A Review of the Geology of Singapore's Southern Islands with emphasis on Pulau Tekukor and Pulau Biola

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ABSTRACT. We introduce the geological terminology from recent standardisation exercises to describe the geology of the Southern Islands of Singapore. We then focus on the geology of two islands, Pulau Tekukor and Pulau Biola, which lie at the eastern and western extremities of the Sentosa Group.

Keywords. Fort Siloso, Jurong, Pulau Biola, Pulau Tekukor, Sentosa Group, terminology.

Introduction

This paper reviews the recently updated understanding of the geology of Singapore and the Southern Islands based on a multi-year project initiated by the Building and Construction Authority (BCA). The BCA-led Singapore Stratigraphy Working Group was formed in 2014 and comprised members from the National Technological University, National University of Singapore, British Geological Survey, and geotechnical experts from industry. A series of field trips revealed areas of geological importance on both mainland Singapore and offshore islands and, augmented by an extensive collection of borehole data and published material, led to a series of papers published in 2019 and 2020 (i.e., Dodd et al., 2019; Gillespie et al., 2019; Leslie et al., 2019; Chua et al., 2020; Dodd et al., 2020). This suite of publications greatly improved the understanding of Singapore's geology and revised the stratigraphic nomenclature to meet international standards via compliance with the guidelines of the International Commission on Stratigraphy (Murphy and Salvador, 1999). The project ended in 2021, culminating in the landmark Singapore Geological Memoir (Leslie et al., 2021), which supersedes all previous versions (PWD, 1976; DSTA, 2009), and now guides all geotechnical and construction work in Singapore.

The second part of the paper provides preliminary surveys of two little-visited islands, namely Pulau Tekukor (south of Sentosa) and Pulau Biola (north of Raffles Lighthouse) (See Fig. 1). The geological and geomorphological information presented are based on short half-day surveys conducted on 21st January and 13th February 2020, respectively, as part of the Southern Islands Biodiversity Survey conducted by the National Parks Board (NParks).

Recent Geological Investigations

A series of boreholes and field outcrops were recently examined, which together with seismic data resulted in the reinterpretation of Singapore's geological setting (Fig. 1). The Southern islands are largely surficially expressed in the newly named Sentosa Group, comprising the Tanjong Rimau and the Fort Siloso Formations (Fig. 2). Figure 2 also reveals the stress field in the region demonstrating a NW–SE trending folding, with Pulau Tekukor and Pulau Biola marking the eastern and western bounds of the Sentosa Group (as demarcated by fault map).

