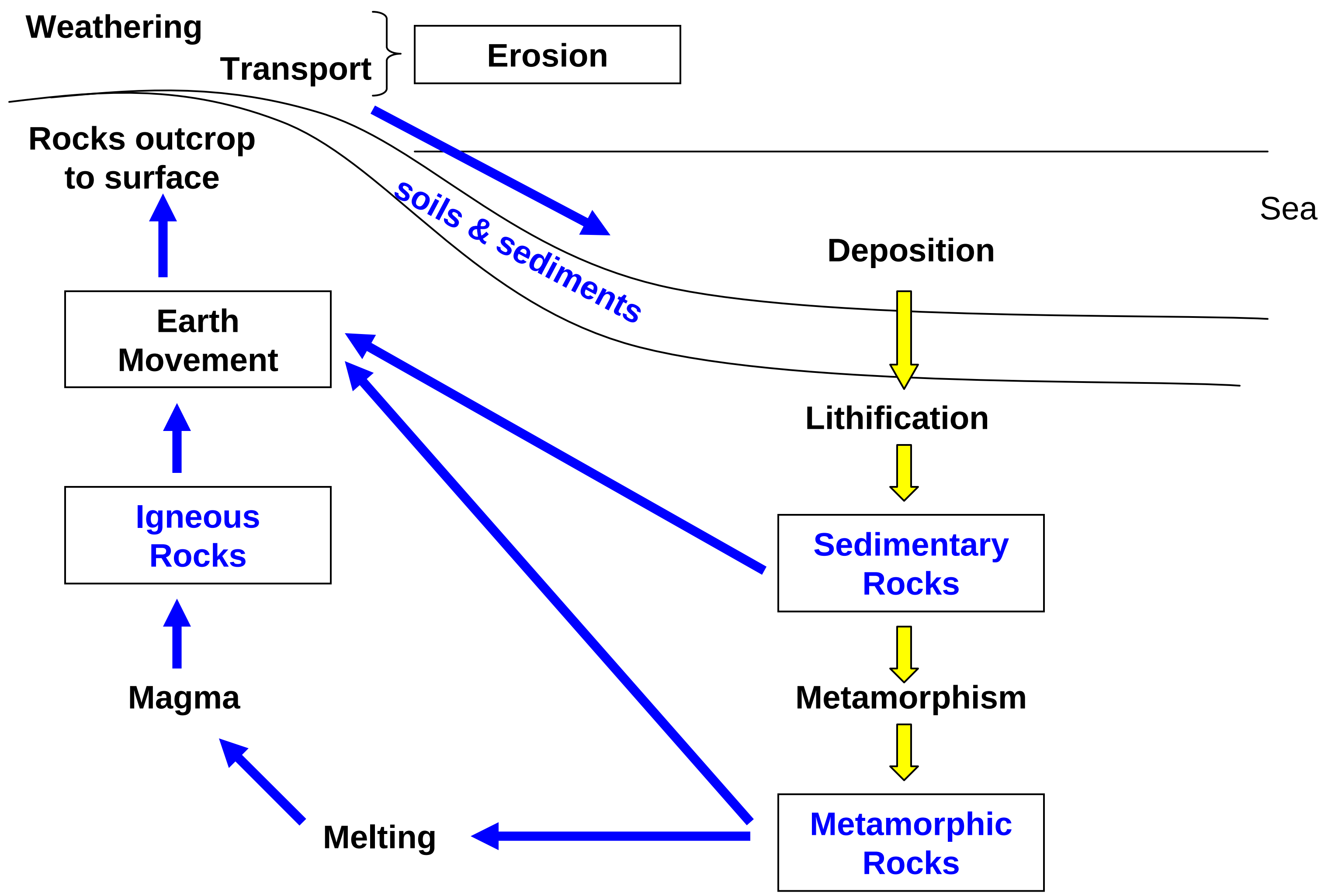
Cyclic Geological Processes



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Significance of Geology in Civil Engineering

- **Civil engineering works** – all carried out **ON (building foundation)** or **IN (excavation & tunneling)** the ground.
- **Interaction between Ground and Civil Works** – Geological formations, geological structures, strength of rocks and soils, and deformation/displacement of rocks and soils may result in **Stable** or **Unstable Ground.**
- **Site Investigation** – where civil engineers encounter geology and get to interpret ground conditions - often from minimal evidence.
- **Unforeseen geologic conditions** – can still occur as ground geology can be almost infinitely variable. They are often unforeseen due to **Inadequate Site Investigation**.
- **Civil engineering design** shall accommodate geologic conditions which are correctly assessed and understood as the best geological knowledge obtained in site investigation.

Geology presents uncertainties and complexities which continually pose challenges to civil engineers.

Geologic risk is the first risk faced by civil engineers

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Recent Geological & Deep Rock Investigations

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Recent Deep Rock Investigations (20 Years)

1. Geologic Investigations for Rock Cavern Construction in the Bukit Timah Granite (Econ), Sponsored by NSTB, Studied By NTU, 1990-1994
2. Site Characterization of Bukit Timah Granite for Rock Cavern Construction (Econ) , Funded by LEO (DSTA) of MINDEF, Studied by NTU and Singapore Technologies Construction (Pte) Ltd, 1995-1997
3. An Investigation of Hot Spring at Sembawang, Funded by Faser and Neave (Singapore), Studied By Zhao Jian and Chen CN, 1994
4. Geologic Investigations for Rock Cavern Construction in the Jurong Formation (S&F), Sponsored by NSTB, Studied By NTU & PWD, 1995-1999
5. Geologic Investigations for Underground Science City at Kent Ridge (S&F), Sponsored by NSTB, Studied By NTU & PWD & JTC, 1997-2000
6. Geologic Investigations for Underground Oil/Gas Storage Rock Caverns at Jurong Island (Tritech), Sponsored by NSTB, Studied By NTU, 2000-2002
7. Geologic Investigations for Proposed Development of Hydrocarbon Caverns Storage in Jurong Island (Tritech) - Phase II-Feasibility Study, Funded ed by JTC, Studied by NTU & Geostock, 2003-2006
8. Complementary Geologic Investigations at Banyan Basin for Development of Hydrocarbon Caverns in Jurong Island (Tritech), Flex I and Flex II Study, Jurong Island, Geostock/JCPL, 2006 -2007
9. Geologic Investigations at West of Jurong island (Tritech), Funded by JTC, Studied by Tritech, 2008.
10. Geologic investigation at Kent Ridge for USC Detailed Feasibility Study (S&F), funded by JTC.
11. Geologic investigation at Jurong Hill for Feasibility Study for Underground Warehouse Development.
12. Other recent geologic findings in building & infrastructure construction projects, i.e. tunneling & excavation of new MRT Lines.
13. A deep geological exploration to cover west and north-east areas is going on by the Geologic Office of BCA.

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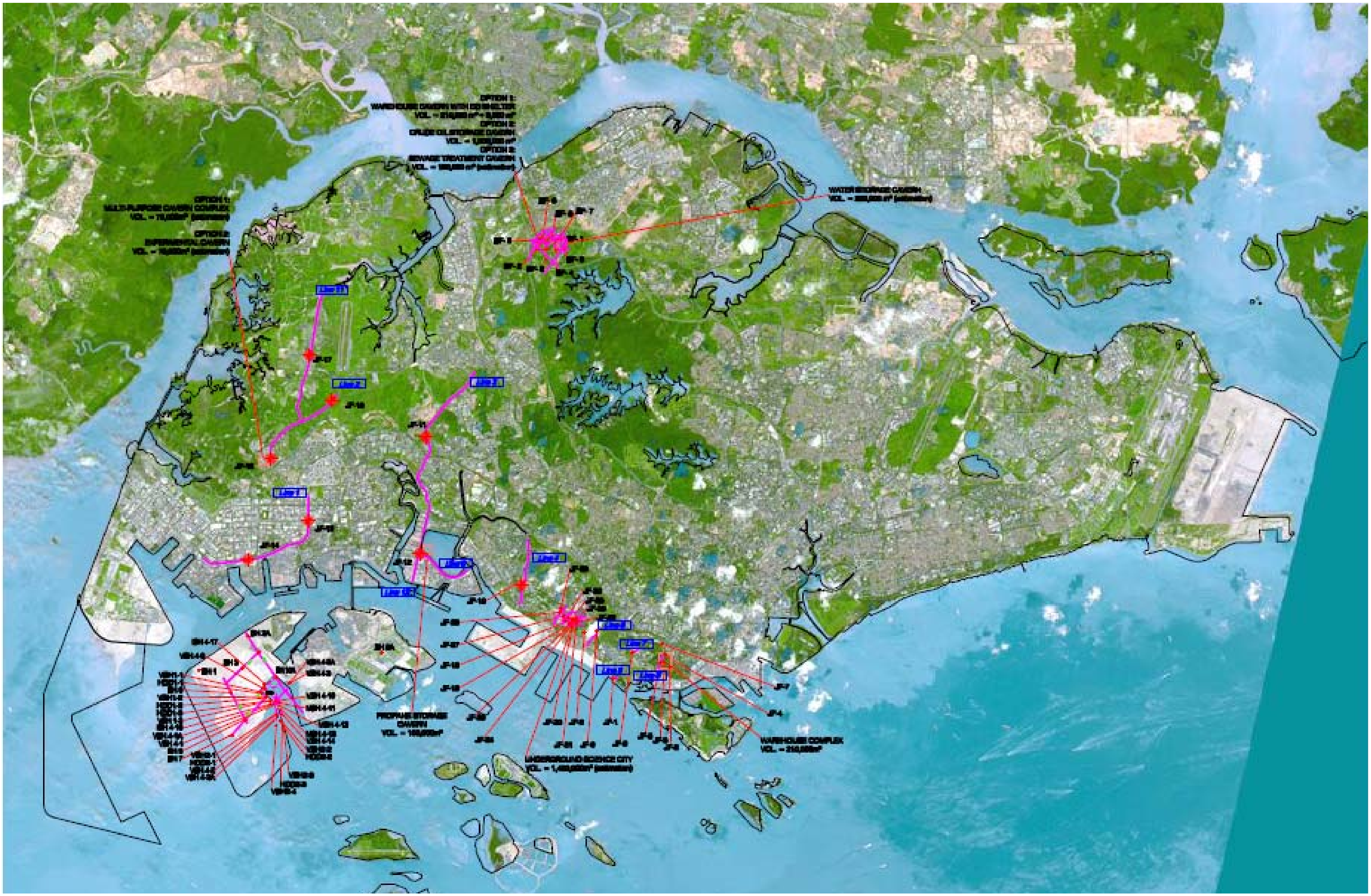
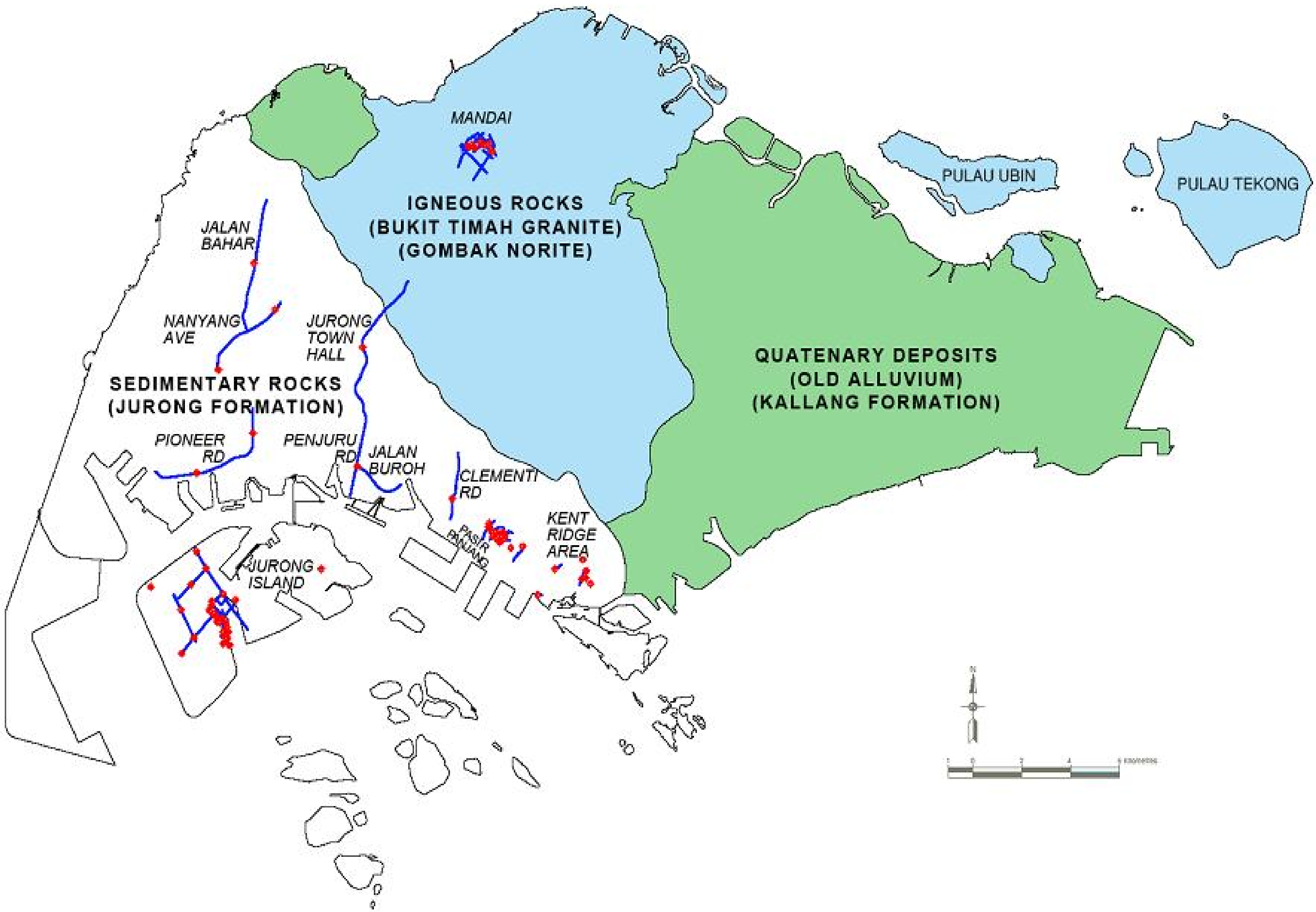
Layout of Recent Rock Investigations with Seismic Exploration and Deep Boreholes



Geology of Singapore and Layout of Major Site Investigations



Singapore & Adjacent Geology

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Singapore & Adjacent Geology

Background

Our geology is closely related to that of Peninsular Malaysia.

Johor has rocks identical to our gabbroic and noritic rocks of the Gombak Norite; our granitic rocks of the Bukit Timah Granite; our sedimentary rocks of the Palaeozoic Volcanics, Sajahat Formation, and Jurong Formation; and our thick deposit of sand and gravel of the Old Alluvium.

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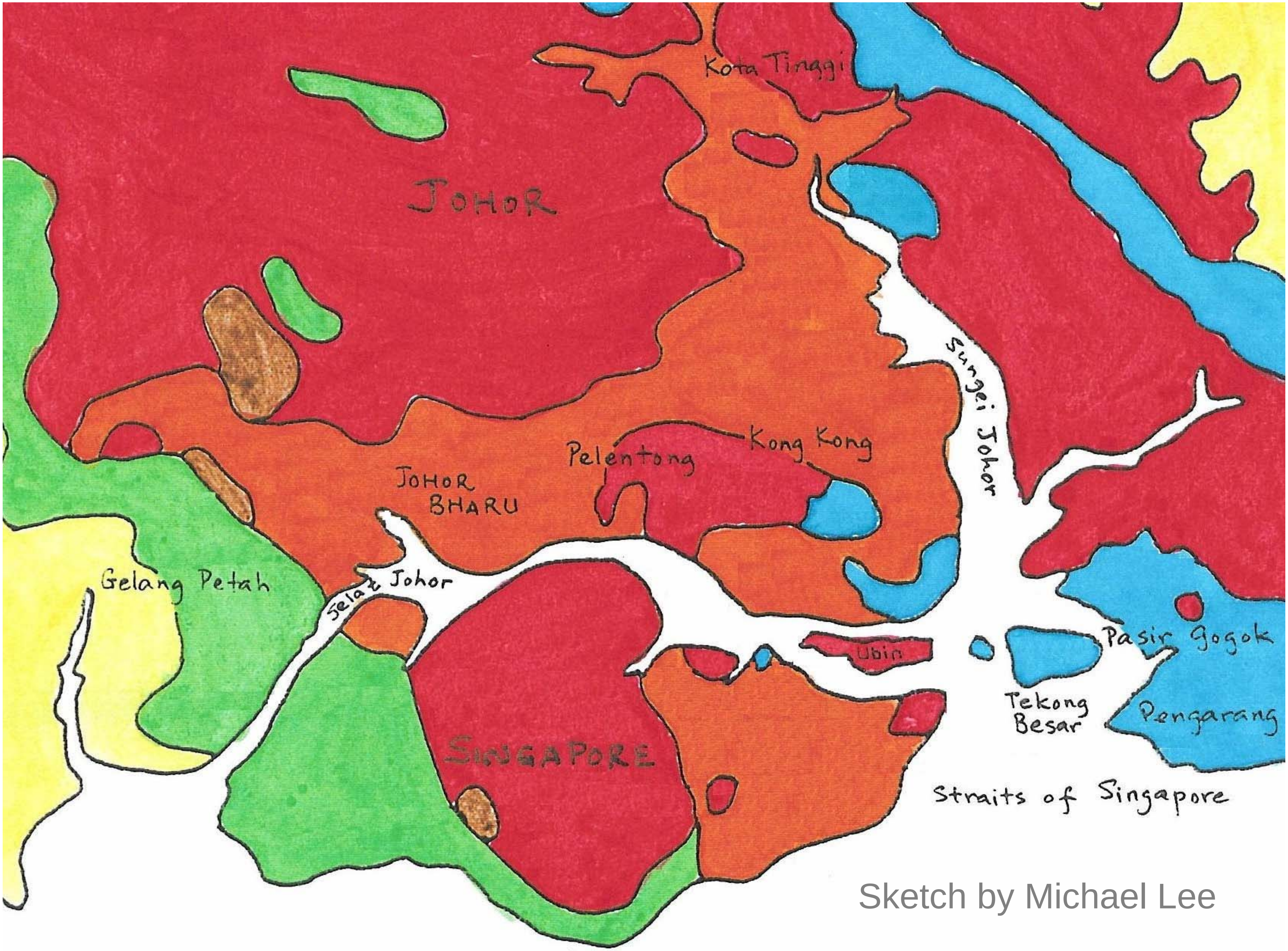

Sketch by Michael Lee

Geological Setting of Singapore

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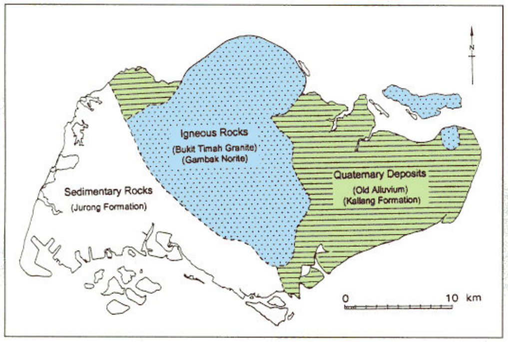
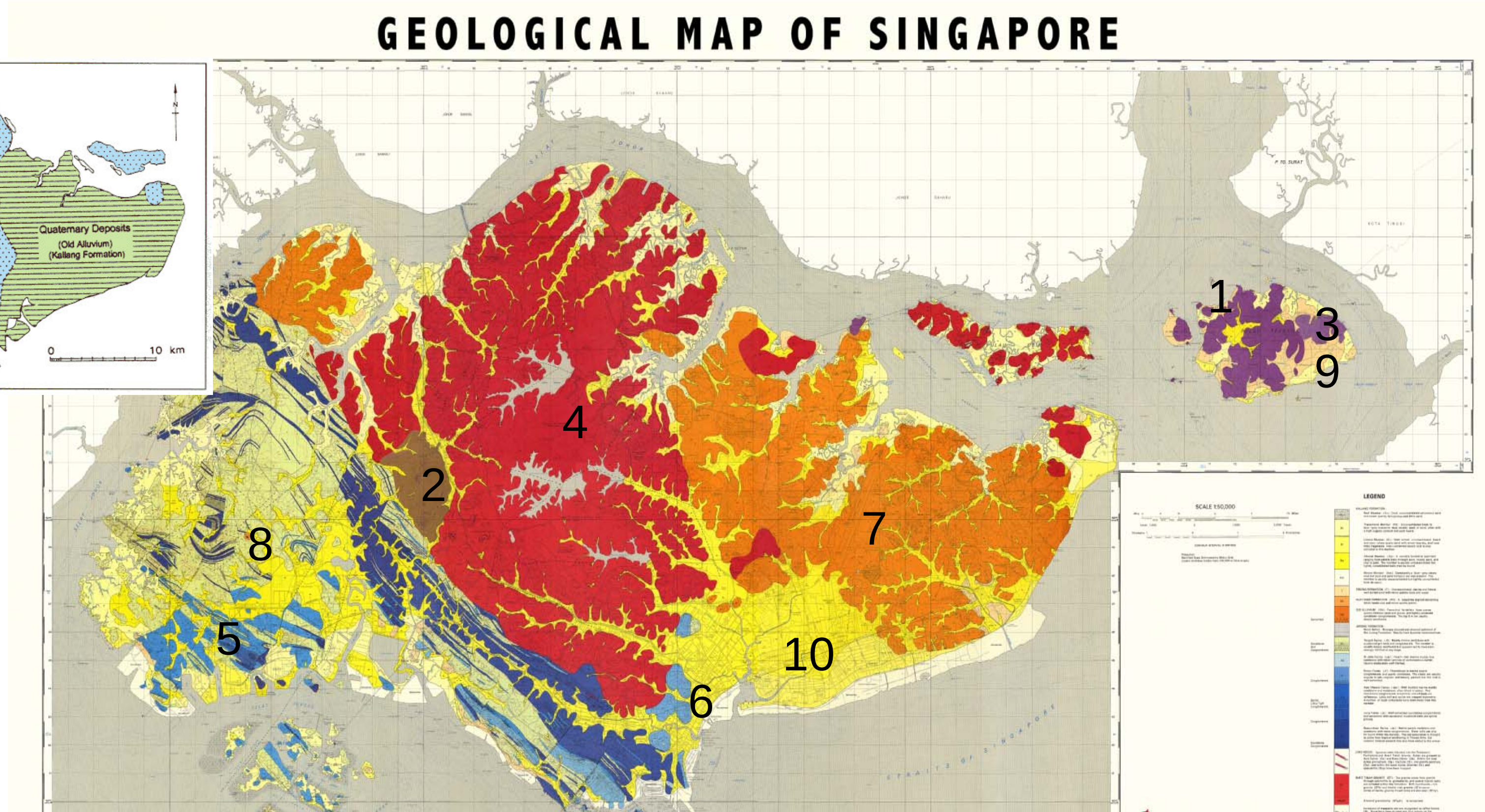
Geologic Setting of Singapore





Singapore's natural deposits are classified under 10 geological formations. In decreasing age, they are outlined with their characteristic rock or sediment types.

1. Sajahat Formation: quartzite, argillite
2. Gombak norite: norite and gabbro
3. Palaeozoic Volcanics: tuff
4. Bukit Timah Granite: granite
5. Jurong Formation: reddish mudstone, grey fossil-rich mudstone and shale, fossil-rich limestone, siltstone, sandstone, conglomerate
6. Fort Canning Boulder Bed: hard red and white sandy silty clay containing many sandstone boulders
7. Old Alluvium: dense muddy sand/gravel
8. Huat Choe Formation: firm white kaolin clay
9. Tekong Formation: loose pebbly sand
10. Kallang Formation: soft grey clay, loose brownish muddy sand, loose light grey to white sand, peaty clay.

Geologic Setting of Major Formations

From Old to Young

Formation	Age	Material	Distribution
Bedrock formations			
Sajahat Formation	Early Palaeozoic (540 – 445 my)	quartzite, argillite	P. Tekong, P. Sajahat, Punggol
Gombak Norite	Early Palaeozoic (540 – 445 my)	Norite, gabbro	Bt. Gombak, Bt. Panjang, and adjacent hills
Bukit Timah Granite	Early to Middle Triassic (250 – 235 my)	granite, granodiorite, adamellite, diorite	central Singapore Island
Jurong Formation	Late Triassic to Early Jurassic (235 – 175 my)	red purplish mudstone and sandstone, grey fossil-rich mudstone and shale, siltstone, conglomerate, fossil-rich limestone	west and southwest Singapore Island and southern islands
Weak rock/Soil formations			
Fort Canning Boulder Bed	Late Cretaceous (100 – 65 my)	hard, often red and white, unstratified sandy silty clay containing many big lens-shaped to rounded fresh sandstone	central business district
Old Alluvium	Late Tertiary to Middle Pleistocene (5 – 0.5 my)	dense to cemented muddy sand/gravel with beds of silt and/or clay	east Singapore
Kallang Formation	Late Pleistocene to Present (0.14 – 0 my)	soft marine clay, loose alluvial muddy sand, loose beach sand, soft peaty and organic mud, and coral.	all river valleys and mouths