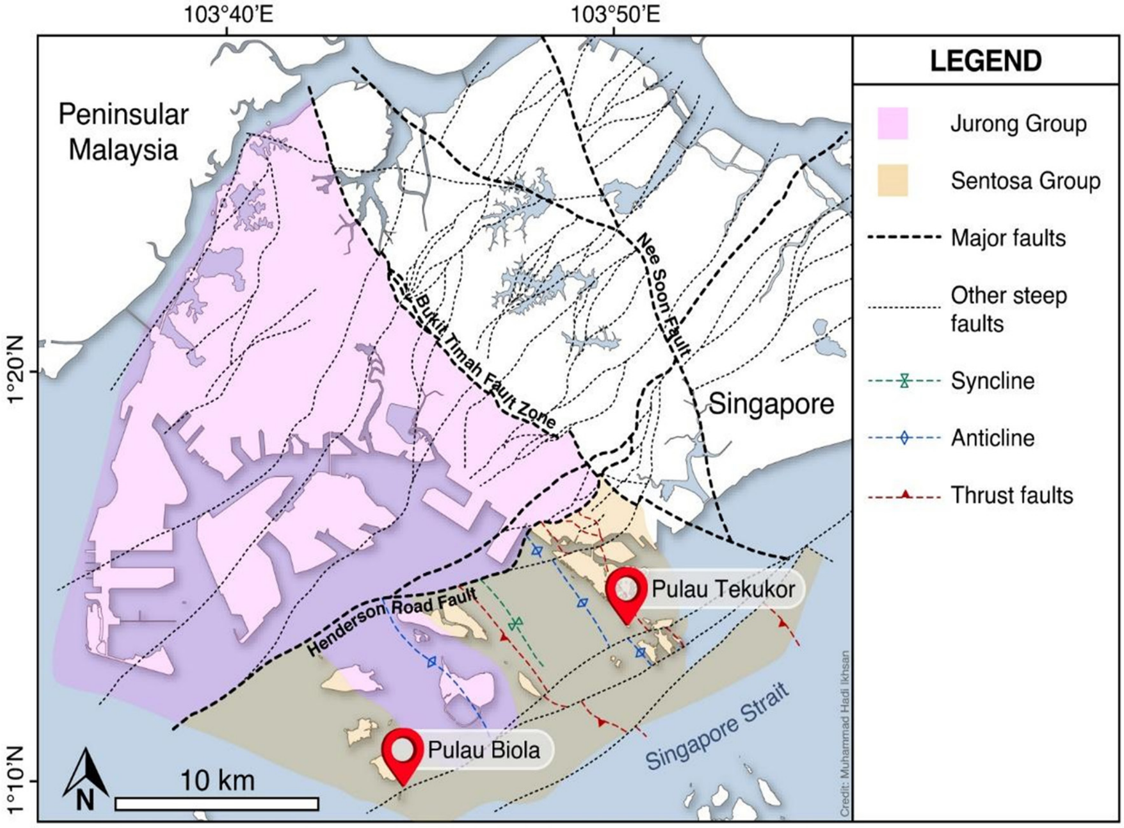

Figure 1. The distribution of the Jurong Group and Sentosa Group strata across Singapore. Linework, including faults, thrust faults, anticlines, synclines, and stratigraphical boundaries. The Sentosa Group strata are mainly encountered south of the Henderson Road Fault (HRF). Adapted from Dodd et al. (2019).

The Sentosa Group

The Sentosa Group is named after Sentosa Island in the Southern Islands planning area of Singapore. The group is predominantly located offshore, but also occurs in the Southern Islands (e.g., Pulau Biola) as well as in Labrador Park on mainland Singapore. The Sentosa Group comprises the Tanjong Rimau Formation and the Fort Siloso Formation (Table 1); the stratotypes for both formations are well-exposed on Sentosa Island, along with the boundary-stratotype (Dodd et al., 2019). This reclassification redefines the hitherto-recognised Jurong Formation, which now stops stratigraphically at the topmost endmember – the Boon Lay Member dated to the Middle Triassic (~240 Ma), as opposed to the Upper Triassic Sentosa Group (~210 Ma). The boundary between the Jurong Group and the Sentosa Group is separated by an unconformity inferred from a *c.* 30 Ma time gap in deposition (Dodd et al., 2019; Leslie et al., 2019).

Table 1. The ICS compliant lithostratigraphical framework for Singapore developed in this study, with only the Sentosa Group displayed. In addition, 'depositional age' information, including new U-Pb age determinations of detrital zircons (red text), along with already published geochronological information (blue text), has been summarised per unit. Readers are encouraged to refer to Dodd et al. (2019) for details.

<table>
<tr><th>System/ Epoch</th><th colspan="2">Lithostratigraphical Framework for Singapore</th><th colspan="3">Depositional Age</th><th>Depositional Environment</th><th>Geological Events</th></tr>
<tr><td rowspan="2">Upper Triassic</td><td rowspan="2">Sentosa Group</td><td>Fort Siloso Formation</td><td rowspan="2">≤209 ± 2 Ma</td><td colspan="2"></td><td>Marginal marine</td><td>└ Onset of thrusting ┘
┌ Marine transgression ┐</td></tr>
<tr><td>Tanjong Rimau Formation</td><td>New Sample ages
AGLE_ 65_01: ≤224 ± 2 Ma
Sample 157a: ≤224 ± 2 Ma</td><td>Published ages
≤209 ± 2 Ma</td><td>Fluvial – braided to meandering</td><td>Regional uplift → Active Erosion
┌ Slab breakoff (?) ┐</td></tr>
</table>

Sentosa Island outcrops were previously examined and interpreted as 'a continental red-bed molasse succession recording alluvial-lacustrine sediments' deposited in a half-graben setting, referred to as Lake Sentosa (Oliver and Prave, 2013). However, Dodd et al. (2019) provide an alternative interpretation which incorporates knowledge of the structural arrangement of Singapore and additional sedimentary evidence exposed on neighbouring islands (Fig. 2).