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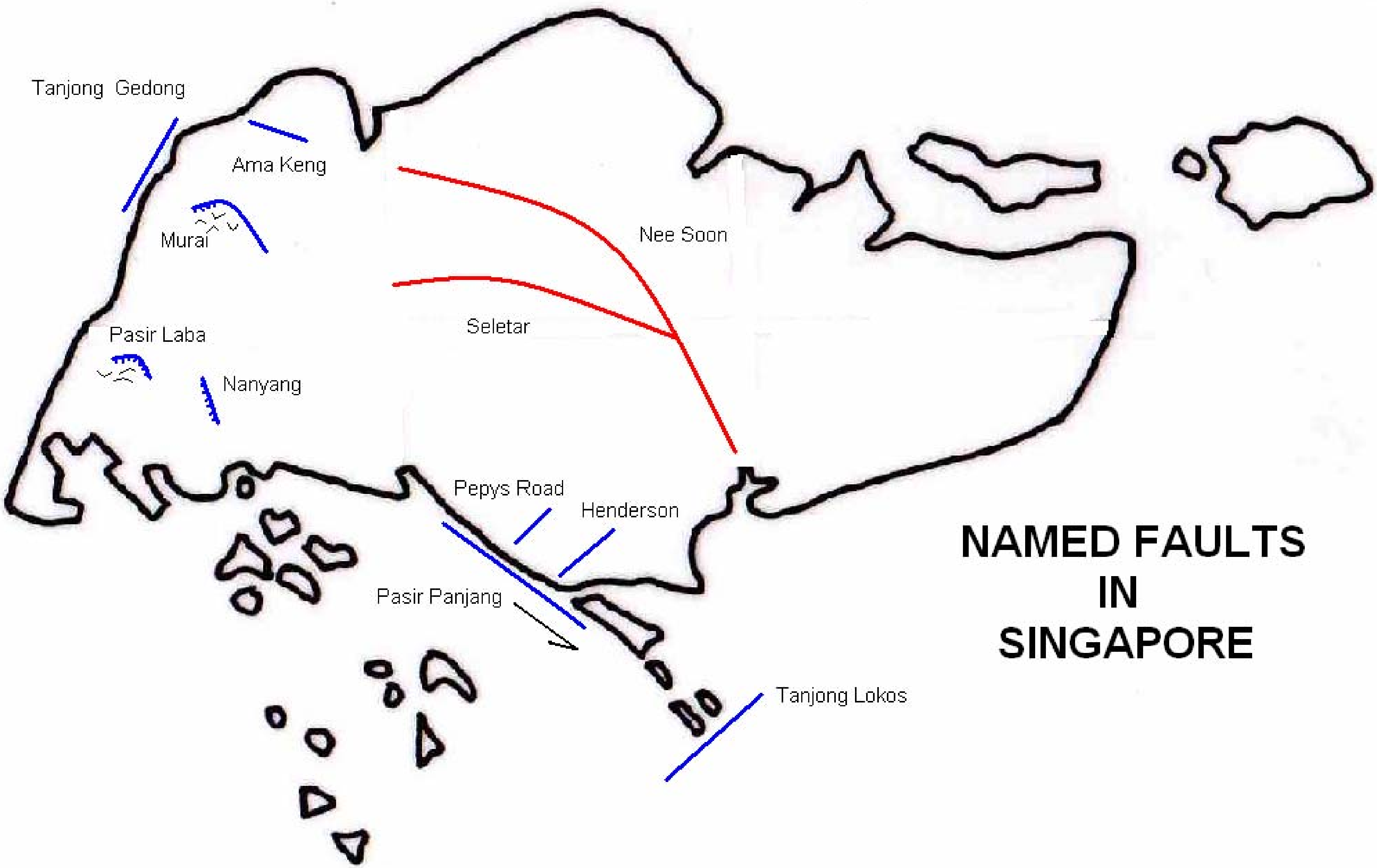
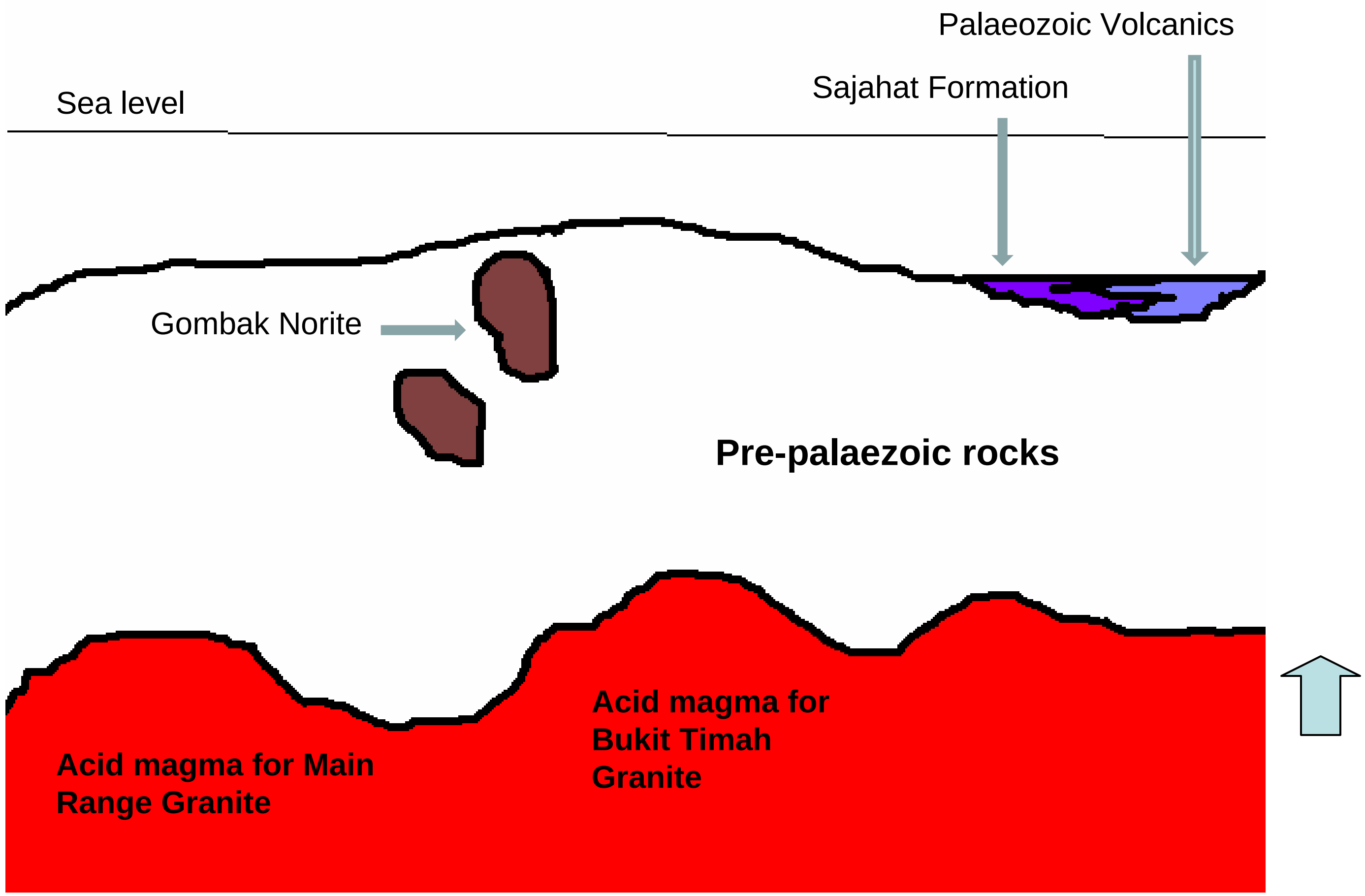
Major Fault Structures



Historical Geologic Setting



Acid magma from great depths rose during the Late Palaeozoic (360 – 250 my)

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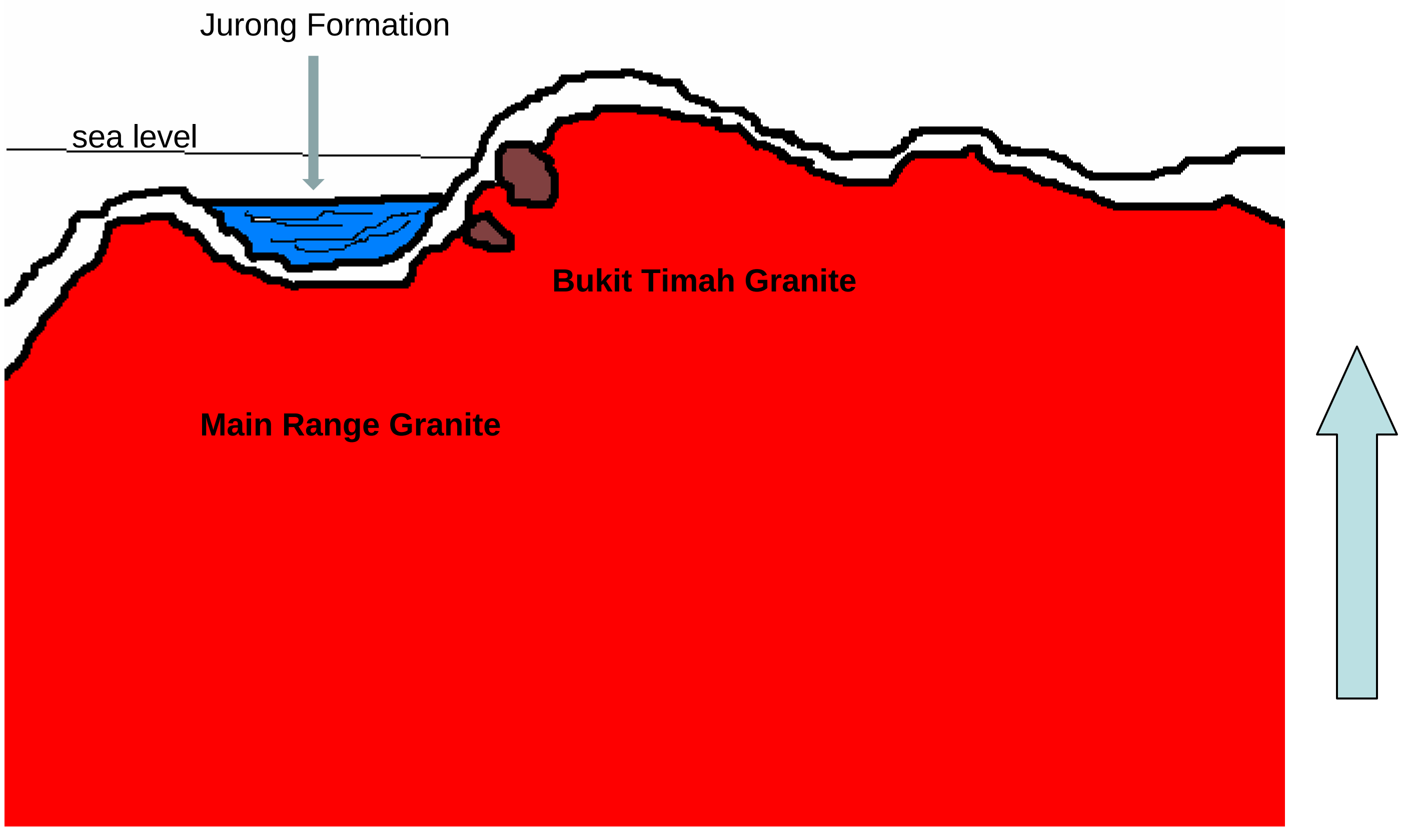
Historical Geologic Setting



Uplift of the Main Range Granite and the Bukit Timah Granite created a shallow basin for the deposition of the Jurong Formation during Early Triassic to Early Jurassic (235 – 175 my)

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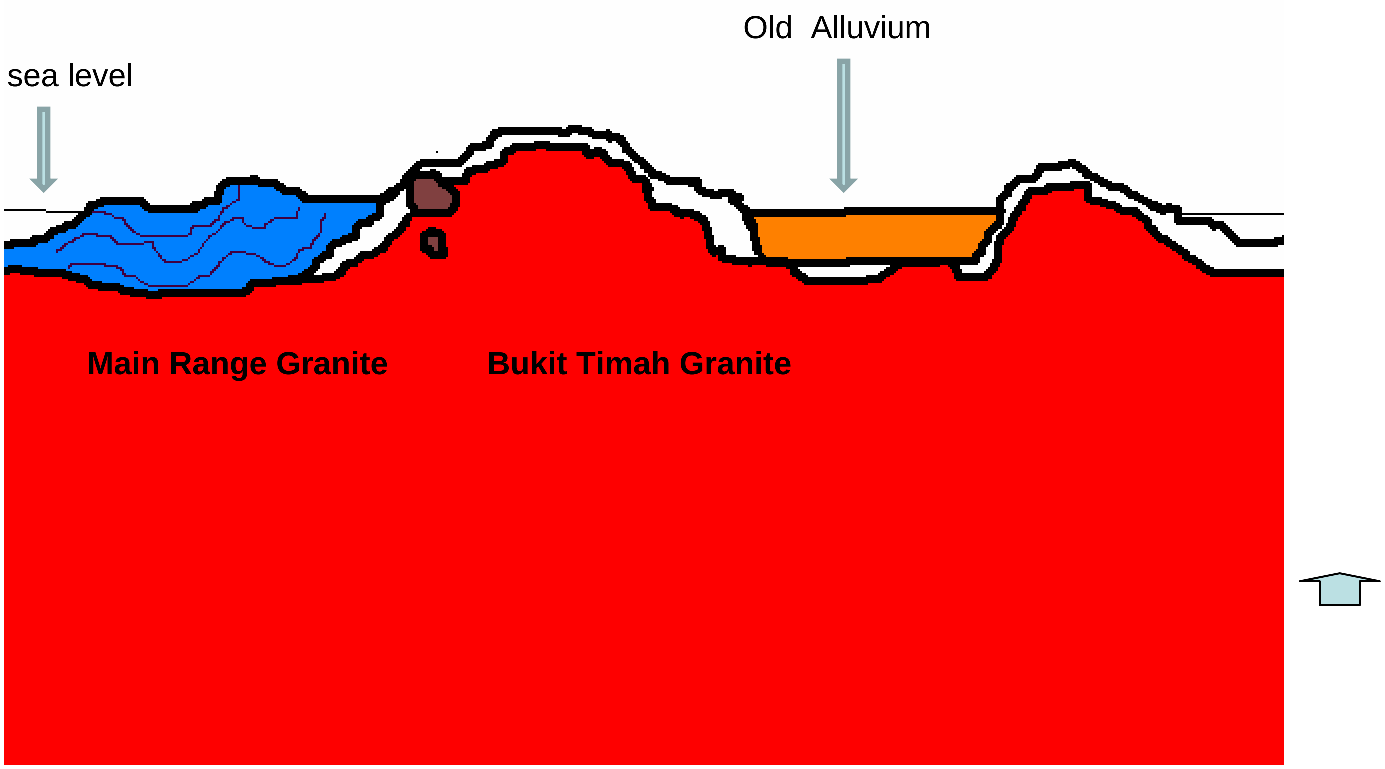
Historical Geologic Setting



After Early Jurassic (175 my), uplift was minimal and much of the land mass was above sea level and marine sedimentation ceased. Alluvial sediments of the Old Alluvium were deposited in a deep faulted trough during Late Tertiary to Middle Pleistocene (5 to 0.5 my)

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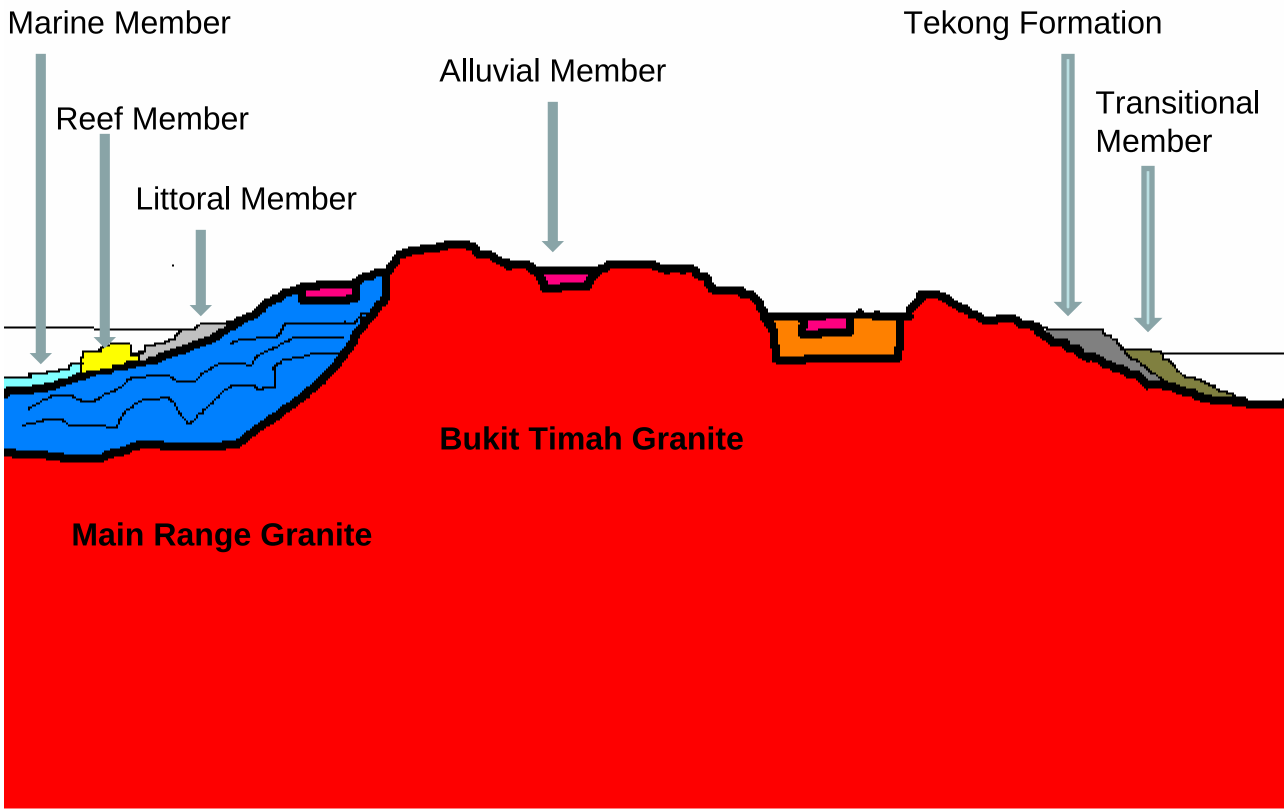
Historical Geologic Setting



Representing the youngest natural deposits, the high-level beach sand of the Tekong Formation were deposited about 5000 to 6000 year ago in Holocene times and the marine clay, coral sand, beach sand, alluvial muddy sand, and peaty clay of the Kallang Formation continues to be deposited in present times since the Late Pleistocene (140,000 years to Present).

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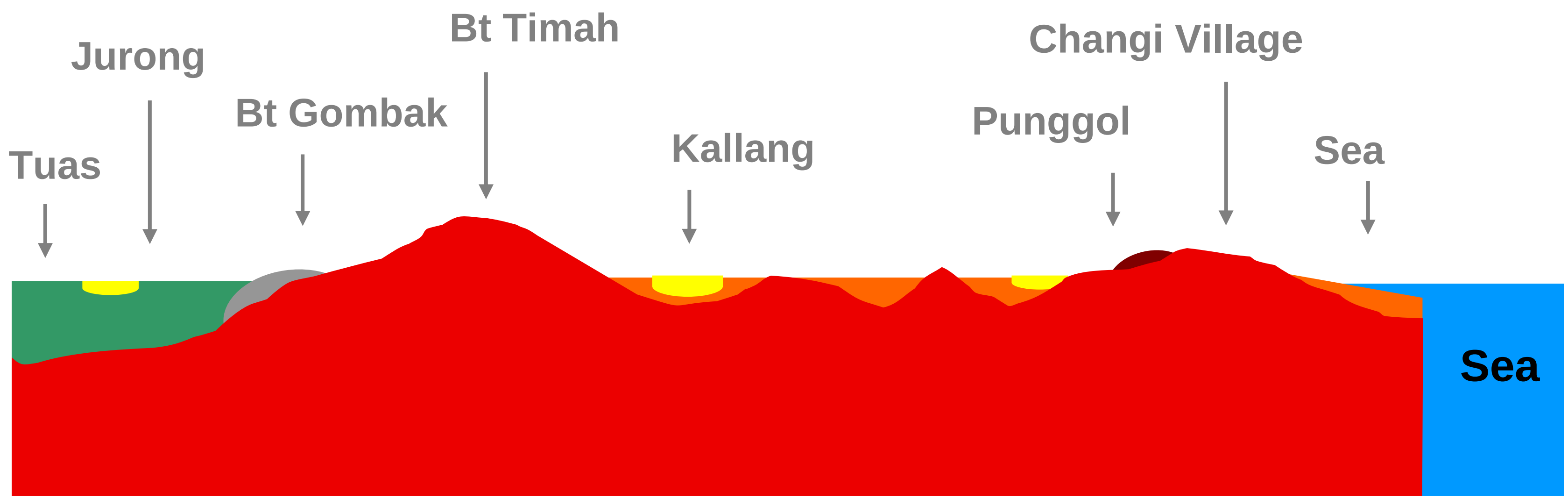
Simplified Singapore Geological Section



from Tuas (West) to Changi (East)

- Jurong Formation
- Gombak Norite
- Bukit Timah Granite (Base)
- Kallang Formation
- Old Alluvium
- Sajahat Formation

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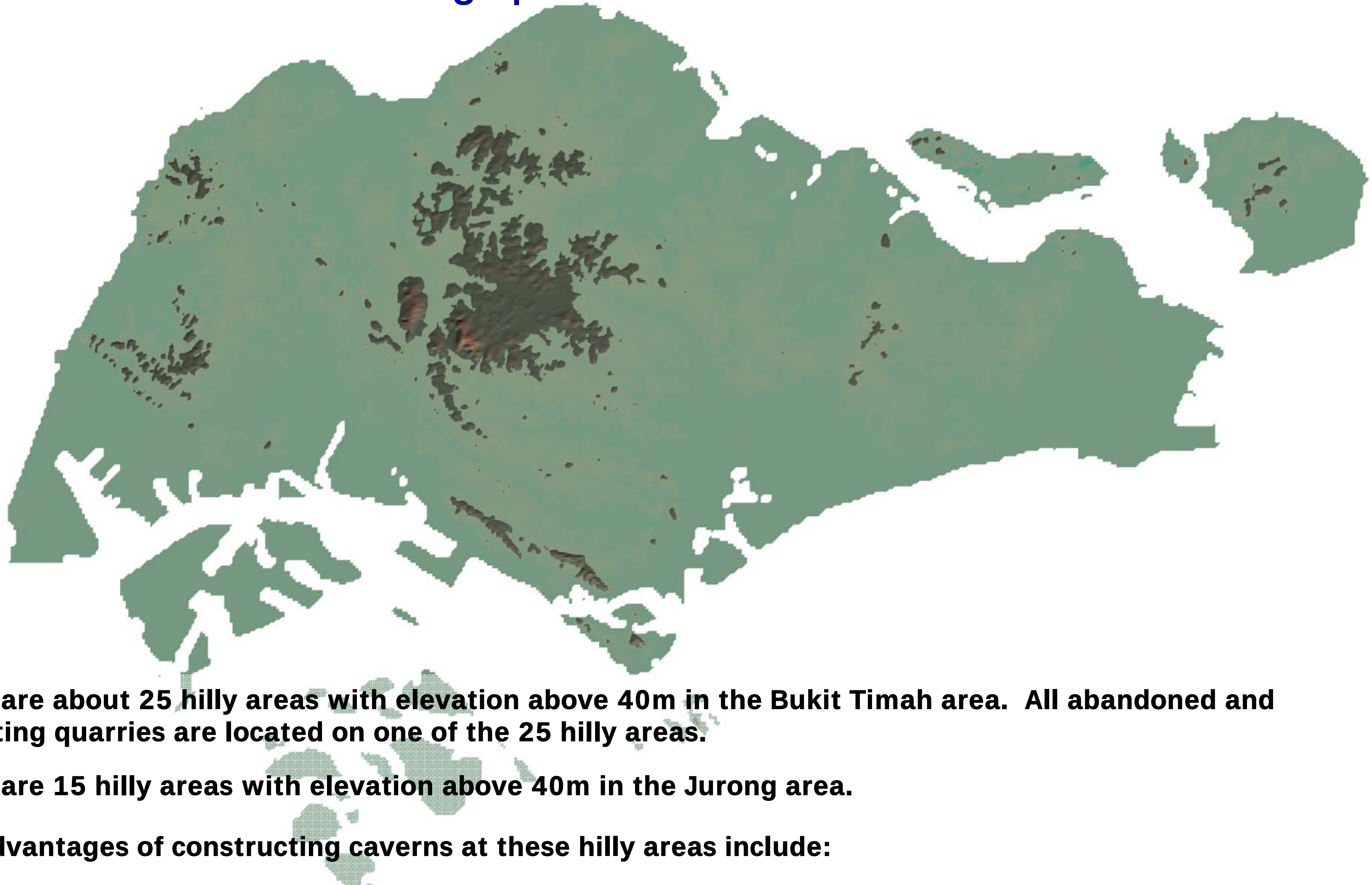
Topographic Feature - Hilly Areas in Relation to Singapore Rocks



There are about 25 hilly areas with elevation above 40m in the Bukit Timah area. All abandoned and operating quarries are located on one of the 25 hilly areas.

There are 15 hilly areas with elevation above 40m in the Jurong area.

The advantages of constructing caverns at these hilly areas include:

- **The hilly areas usually have shallow overburdens, shallow bedrock depths, and good quality rock mass.**
- **Only horizontal tunnel access or inclined tunnel access are required, resulting in a much lower construction cost**

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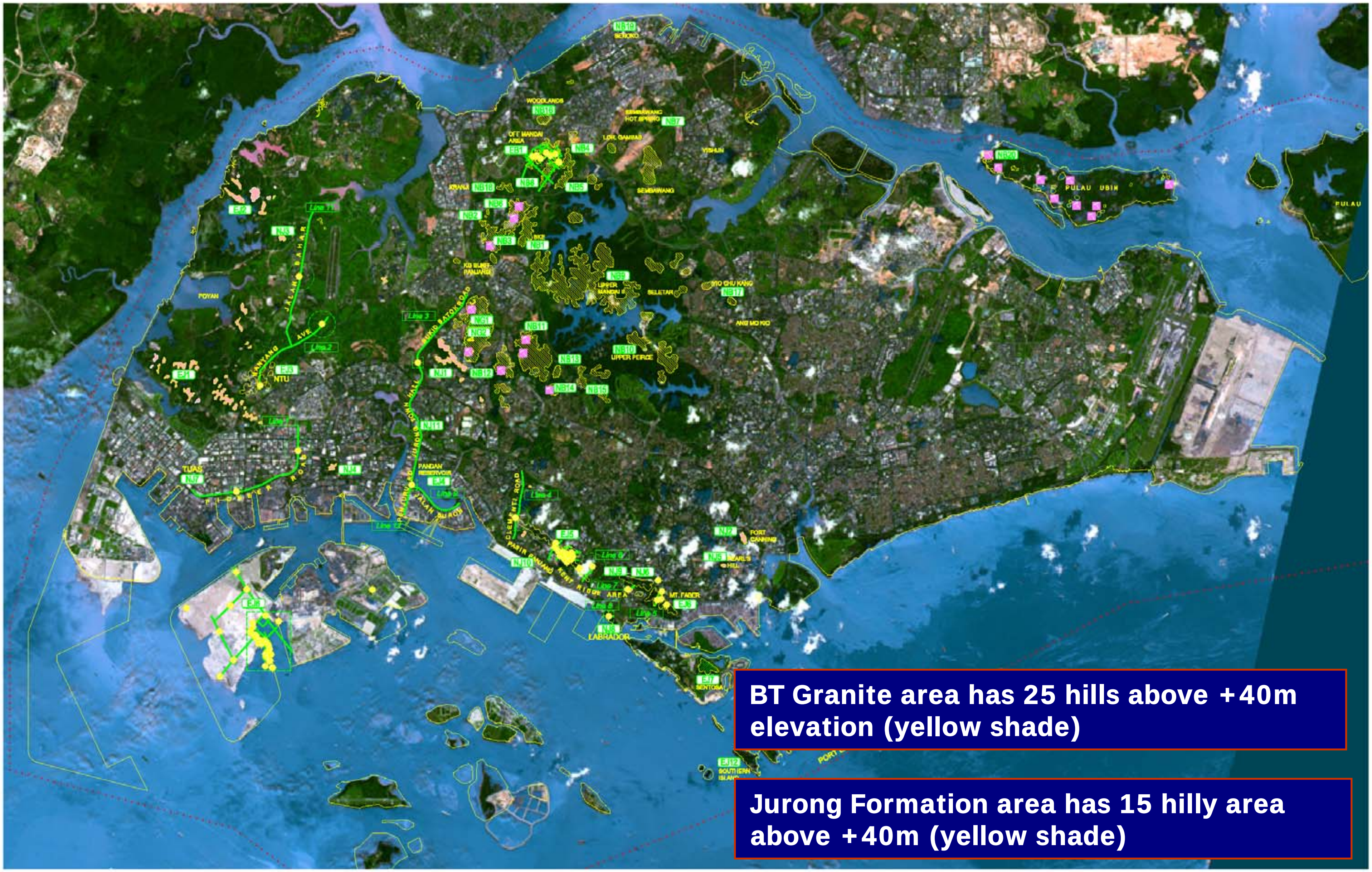
Geographic feature - Hilly Areas in Relation to Singapore Rocks



BT Granite area has 25 hills above +40m elevation (yellow shade)

Jurong Formation area has 15 hilly area above +40m (yellow shade)

Features of Singapore's Geological Formations

Bukit Timah Granite

General

Rocks: predominantly granite; less common are granodiorite, adamellite, and diorite

Mineralogy: quartz (30%), feldspar (60-65%), biotite, and hornblende (less than 10%)

Texture: medium to coarse grained, light grey but sometimes pinkish

Age: Early to Middle Triassic (250 – 235 my)

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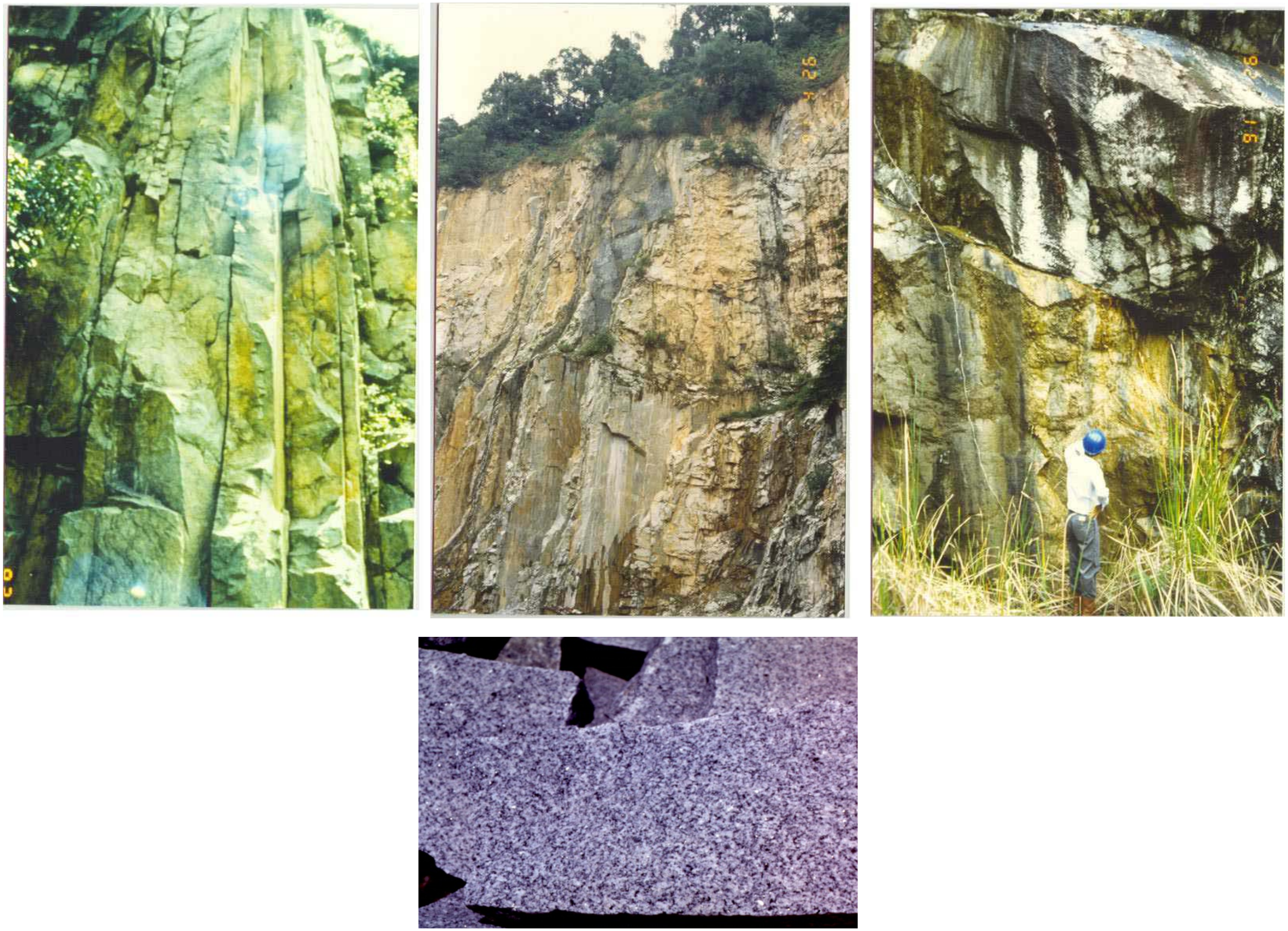

Typical Outcrops of Bukit Timah Granite

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Bukit Timah Granite

Distribution

It underlies about a third of Singapore Island and the whole of P. Ubin.