The Tanjong Rimau Formation represents the lowermost unit of the Sentosa Group and was deposited when large volumes of immature sediments were actively eroded from the Singapore region of the Semantan Basin (hinterland). The sediment was transported predominantly through braided to meandering fluvial systems (Fig. 2A) that produced thick, trough cross-bedded to planar cross-bedded sandstones as a series of longitudinal bars, transverse bars, point bars, and channel elements. Thinly interbedded, laminated mudstone and very fine-grained sandstones represent some element of overbank preservation. These fluvial systems may have eroded into and re-worked the underlying Jurong Group strata.

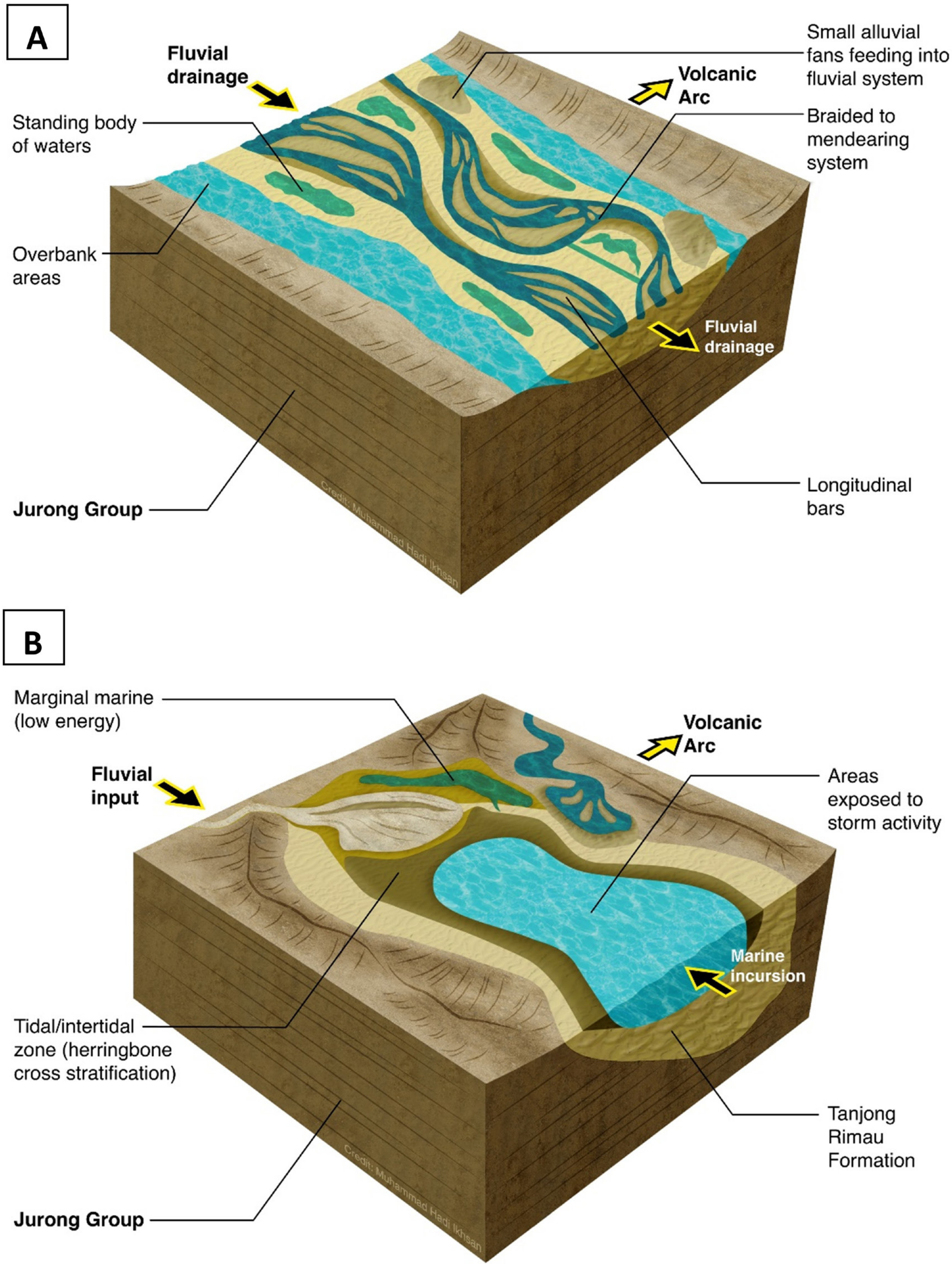

Figure 2. 3D schematic block diagrams of the depositional environments for the formations within the new lithostratigraphical framework for Singapore. **(A)** The fluvial, braided to meandering environment of the Tanjong Rimau Formation. **(B)** The low energy, marginal marine depositional environment of the Fort Siloso Formation, which was deposited following the marine transgression of the underlying Tanjong Rimau Formation. Adapted from Dodd et al. (2019).