It is recognised as the base rock as it underlies all other formations.

It was originally formed from a large body of acidic magma which intruded from great depths into the Gombak Norite and other older formations such as the Sajahat Formation and Palaeozoic Volcanics. The older rocks were eventually removed by erosion and the Bukit Timah Granite is exposed.

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Bukit Timah Granite

Weathering and Bedrock Profile

Weathering: very extensive through mineral decomposition; depth varies from a few to 80 m with a commonly occurring depth about 25 m.

Profile: tropical humid soil profile is characteristic; an undulating rock surface with a sharp change from residual soil to granite is usually observed; large boulders are sometimes present.

Bukit Timah Granite

Strength and Modulus

Compressive:	**very high; fresh material has average UCS of 160 MPa with the highest value in excess of over 300 MPa; weathered materials have much lower strength**
Modulus:	**average of 70 GPa.**
Tensile:	**about a tenth of UCS values**
Criterion:	**Mohr-Coulomb at low stress level; best with Hoek-Brown criterion (mi = 30 - 33).**

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Bukit Timah Granite

Jointing and Rock Mass

Jointing:	**4 to 5 joint sets; dominant one is sub-vertical with a NNW-SSE strike**
Joint Surface:	**usually rough and little weathered**
Shear Strength:	**shear friction angle varying with smooth joints having angles of about 30 degrees and rough joints up to 70 degrees**
Rock Mass:	**usually good and above-good quality**

Bukit Timah Granite

Groundwater and Stress

Permeability: very low within the range of 10^{-7} to 10^{-9} m/s,; As the granite rock mass is quite impermeable, groundwater flow is only likely in fractured zones and faults

Springs: large groundwater flow and springs can be found in fault zones (e.g., Sembawang hot spring)

In-situ

Stresses: high in-situ horizontal stress (about 2 - 3 times vertical stress) in a NNE-SSW direction

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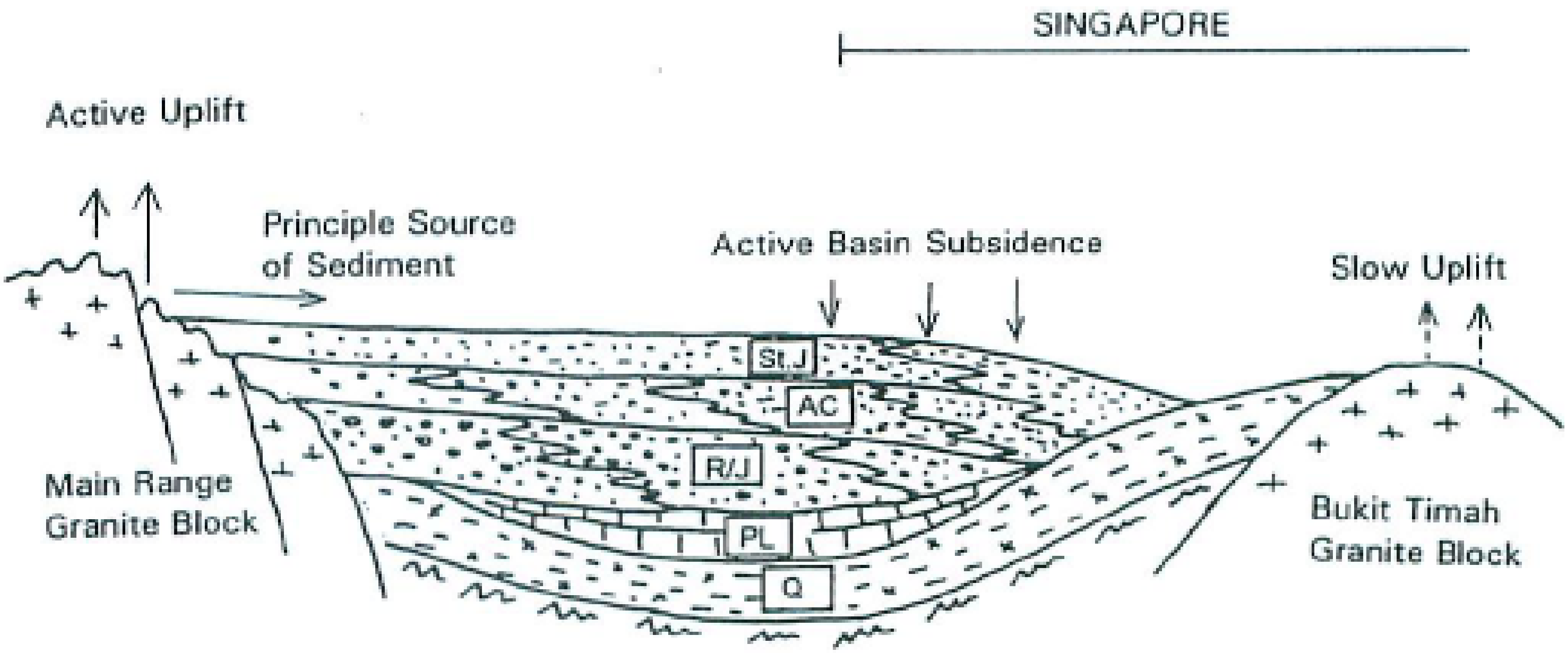
Jurong Formation

Distribution: western and southwestern Singapore Island and the southern islands.

Age: Late Triassic to Early Jurassic (235 – 175 my)

Development: sediments from weathered material of older rocks were deposited in a shallow marine basin formed between Bukit Timah Granite and the Main Range Granite and later lithified into rocks. Through lateral basin compression, they were uplifted, folded, faulted, and metamorphosed.



St.J	St. John Facies	Late stage delta top clastics and fore delta turbites
AC	Ayer Chawan Facies	Coarse to fine clasic delta deposits, associated with pulsatory uplift
R/J	Rimau/Jong Facies	Coarse clastic delta/fanglomerates, associated with active uplift
PL	Pandan Limestone	Stable basin, calcareous deposit
Q	Queenstown Facies	Stable basin, calcareous siltstone/mudstone deposits

Basin formation of the Jurong Formation (after Redding et al, 1999)

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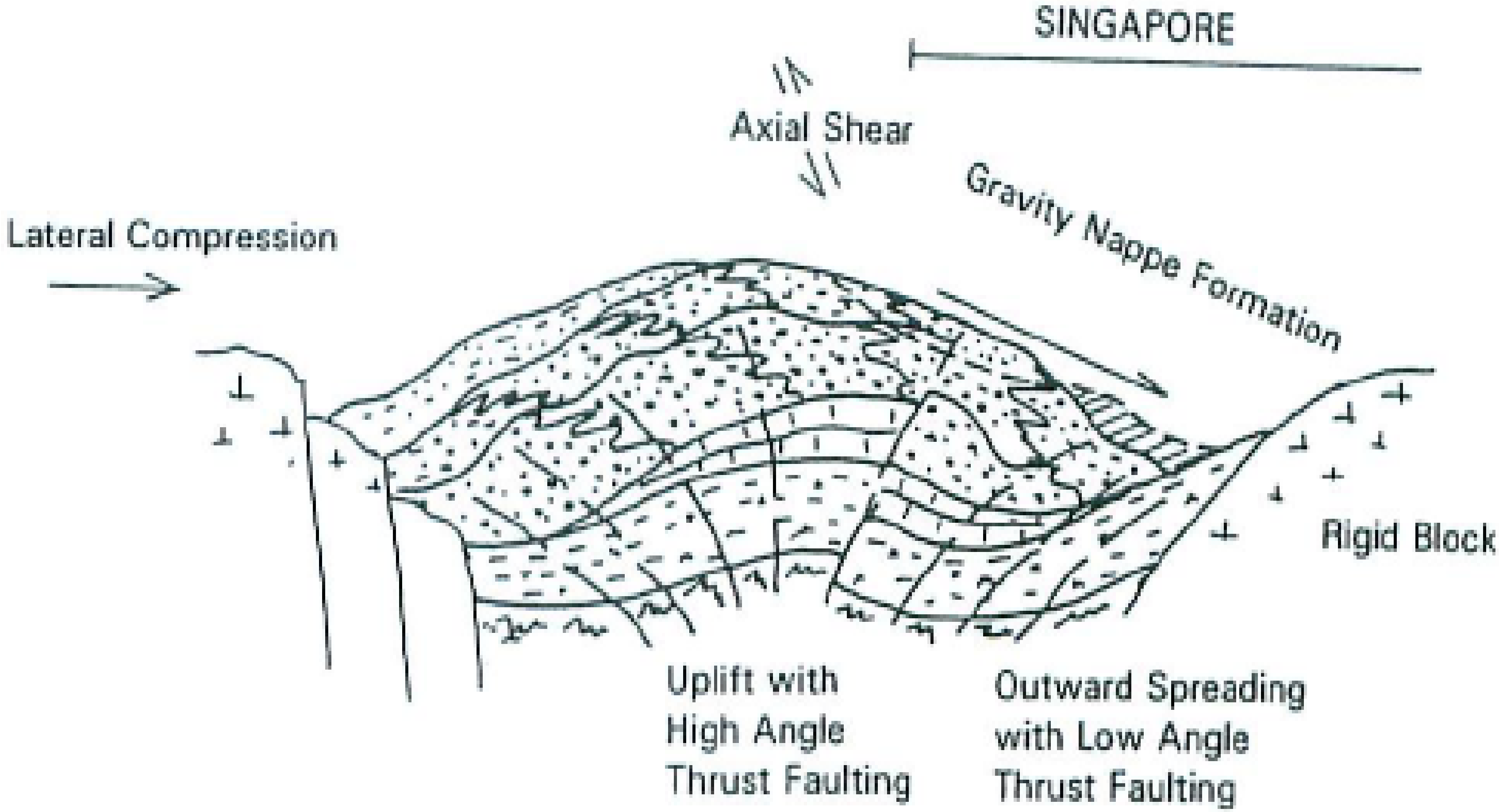

Basin uplifting of the Jurong Formation (after Redding et al, 1999)

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Jurong Formation

Geological Structure and In-Situ Stresses

Bedding: many beds are thin with some reaching a few metres in thickness. Weak and strong beds are often interbedded.

Folding: many folds trend NWW - SEE.

In-situ

Stresses: horizontal stress in NNE-SSW is 2.4 - 2.8 times the vertical stress in some strong rocks. Folding and high horizontal stresses are related to regional tectonic movements.

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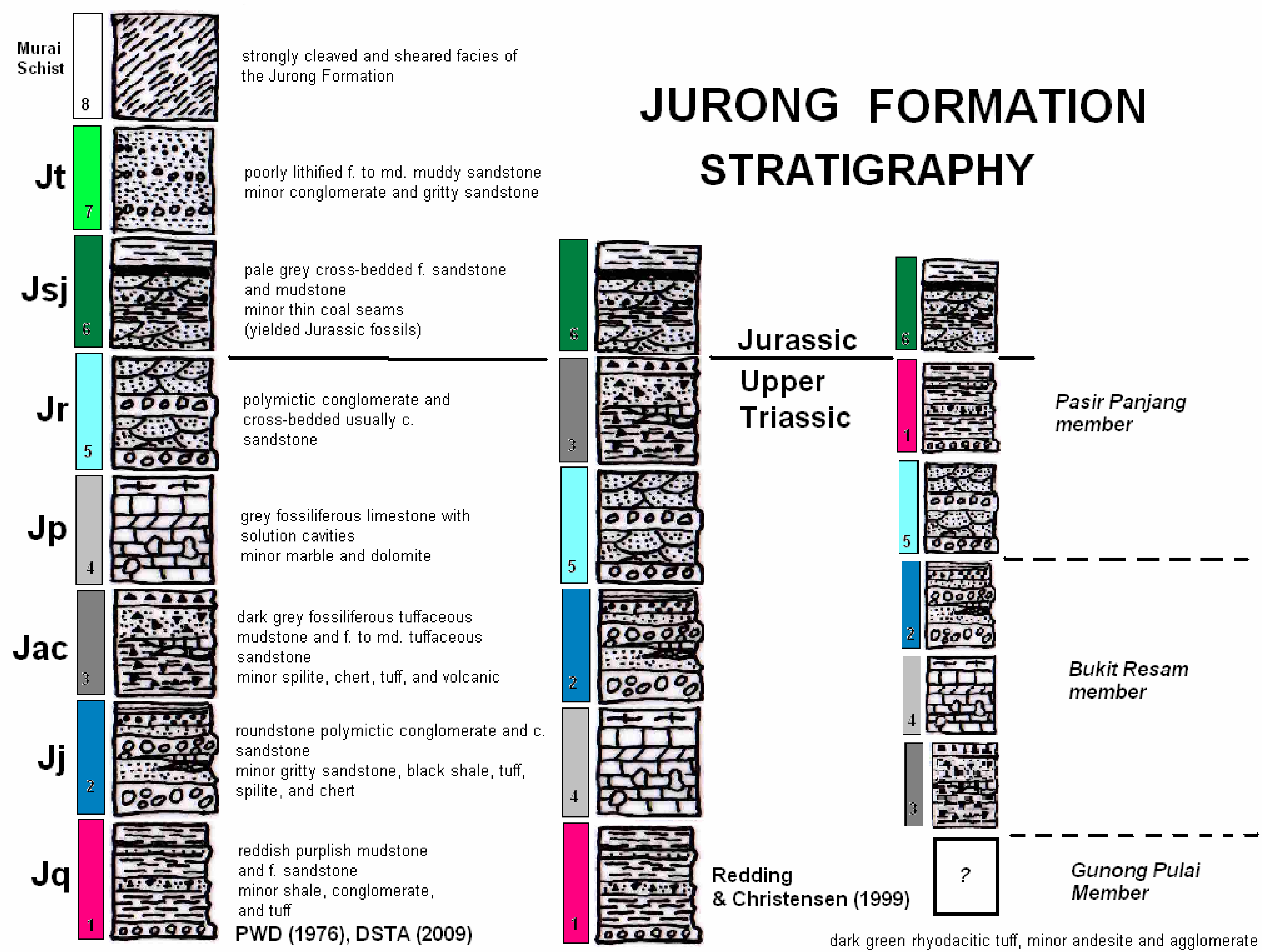

JURONG FORMATION STRATIGRAPHY
Murai Schist
8
strongly cleaved and sheared facies of the Jurong Formation
Jt
7
poorly lithified f. to md. muddy sandstone
minor conglomerate and gritty sandstone
Jsj
6
pale grey cross-bedded f. sandstone and mudstone
minor thin coal seams
(yielded Jurassic fossils)
Jr
5
polymictic conglomerate and cross-bedded usually c. sandstone
Jp
4
grey fossiliferous limestone with solution cavities
minor marble and dolomite
Jac
3
dark grey fossiliferous tuffaceous mudstone and f. to md. tuffaceous sandstone
minor spilite, chert, tuff, and volcanic
Jj
2
roundstone polymictic conglomerate and c. sandstone
minor gritty sandstone, black shale, tuff, spilite, and chert
Jq
1
reddish purplish mudstone and f. sandstone
minor shale, conglomerate, and tuff
PWD (1976), DSTA (2009)
Jurassic
Upper Triassic
Redding & Christensen (1999)
Pasir Panjang member
Bukit Resam member
?
Gunong Pulai Member
dark green rhyodacitic tuff, minor andesite and agglomerate

Jurong Formation

Lithological Facies

Queenstown:	**red to purple mudstone and sandstone**
Jong:	**roundstone conglomerate and sandstone**
Ayer Chawan:	**dark grey fossil-rich mudstone, fossil-rich shale, muddy sandstone, and tuff**
Pandan:	**grey fossil limestone**
Rimau:	**conglomerate and sandstone**
St. John:	**siltstone and fine muddy sandstone**
Tengah:	**muddy sandstone with some conglomerate**

Volcanic rocks such as tuff and spilite were added to the Jurong Formation during volcanic activity.

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Jurong Formation

Pandan Facies

Besides the Pandan area, limestone is also found at Pasir Panjang, Seraya, the Banyan Basin in Jurong Island, Tuas, and many other areas in Jurong.

The limestone facies has been named the Pandan Facies because cores of fossil-rich limestone recovered from Pandan Road are the first cores to be described in detail.

The limestone from some areas has been partially metamorphised to marble.

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Interbedded
conglomerates and sandstone at Labrador

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Interbedded
sandstone and fissile shale at Tuas

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Conglomerate from Kent Ridge (BH 11)

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Conglomerate and sandstone from NTU

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Sandstone from Kent Ridge (BH 11)

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Siltstone from Kent Ridge (BH 2)

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Siltstone from Jurong Island

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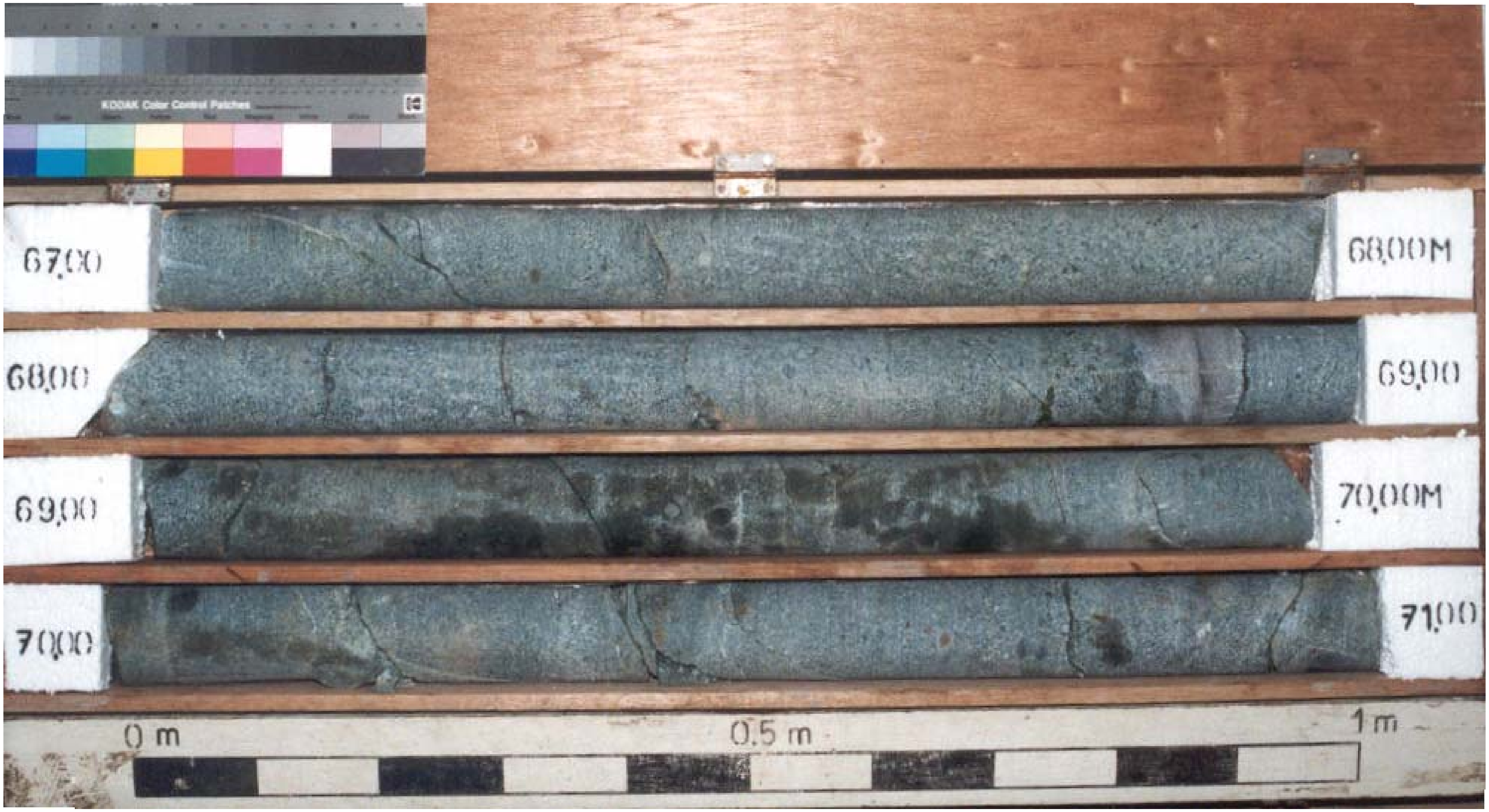

Tuff from Kent Ridge (BH 13)

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Marble in contact with siltstone from Kent Ridge (BH 7)

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Limestone with cavities from Kent Ridge

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Jurong Formation

Metamorphism

The Jurong Formation had been subjected to low-grade metamorphism.

The Pandan Facies were affected more than the other facies.

The evidence for metamorphism includes:

- **wide-spread occurrences of cleavage, foliation, and recrystallization**
- **presence of metamorphic minerals such as chlorite, sericite, and micas**
- **occurrence of metamorphic rocks such as slates, phyllite, and marble**

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Shale with cleavages from Mount Faber

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Jurong Formation

Rock Properties and Quality

Strength: most rocks are weak.

Quality: rock mass quality is usually fair to poor due to extensive fracturing and low strength of the rocks.

Variation: rock properties and rock mass quality can vary rapidly due to folding.

Permeability: intermediate permeability within the range from 10^{-6} to $2x10^{-8}$ m/s due to frequent fractures.

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Jurong Formation

Weathering

- **deep due to humid tropical climate**
- **thickness of residual soil and weathed zone ranges from a few to 80 m with an average thickness of 35 m.**
- **karstic features such as solution cavities may be present in the limestone.**

Jurong Formation

Groundwater

- **The groundwater table is located between 5 and 20 m below ground surface.**
- **It is usually present in the zone of residual soil or completely weathered rock**

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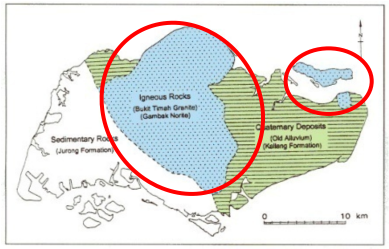
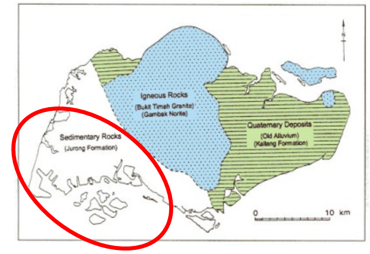
Bukit Timah Granite versus Jurong Formation

Properties	Bukit Timah Granite	Jurong Formation
Distribution		
Strength of Rock Material	high strength (160 MPa) excellent medium for hosting cavern space	low strength (10-160MPa) still a good medium hosting cavern space
Thickness of Overburden	usually around 20 m	usually around 25m
Thickness of Weathered Zone	usually around 5 m	usually around 10 m
Permeability	low (usually $10^{-7\sim-9}$ m/sec) strong inflow of groundwater is not expected water-proof grouting is not required.	relatively high (usually $10^{-6\sim-8}$ m/sec) strong inflow of groundwater is expected water-proof grouting is required.

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Bukit Timah Granite versus Jurong Formation (Cont'd)

Properties	Bukit Timah Granite	Jurong Formation
In-situ Stress	horizontal to vertical stress ratio is 2 – 3 high ratio helps stability of cavern roof and hence affords larger cavern span	horizontal to vertical stress ratio is 2.4 - 2.8 high ratio helps stability of cavern roof and hence affords larger cavern span
Degree of Fracturing	massive and more intact (RQD is usually 75 - 100) intact rock mass results in better overall rock mass quality and lower permeability.	bedded and more fractured (RQD is usually 20 - 90) more fractured rock mass results in poorer rock mass quality and higher permeability.
Rock Mass Quality	75% of rock mass is classified as equal or exceeding good quality (Q>=10) 98% of rock mass is classified as equal or exceeding fair (Q>=4) is slightly better than the rock mass quality of the Gjovik Gneiss which hosts the Gjovik Sports Hall. It has a cavern span of 61 m – the world's largest.	30% of rock mass is classified as equal or exceeding good quality (Q>=10) 50% of rock mass is classified as equal or exceeding fair (Q>=4)

Bukit Timah Granite versus Jurong Formation (Cont'd)

Properties	Bukit Timah Granite	Jurong Formation
Cavern Dimension	span can be 20 – 40 m with fair rock supports. span larger than 40 m and up to 75 m may be possible with sites having high horizontal to vertical stress ratios	span can be 20 – 25 m with fair rock supports. span larger than 25 m and up to 40 m may be possible with substantial rock support measures in sites having favorable geologic conditions

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Old Alluvium

Distribution and Development

Distribution: mainly on eastern Singapore Island; much less on northwestern Singapore Island

Thickness: varies from a few tens of meters to more than 200 meters

Development: made up of sediments brought down by closely-connected rivers and deposited in a deep basin in eastern Singapore Island

Age: Late Tertiary to Middle Pleistocene (5 – 0.5 my)