The stratigraphically highest parts of the Tanjong Rimau Formation display upwards-increasing evidence of marine indicators suggesting a progressive marine incursion into the fluvial setting during this time. This is supported by the interpretation of a 'beach' or 'shore' environment, formed possibly under conditions of uplift and late Triassic sea-level rise.

The transition from the Tanjong Rimau Formation into the overlying Fort Siloso Formation depositional environment is marked by the final dominance of marine process over fluvial process and upwards absence of coarse-grained sediments. The Fort Siloso Formation was deposited in a low energy, marginal marine to fluvio-deltaic/fluvio-lacustrine setting (Fig. 2B) where tidal processes influenced deposition. A low-energy, tidal flat likely surrounded a suite of low-relief tidal channels, depositing repeated successions of very fine-grained sands, formed inclined heterolithic stratification. The absence of coarser-grained sediments was likely controlled by the flooding of the hinterland during the transgression, possibly during sea-level highstand conditions by late Triassic times (Dodd et al., 2019).

Pulau Tekukor

Pulau Tekukor lies at or close to the eastern bound of the Sentosa Group. It is a narrow, elongate island of approximately 700 m in length, 150 m in width, and roughly oriented north-west to south-east (Fig. 3). Pulau Tekukor can be described broadly as a rocky hummocky sandstone exposure, with wave-cut rocky platforms on the northern (B) and southern tips (E). A narrow strip of littoral sand is observed on the eastern shore (A) which provides the best landing site where this survey commenced.

Figure 3. Google Earth map of Pulau Tekukor showing areas of interest (A-E) demarcated by white rectangles.

Area A

A narrow sandy beach is located on the eastern coast, where presumably erosion by wave-cutting resulted in a low-gradient foreshore backed by vertical rocky exposures and low cliffs, belonging to the Sentosa Group, overrun by vegetation (Fig. 4A). Reddish sandstone cliffs are located in the centre of the island, characterised by hummocky cross-stratification from the Tanjong Rimau Formation (Dodd et al., 2019). More resistant sandstone sporadically outcrops the intertidal and supratidal zones (Fig. 4B). These aerially exposed interbedded graded coarse sandstones appear pale pink to the eye, and contain occasional pebble to cobble-sized inclusions within a poorly sorted matrix. In some instances, precipitated quartz forms beds of ~2–5 cm thickness. Generally, these outcrops are vertically or near-vertically dipping (Fig. 4B); these outcrops strike generally along the orientation of Pulau Tekukor (i.e., trending Northwest-Southeast) which parallels the proximal thrust fault to the east (Dodd et al., 2019).

Figure 4: (A) Eastern shoreline of Pulau Tekukor showing steep rocky cliffs overtopped by dense vegetation. **(B)** Near vertical outcrop comprising coarse sandstone with quartz beds intrusions. Photo credit: Stephen Chua, EOS, NTU.

Area B

The northern tip of Pulau Tekukor is composed of a flat, quartz sand dominated beach (littoral zone) strewn with clasts of variable sizes (from cobble to boulder-sized clasts). Tidal sorting is evident, with a central sandy lobe, sub-aerially exposed during low tides, surrounded by cobble to sub-boulder-sized clasts in the adjacent shoreface. The larger clasts are highly angular, suggesting short transport distances, and presumably eroded from the original landscape leaving behind more resistant rock, including a lithified 'tooth-like' coarse sandstone structure ~ 5–7 m in height (Fig. 5A). This rocky, hummocky northern tip of Pulau Tekukor provides suitable substrate for a host of biota, including sea cucumbers and sea anemones (Fig. 5B).

Figure 5. (A) Rocky (erosional) platform with more resistant sandstone structure on the left. Person on the right provides scale. **(B)** Rocky erosional platform provides a suitable substrate supporting a diversity of fauna. Photo credit: Stephen Chua, EOS, NTU.

Area C

Figure 6. Intertidal and subtidal coral reef /seagrass meadow fronting the seawall. Photo credit: Jonathan Tan, NParks.