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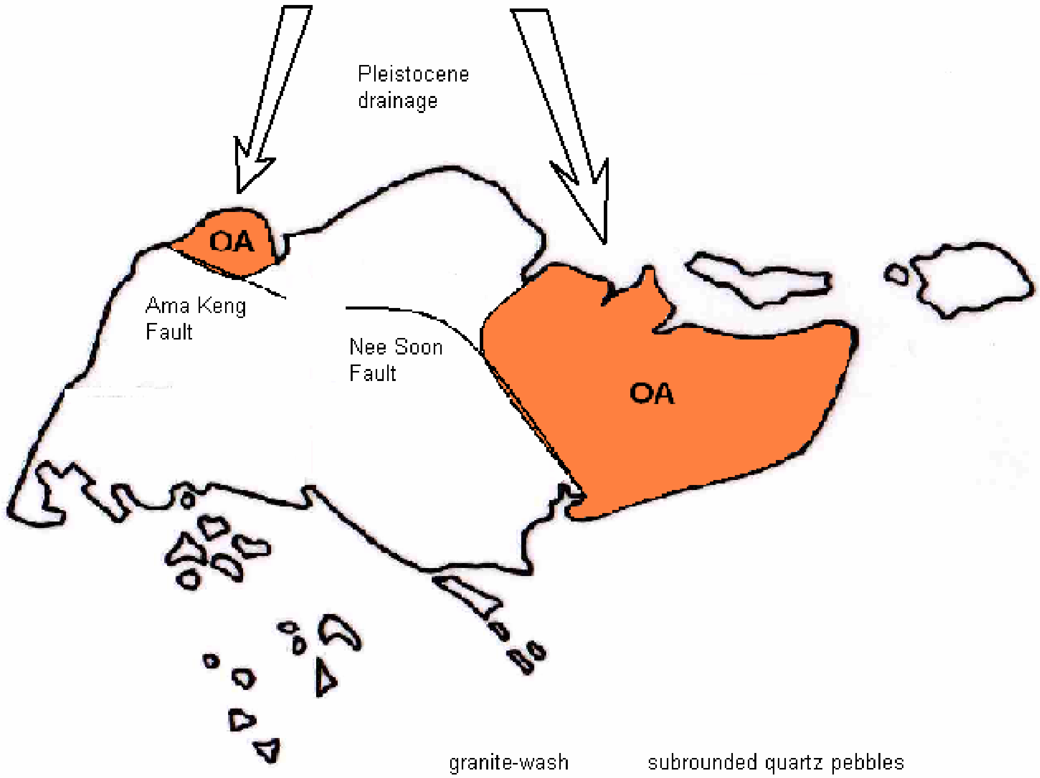
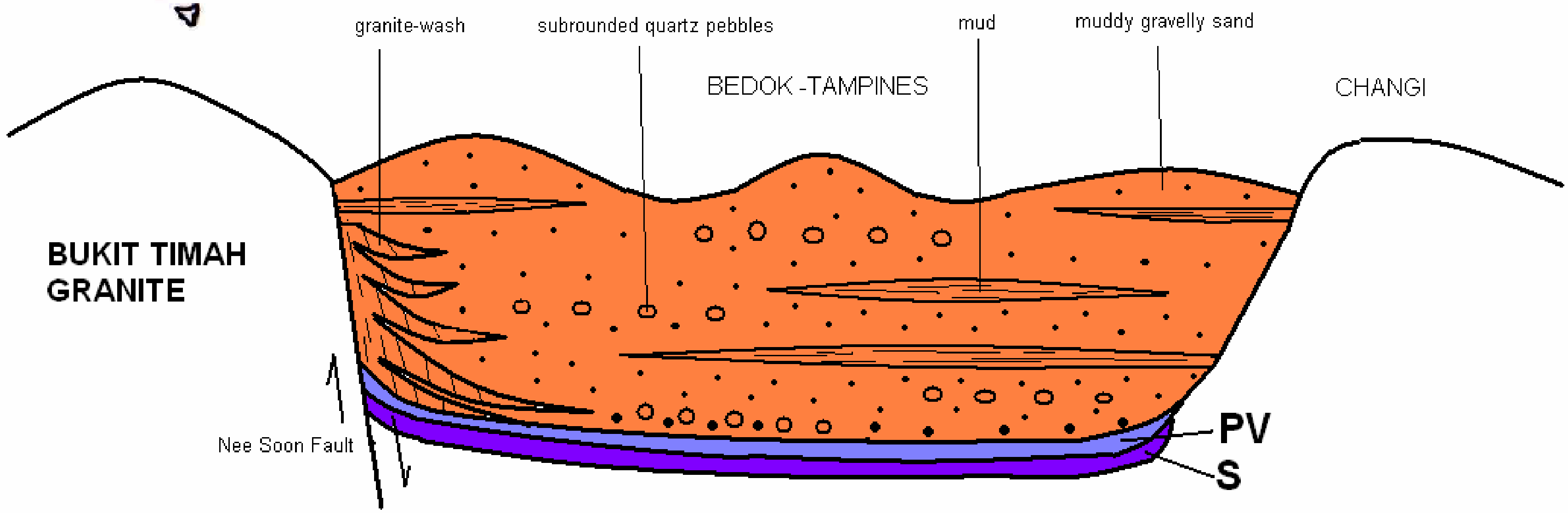
OLD ALLUVIUM - GEOLOGICAL SETTING





Old Alluvium

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Old Alluvium

Material and Properties

Materials: **dense/cemented muddy sand/gravel with lenses of silt and/or clay.**

Properties: **refer to Li, 1999 and Sharma, Chu, and Zhao, 1999 in Geological and Geotechnical Features of Singapore: an Overview *Tunneling and Underground Space Technology, Vol.15, No.4, pp.419 - 431*).**

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Old Alluvium

Properties (average values are presented for reference only)

0 – 8m Old Alluvium Layer 1 (OA1)	**SPT Blow Count (N) $\leq$ 25** **Colour: Yellowish, reddish, or greyish** **Composition: Clayey and silty sand, clayey silt** **Consistency: Loose to medium dense for sand, medium stiff to very stiff for clay** **Water Content, w (%) = 22** **Bulk Density, ρ_{bulk} (kN/m^3) = 20.3** **Dry Density, ρ_d (kN/m^3) = 16.6** **Specific Gravity, G_s = 2.65** **Liquid Limit, w_L (%) = 55** **Plastic Limit, w_P (%) = 23** **Plasticity Index, PI (%) = 32** **Avg. Undrained Shear Strength, s_u (kPa) = 100** **Cohesion, c' (kPa) = 1.9** **Friction angle, ø' (°) = 36.1** **Horizontal Permeability, k_h ($\times 10^{-8}$m/s) = 18.8** **Compression Index, C_c = 0.2** **Recompression Index, C_r = 0.025** **E_u/s_u = 40 - 400, recommended value: $\approx$ 170**

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Old Alluvium

Properties (average values are presented for reference only)

8 – 13 m Old Alluvium Layer 2 (OA2)	**SPT Below Count (N) = 26-100** **Colour: yellowish brown to light grey or greenish grey** **Composition: clayey and silty sand** **Consistency: medium dense to very dense for sand; very stiff to hard for clay** **Water Content, w (%) = 18.2** **Bulk Density, ρ_{bulk} (kN/m^3) = 20.7** **Dry Density, ρ_d (kN/m^3) = 17.6** **Specific Gravity, Gs = 2.64** **Liquid Limit, wL (%) = 49** **Plastic Limit, wP (%) = 20** **Plasticity Index, PI (%) = 28** **Avg. Undrained Shear Strength, s_u (kPa) = 195** **Cohesion, c' (kPa) = 8.4** **Friction angle, ø' (°) = 35.9** **Horizontal Permeability, k_h ($\times 10^{-8}$m/s) = 6.4** **Compression Index, C_c = 0.1** **Recompression Index, C_r = 0.02** **E_u/s_u = 40 - 400, recommended value ≈ 170**

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Old Alluvium

Properties (average values are presented for reference only)

More than 13m Old Alluvium Layer 3 (OA3)	**SPT Blow Count (N) >100** **Colour: light grey to greenish grey** **Composition: clayey and silty sand** **Consistency: very dense to moderately strong** **Water Content, w (%) = 16.3** **Bulk Density, ρ_{bulk} (kN/m^3) = 20.3** **Dry Density, ρ_d (kN/m^3) = 17.8** **Specific Gravity, Gs = 2.64** **Liquid Limit, wL (%) = 38** **Plastic Limit, wP (%) = 19** **Plasticity Index, PI (%) = 19** **Avg. Undrained Shear Strength, s_u (kPa) = 362** **Cohesion, c' (kPa) = 30.3** **Friction angle, ø' (°) = 35.0** **Horizontal Permeability, k_h ($\times 10^{-8}$m/s) = 3.4** **Compression Index, C_c = 0.07** **Recompression Index, C_r = 0.015** **E_u/s_u = 40 - 400, recommended value ≈ 170**

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Kallang Formation

Distribution and Development

Distribution: extensively found in river valleys, river mouths, river plains, coastal areas, and the near offshore.

Thickness: up to 80 m

Development: buried marine clay, beach sand, river sand, organic peaty mud, and coral have been deposited during rising sea levels. They are still being deposited.

Age: Late Pleistocene to Present (0.14 – 0 my).

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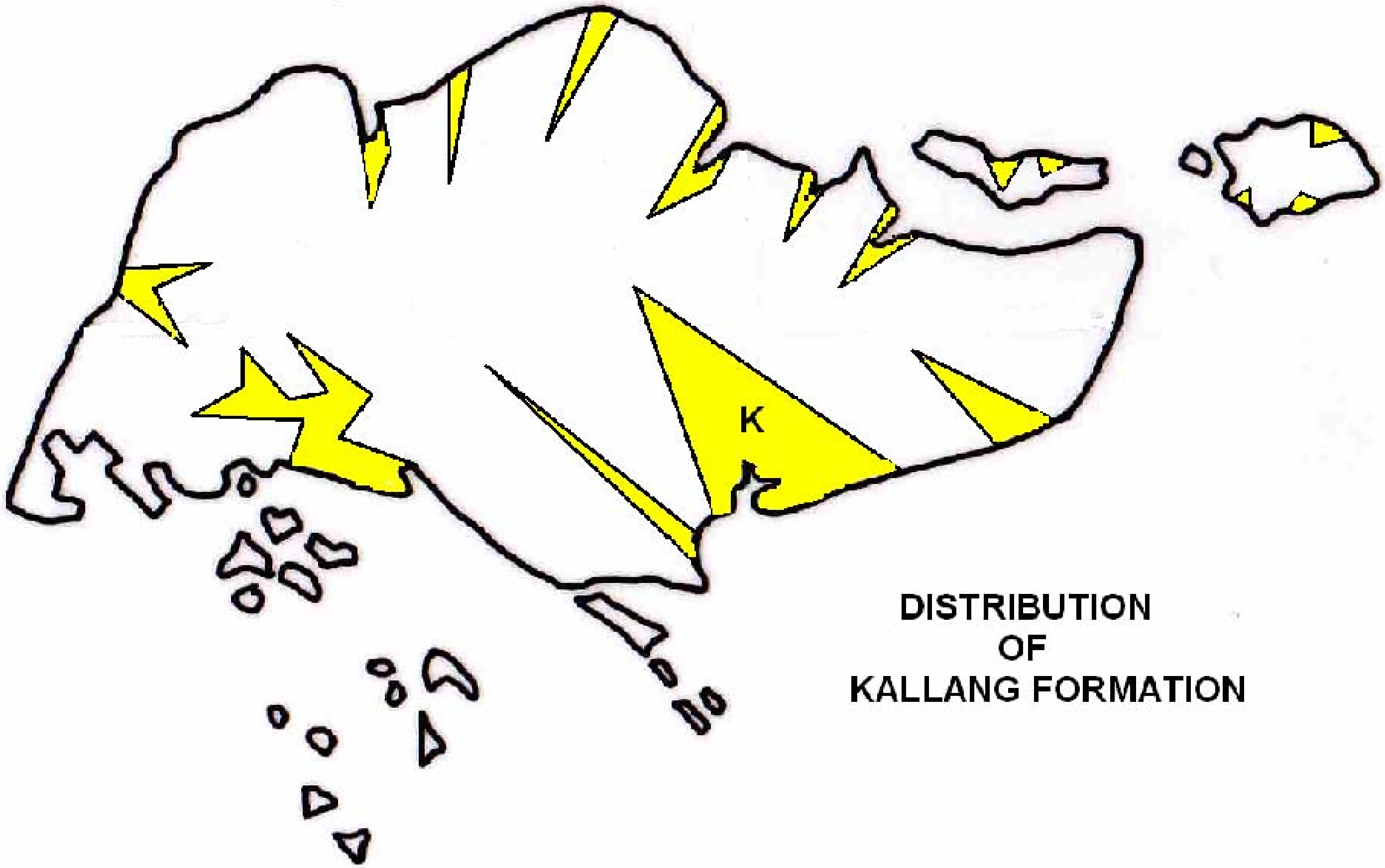

DISTRIBUTION
OF
KALLANG FORMATION

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Kallang Formation

Materials

It consists of sediments with marine, alluvial, littoral, and estuarine origins. It includes 5 members.

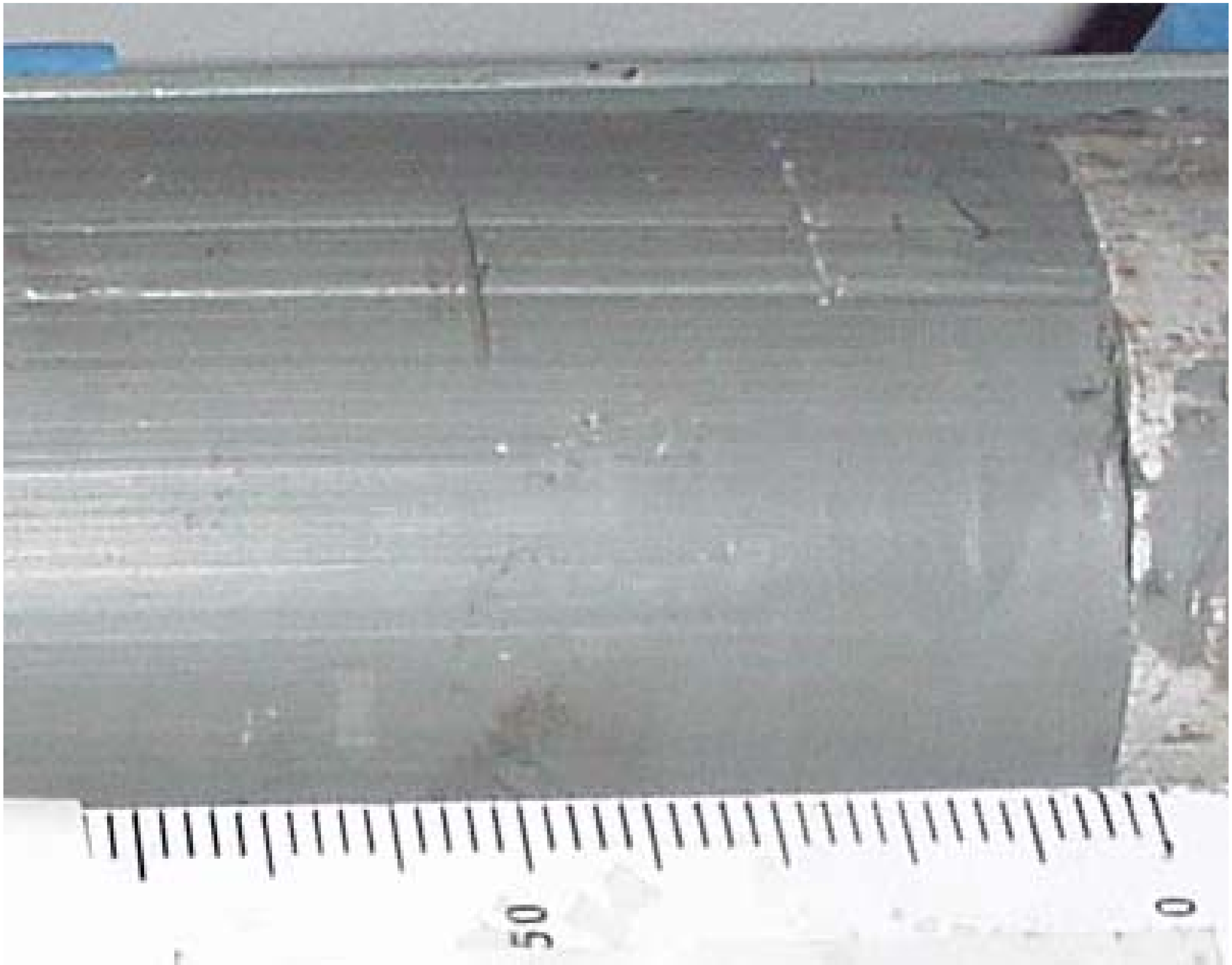
Marine Member: soft grey clays deposited offshore

Alluvial Member: loose muddy sand and sand deposited in river valleys

Littoral Member: loose muddy sand and sand with shells deposited on coastal beaches

Transitional Member: soft dark grey organic/peaty clay and clayey peat deposited in mangrove areas

Reef Member: loose calcareous sand and corals formed offshore



Singapore Marine Clay

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Kallang Formation

Properties of Singapore Marine Clay

Properties: **refer to Sharma, Chu, and Zhao, 1999 in Geological and Geotechnical Features of Singapore: an Overview, *Tunneling and Underground Space Technology, Vol.15, No.4, pp.419 - 431***

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Other Geological Formations

Gombak Norite

Distribution: **Bukit Gombak, Bukit Panjang, and adjacent hills**

Rocks: **norite and gabbro (coarse-grained basic igneous rocks consisting of interlocked calcium-rich plagioclase minerals with pyroxene minerals)**

Properties: **high strength and modulus (similar to the properties of Bukit Timah Granite)**

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Other Geological Formations

Sajahat Formation

Distribution: **P. Tekong, P. Sajahat, Punggol.**

Rocks: **Well lithified quartzite, quartz sandstone, and argillite**

Age: **Lower Paleozoic (540 – 445 my)**

It is the oldest formation in Singapore.