Area D

A beautiful suite of high-variable successions of coarse to fine sandstones are observed at the southern and southeastern coasts. These sub-vertical pale-dark pink outcrops reveal complex features with evidence of possible past fluvial or lacustrine depositional environments (Tanjung Rimau Formation). Well-defined platy cross-bedded sandstone outcrops at the south-eastern coast were possibly deposited in a riverine environment (Fig. 7).

Figure 7. Sub-vertical cross-bedded sandstones formed possibly under fluvial conditions. Photo credit: Stephen Chua, EOS, NTU.

Other distinctive features in the southern part of the island include very coarse conglomerates that are abruptly overlain by fine unlaminated pale grey sandstone (Fig. 8). These beautiful sedimentary protrusions are approximately 40–50 cm in diameter and characterised by gravelly inclusions within the sandstone matrix. Such highly heterolithic sedimentary features could indicate a significant change in the depositional environment at some time. Such successions could be formed by a change from a higher-energy (e.g., shallow marine) to low-energy (e.g., lagoonal). Cursory observations reveal some degree of imbrication shown in the clast alignment suggesting deposition possibly by flowing water. There could also be an unconformity (hiatus in time) between the two units given the sharp erosional contact. However, it is difficult to discern the way-up or younging direction and hence it cannot be concluded which unit is older based solely on field observations.

Figure 8. (A) Beautiful bleached sandstones capping gravel bands. **(B)** Sharp contact between cemented conglomerates and fine massive sandstone with banded gravel inclusions. The handheld GPS provides scale. Photo credit: Stephen Chua, EOS, NTU.

Area E

The wave-cut platform here is smaller than the northern tip, and due to the undulations produce a series of tidal ponds where coral microatolls are observed (Fig. 9) These ponds are typically infilled with littoral sands and provide a sheltered environment for flora (e.g., seagrass) and fauna (e.g., sea cucumbers) to thrive. There is less eroded rubble, possible due to reduced wave action and weaker currents at this location.

Figure 9. Sheltered tidal pool in the southern tip of Pulau Tekukor. Coral microatolls have been observed at higher-than-expected elevations (relative to the tidal frame) due to marine ponding. Photo credit: Stephen Chua, EOS, NTU.

Pulau Biola

Pulau Biola lies at or close to the western bound of the Sentosa Group. It is a small, 'pear-shaped' islet (hence its name, which means "Violin Island" in Malay) 13 km south of mainland Singapore and proximal to our southernmost territorial water boundary marked by Raffles Lighthouse (Fig. 1). It is approximately 200 m in length, 95 m at its widest, and roughly oriented north-west to south-east, similar to Pulau Tekukor.

Pulau Biola (Fig. 10) can be characterised as a sandstone island with near-vertical (patterned) cliffs fronted by sandy beaches (Area A) comprised of littoral sands and eroded material from nearby sources (e.g., cliff slump). Beachrock features were observed forming at Area B. Coarse sandstone beds outcrop on the south/south-eastern end of the island (Area C), where the topography has produced an (upper) intertidal pool protecting several coral micro-atolls at the southern tip.

Figure 10. Google Earth map of Pulau Biola showing areas of interest (A-C) demarcated by white rectangles.

Area A

An erosional coastline is seen clearly on the northeast shore, evidenced by a near-vertical exposed cliff fronted by littoral sands, highly rounded dark red fine sandstone clasts and larger more angular clasts of variable size (up to gravel and occasional sub-boulder size) (Fig. 11A). These detrital clasts are predominately sourced from the rapidly eroding and retrograding sandstone outcrop (Fig. 11B).

Figure 11. (A) Northeastern shoreline of Pulau Biola showing beautiful wave-patterned sandstone exposures overtopped by vegetation. **(B)** eroded sandstone sourced from outcrop laying at cliff base. Photo credit: Stephen Chua, EOS, NTU.

The aesthetic value of Pulau Biola cannot be overstated. The undulating wavy patterns on the sandstones here in sometimes planar/laminar and others near-concentric fashion are breathtaking for any visitor. Thin decimeter to centimeter thick lines of alternating brown and white planar beds/laminations are visible across the landscape. Often chaotic patterns are seen at various junctures (Fig. 12), adding to the complexity and aesthetic value of these cliff faces.

Figure 12. Wavy fine millimetre-scale lines of alternating brown and white in chaotic, truncated patterns. Photo credit: Dr Stephen Chua, EOS, NTU.