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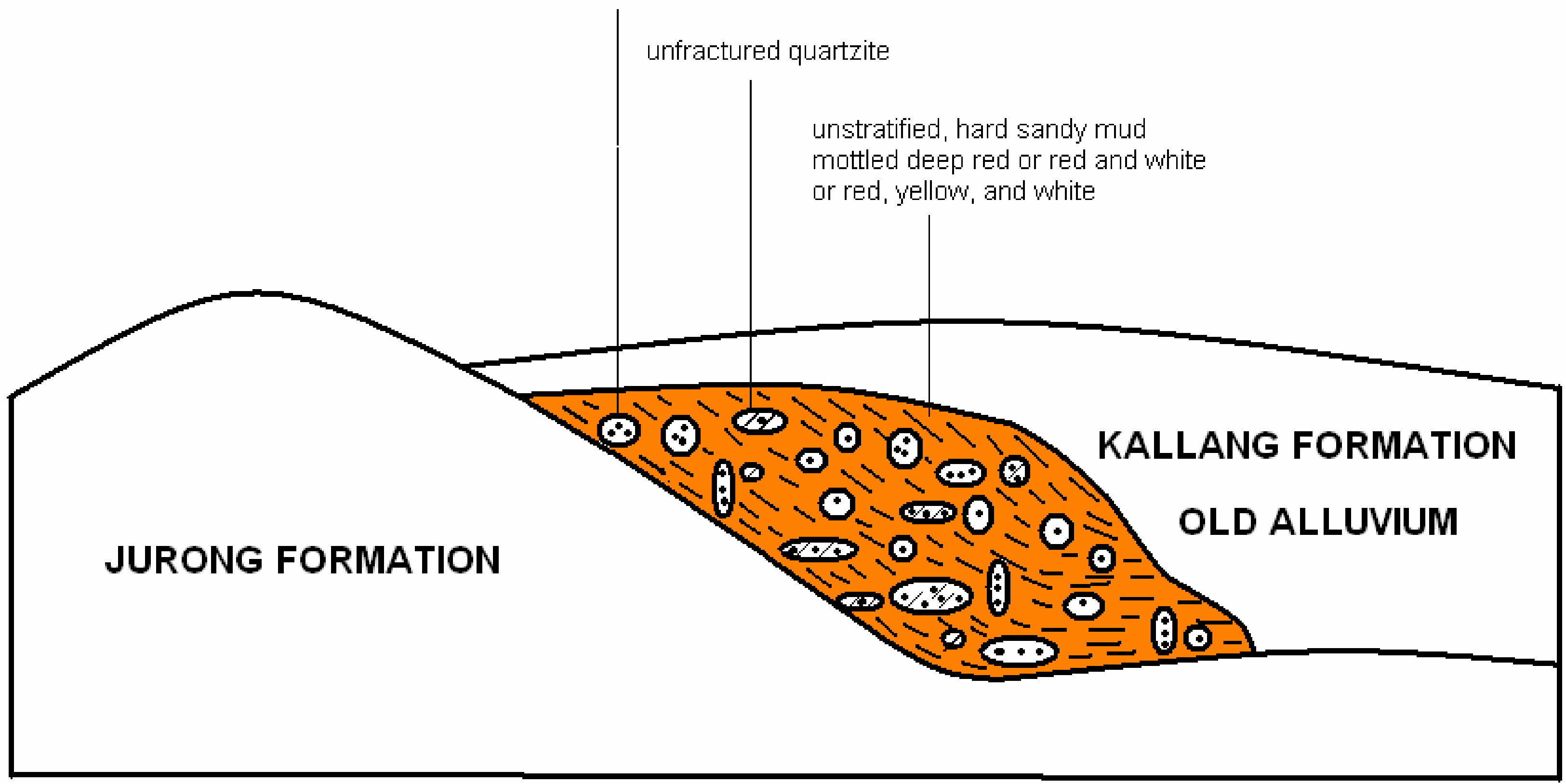
Fort Canning Boulder Bed

Distribution: Central business district, i.e. underlying an area bounded by Fort Canning Park, The Cathay Building, Middle Road and Raffles City.

Rocks: Sandstone or quartzite boulders in hard matrix of sandy clayey silt or sandy silty clay coloured in red, yellow and white.

Age: Late Cretaceous (older than the Old Alluvium but younger than the Jurong Formation)



FORT CANNING BOULDER BED - GEOLOGIC SETTING

Description of Rocks and Soils for Civil Engineering Practice in Singapore

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Description of Rocks and Soils for Civil Engineering Practice in Singapore

Geo-Notation	Origin	Description	Geological Formation
B	BEACH	loose muddy sand and sand with some gravel, coral, and shells.	KALLANG (Littoral Member) and TEKONG.
E	ESTUARINE	soft dark grey peaty/organic clay and clayey peat	KALLANG (Transitional Member)
F	FLUVIAL	soft mud, loose muddy sand and sand	KALLANG (Alluvial Member) and TEKONG
F1		granular sediments of silt, sandy silt, silty sand, sand	Bed of Alluvial Member of KALLANG
F2		cohesive sediments of silty clay, sandy clay	Bed of Alluvial Member of KALLANG
M	SHALLOW MARINE	soft blue or grey clay with some shells	KALLANG (Marine Member)

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Description of Rocks and Soils for Civil Engineering Practice in Singapore (Cont'd)

Geo-Notation	Origin	Description	Geologic Formation
O	FLUVIAL	dense to cemented muddy sand/gravel with beds of silt and/or clay	OLD ALLUVIUM
FC	COLLUVIAL	hard, unstratified, often red and white coloured silty clay containing many big lens-shaped and rounded fresh boulders.	FORT CANNING BOULDER BED
S	SHALLOW MARINE	red purplish mudstone and sandstone; grey fossil-rich mudstone, fossil-rich shale, and tuff; fossil-rich limestone; coarse sandstone and conglomerate; siltstone and fine sandstone; and muddy sandstone.	JURONG (Queenstown, Jong, Ayer Chawan, Pandan, Rimau, St John, and Tengah Facies)
G	PLUTONIC	Granite, granodiorite, adamellite, diorite	BUKIT TIMAH GRANITE

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Weathering Classification of Rocks for Civil Engineering Practice in Singapore

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Weathering Classification for Bukit Timah Granite & Gombak Norite

in accordance with Approach 2 in BS Code 5930 Section 6 (1999)

Geo-Notation	Grade / Class	Classification	Basis for assessment
G(1)	I	fresh	intact strength unaffected by weathering; not broken easily by hammer; rings when stuck with hammer; no visible discoloration.
G(II)	II	slightly weathered	not broken easily by hammer; rings when stuck with hammer; fresh rock colors generally retained but stained near joint surfaces.
G(III)	III	moderately weathered	cannot be broken by hand but easily broken by hammer; makes a dull or slight ringing sound when stuck with hammer; stained throughout.
G(IV)	IV	highly weathered	core can be broken by hand; does not slake in water; completely discoloured.
G(V)	V	completely weathered	original rock texture preserved; can be crumbled by hand; slakes in water; completely discoloured.
G(VI)	VI	residual soil	original rock structure completely degraded to a soil with none of the original fabric remains; can be crumbled by hand

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Weathering of Bukit Timah Granite

Mandai

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Weathering Classification for Jurong Formation

in accordance with Approach 2 in BS Code 5930 Section 6 (1999)

Geo-Notation	Grade / Class	Classification	Basis for assessment
S(I)	I	fresh	intact strength unaffected by weathering
S(II)	II	slightly Weathered	slightly weakened with slight discoloration particularly along joints
S(III)	III	moderately weathered	considerably weakened & discolored; larger pieces cannot be broken by hand (RQD generally > 0 but RQD should not be used as the major criterion for assessment)
S(IV)	IV	highly weathered	core can be broken by hand; generally highly to very highly fractured but majority of sample consists of lithorelics (RQD generally is 0 but RQD should not be used as the major guide for assessment). For siltstone, shale, sandstone, quartzite, and conglomerate, the slake test can be used to differentiate between Grade V (slake) and Grade IV (does not slake)
S(V)	V	completely weathered	rock weathered down to soil-like material but bedding still intact; material slakes in water.
S(VI)	VI	residual soil	rock degraded to a soil in which none of the original bedding remains.

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Beds of weathered rocks of Jurong Formation at Outram Park

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Steeply dipping beds of weathered Jurong Formation rocks at Outram Park

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Weathering Classification of Old Alluvium

in accordance with Approach 4 in BS Code 5930 Section 6 (1999)

<table>
<tr><th>Geo-Notation</th><th>Grade / Class</th><th>Classification</th><th>Characteristics</th><th>Indicative SPT Blows/300mm (not used in isolation)</th></tr>
<tr><td>O(A)</td><td>A</td><td>unweathered</td><td>original strength</td><td rowspan="2">> 50 (cannot usually be penetrated by CPTs with 20t load capacity)</td></tr>
<tr><td>O(B)</td><td>B</td><td>partially weathered</td><td>slightly reduced strength</td></tr>
<tr><td>O(C)</td><td>C</td><td>distinctly weathered</td><td>further weakened</td><td>30 - 50</td></tr>
<tr><td>O(D)</td><td>D</td><td>destructed</td><td>greatly weakened
often mottled; bedding disturbed</td><td>10 - 30</td></tr>
<tr><td>O(E)</td><td>E</td><td>residual soil</td><td>no bedding remains</td><td>< 10</td></tr>
</table>

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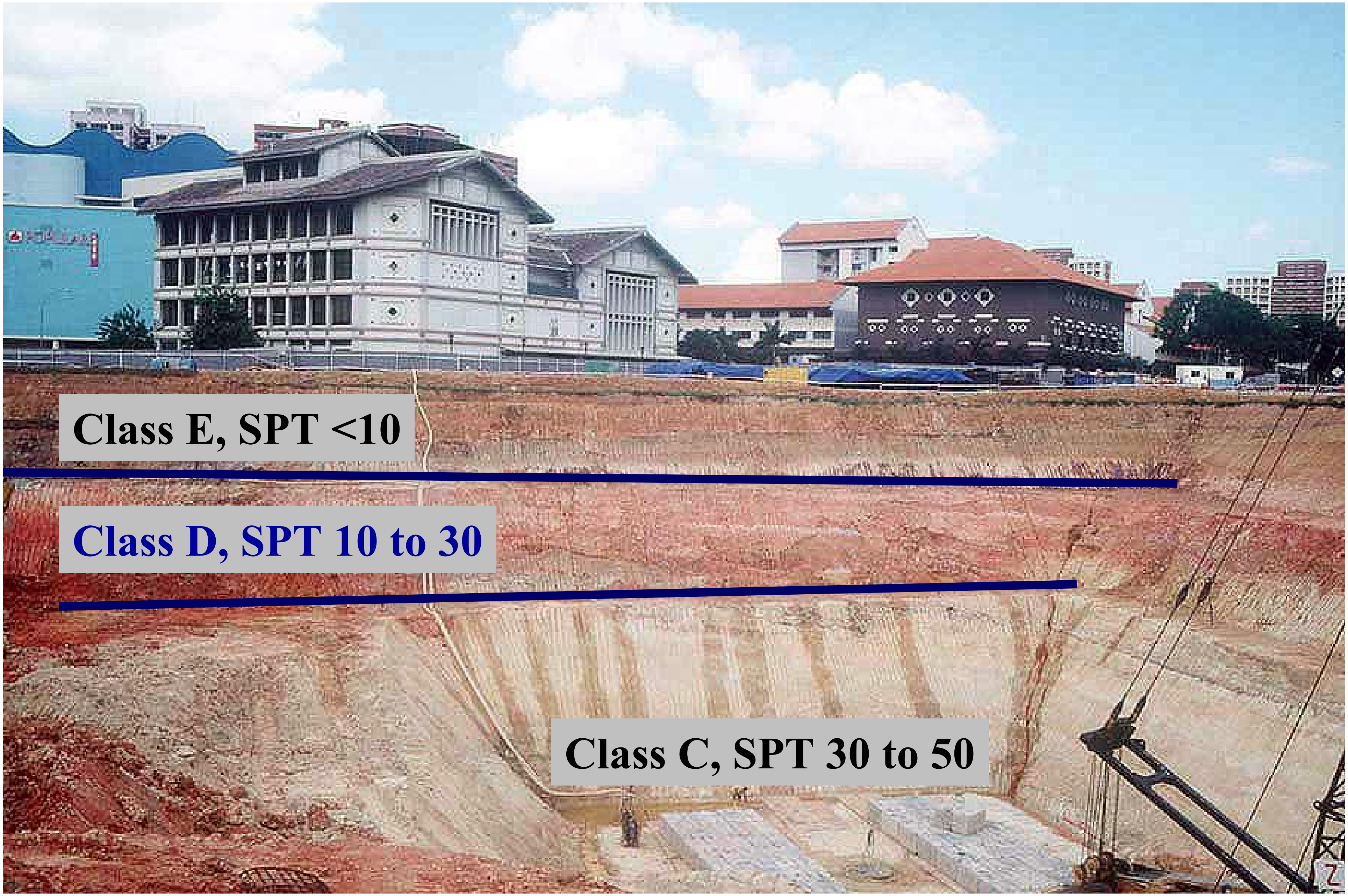

Weathered Old Alluvium, Hougang

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Updated Geological Maps & Report
2nd Edition, DSTA (2009)

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