It may be easy to interpret the sedimentary structure as layers of brown (organic-rich) and white (organic-poor) layers being deposited in a low energy environment (highly planar laminae). However as shown in Figure 12 above, the darker horizontal line bifurcates and 'flowers' moving from right to left before disappearing into white highly bleached sandstone. This provides indications that these layers are not the primary bedding structure but are instead 'imprinted' due to post-depositional diagenesis through a secondary process known as 'Liesegang banding' (e.g., Fu et al., 1994; Balsamo et al., 2013). Such staining on the original sandstone is due to leaching/percolation of iron oxides through porous sandstone, preferentially traversing through joints and fractures within the sandstone structure. This is not surprising in Singapore where our soils are generally lateritic (iron rich), derived from weathering of base granitic rock which is characterized by high iron and aluminum content (Chua et al., 2023). Similar phenomena have been observed in locations such as the Hawkesbury sandstone in Sydney and Maria Island off the east coast of Tasmania, the latter boasting of its 'Painted Cliffs' which made the island a hugely popular tourist destination.

Figure 13. Honeycomb weathering on foreshore sandstone (near upper tidal limits). Photo credit: Stephen Chua, EOS, NTU.

Honeycomb weathering (Fig. 13) is a common occurrence found in many sandstone dominated coastal areas. This extensive network of cavities ranges from millimeters to several centimetres. These beautiful features in coastal environments are potentially caused by salt weathering through evaporation of wave splash or salt crystals in saline pore water wedging mineral grains apart, coupled with possible dissolution of silicate minerals in the sandstone and exacerbated by windy conditions which promote rapid evaporation (Rodriguez-Navarro et al., 1999).

Area B

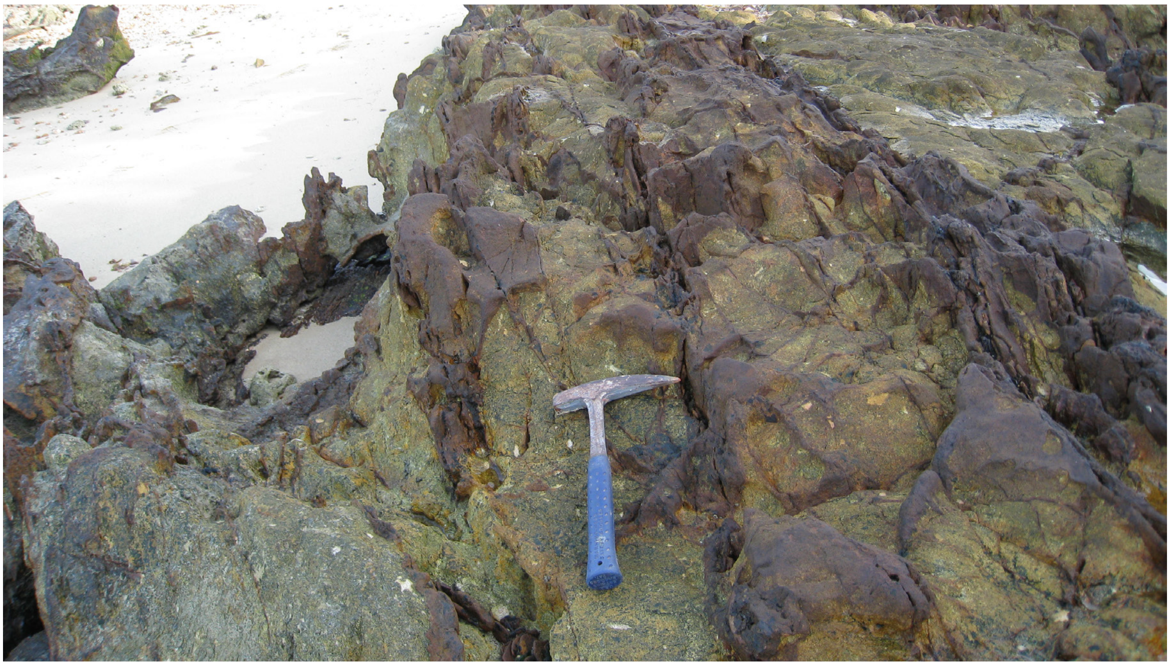

Figure 14. Near vertical-dipping coarse cross bedded sandstone outcrop. Photo credit: Dr Stephen Chua, EOS, NTU.

Like Pulau Tekukor, more resistant sandstone outcrops the intertidal and supratidal zones at the southern-southeastern part of Pulau Biola. These aerially exposed planar cross-bedded coarse sandstones appear reddish brown on the surface and mostly white/bleached underneath. These outcrops are vertically or near-vertically dipping (Fig. 14); these outcrops dip generally parallel to the orientation of Pulau Biola.

Figure 15. Sheltered tidal pool in the southern tip of Pulau Biola. Coral microatolls (Porites sp.) have been observed at higher elevations than expected due to marine ponding. Photo credit: Stephen Chua, EOS, NTU.

A tidal pool was observed at the southern tip of Pulau Biola with several coral microatolls exposed during low tide. Although not a geological feature, coral microatolls rely on the underlying strata to anchor upon and grow, typically hard rock like granite but in this case lithified sandstone. With much focus on rehabilitating corals in the Southern Islands (Guest, 2013; National Parks Board, 2023), understanding nearshore and seabed geology is critical for planning locations and type of corals at specific localities for optimal and sustainable growth. Their presence at higher elevations than expected due to marine ponding suggests that tidal pools (natural or artificial) could play an important role in restoration efforts by increasing live coral cover in the intertidal zone.

Microatolls have also been used as reliable sea-level indicators in recent years in Singapore and Southeast Asia (Meltzner et al., 2017; Majewski et al., 2018; Majewski et al., 2022) as they responded to sea-level change over the last 10,000 years (Chua et al., 2021). These corals require suitable underlying (hard) geology and preserving such important past environmental archives are critical to Singapore's sustainable development in view of current and future sea level and climate change.

Area C

Figure 16. Cemented layers of sedimentary beachrock at the (upper) intertidal zone. Photo credit: Stephen Chua, EOS, NTU.

In a small localised area in Area C, beach rock of approximately 30–50 cm in height abuts the littoral beach sands in front and teminates roughly midway to the eroding stained cliffs.

Beachrock are lithified coastal deposits formed by rapid cementing through precipiation of mainly carbonate cements consiting of calcite or aragonite (Vousdoukas et al., 2007). The pinkish-white band at the exposed base suggest cementing by calcium carbonate. Lithification is usually constrained to the (upper) intertidal zone and may involve a variety of sediments of clastic and biogenic sources. Cementation can occur as fast as within a few decades once suitable coastal morphology provides adequate accommodation space. Their close relationship to relative sea level makes beachrock a suitable sea-level indicator (Mauz et al., 2015) to complement other proxies such as mangroves and corals.

Conclusion

Pulau Tekukor and Pulau Biola fortuitously mark the eastern and western limits of the Sentosa Group. They are also rarely visited and less studied islands compared with Sentosa (Oliver and Prave, 2013) and the other southern islands (Oliver and Gupta, 2017). They provide rare glimpses into the geological richness of Singapore in a natural setting, in clear contrast to the highly urbanised and engineered mainland. Such offshore outcrops and geological features provide invaluable information on subsurface conditions upon which the buildings and infrastructure of Singapore are built. Conservation of these islands is critical to upholding key geological information and insights for the current and future generations of Singapore.

Therefore, in addition to highlighting the ecological aspects of the Southern Islands, the above mentioned elements of geological interest (of which similar features are also found on other islands such as Sisters' Islands, Sentosa, St. John's Island, Lazarus Island, Pulau Jong) should likewise be prominently featured in public outreach. Some ideas include a rock map, signage, information panels etc. which would serve to educate the public and raise awareness to protect these places as geological archives. To build local capacity for geosciences these islands could form a strong fieldwork component from secondary to undergraduate students to explore and be amazed at local geology, in sharp contrast to the common perception that "Singapore has no geological or geoscience features". The authors cannot emphasise more the need for further study of the rocks on these islands. This brief report on the two islands is a preliminary one based on short discrete surveys where the lead author had only a couple of hours to circumvent them armed with rudimentary tools of the trade. The authors hope that this chapter will inspire further in-depth studies to confirm or contradict the reported information in this chapter.

These islands are part of our geological heritage and have the potential to be part of geoparks. In particular, Pulau Biola has beautiful natural 'paintings' on its stained cliffs, while Pulau Tekukor has its own 'dragon tooth' and sand-capped erosional features, of the sort which have made locations such as Yehliu Geopark in Taiwan famous. These islands unequivocally possess great geological and educational value and should be preserved and promoted as key landmarks for future generations.

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