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Extant shore-platform stromatolite (SPS) assemblage

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Abstract. Extant peritidal, micritic stromatolites and tufa are growing discontinuously along the southeast African Indian Ocean rocky peritidal zone. Microbialites are ubiquitous on this coast but only calcify when carbonate rich groundwater is present; if horizontal surfaces (shore platforms) are present stromatolites develop, if vertical surfaces are present tufa forms. Tufa and stromatolites are end members of a spectrum dictated by coastal topography. Extant shore-platform stromatolites (SPS) occur in very high wave energy settings, often around headlands, boulder beaches and/or beach ridges, storm swash-terraces and coastal dunes. Stromatolite growth is seen on soft coastlines but the preservation potential is very low/ zero. SPS are produced by mineral precipitation, not trapping and binding. SPS are developing in a mildly transgressive siliciclastic setting. Laminar and colloform stromatolite morphologies could be preserved in the geological record as micritic lenses on a palaeo-shore platform surface. SPS share many features with Precambrian stromatolites. Terraces associated with oceanic or lacustrine flooding surfaces should not be ignored when searching for potential stromatolite deposits on Mars.

1 Introduction

Stromatolites are defined as biosedimentary structures produced by sediment trapping and binding and/ or mineral precipitation as a result of the growth and metabolic activity of Cyanobacteria (Awramik & Marguilis, 1976). The oldest known stromatolites include those of the Isua Group (3.7 Ga), Greenland (Nutman et al., 2016), the Strelley Pool occurrence (3.43 Ga), Australia (Allwood et al., 2006), the Barberton Mountain Land (3.22 Ga), South Africa (Gamper et al., 2011) and the Pongola Group (2.9 Ga), South Africa (Mason & von Bruun, 1977; Bolhar et al., 2015). Comparison of conditions in which extant and sub-fossil stromatolites occur with ancient examples has the potential to shed light on conditions under which life originated, in what environment and whether it began on Earth or elsewhere. Conventional extant stromatolite models of Shark Bay and the Caribbean are for the trapped and bound stromatolite variety, whereas Precambrian stromatolites are of the mineral precipitation variety (Awramik & Grey, 2005; Reid et al., 2011). Extant shore-platform stromatolites (SPS) are mineral-precipitated and represent a more plausible Precambrian stromatolite analog.

Prokaryotes, which includes Cyanobacteria (the stromatolite builders) account for at least half the contemporary global biomass (Rodell et al., 2005). Prokaryotes, however, do not react well to Metazoan competition (Perissinotto et al., 2014); however, if Metazoans are not present, as was the case in most of the Precambrian, then prokaryotes should flourish. As long as there is a source of phosphorous, prokaryotes can thrive and if carbonate is present (and the pH is right) in the aqueous system carbonate stromatolites can develop.

Prokaryotes dominated the Earth during the Archaean and Proterozoic, but under contemporary conditions they can only thrive in extreme environments that limit Metozoan competition, such as geothermal springs (Jones et al., 2000; Berelsen et al., 2011) peritidal marine (Logan et al., 1964; Reid et al., 2000; Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al 2016) and salt pans (Martin & Wilczewski, 1972). Prokaryotes are also recorded from the Earth's upper crust to depths of (at least) 7km (Sankaran, 1997) and from within the atmosphere (DeLeon-Rodriguez et al., 2012).

Cape Morgan (Fig. 1) in the Eastern Cape province, South Africa, was the first peritidal marine SPS assemblage environment discovered (Mountain, 1937), although its significance was only realized later (Smith & Uken, 2003). Smith et al. (2011) proposed the extant Cape Morgan (Fig. 1) stromatolites as a partial analogue for the 3.43 Ga examples from Strelley Pool Australia. Here we further describe SPS localities on the southern African coast. This Precambrian stromatolite analogue can only be partial as the Precambrian ocean and atmospheric conditions were different, however we believe that the SPS model can be used to increase our understanding of Precambrian stromatolites.

Since the work of Smith et al. (2011), the distribution of peritidal stromatolites along the southeast African Indian Ocean Coast, has been found to be much more extensive than previously thought. SPS occurrences at Mtentu, Luphathana, Port Edward, Ballito, Tinley Manor, Richards Bay and Cape Point have not previously been reported (Fig. 1). They have now been documented from 15 locations in southern Africa (Table 1). SPS have also been recorded from Giant's Causeway, N. Ireland (Cooper et al., 2013). Their much more extensive and probable global distribution, combined with new information on SPS occurrences, provide important evidence relevant to their preservability.

The aim of this paper is to compile a record of both new and existing SPS localities and to assess their suitability as a general Precambrian analog. First, the major geomorphological elements in which SPS are present are described in order to synthesize the geomorphological and environmental context. Second, we compare them with extant stromatolites from elsewhere on the globe. Thirdly, we discuss SPS preservation potential. Fourthly, we discuss the potential of SPS as Precambrian analogs. Finally, we comment on the suitability of possible shore-platform palaeoenvironments on Mars as possible SPS sites.

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2 Location

The southeast African coastal climate varies from Tropical to Temperate (SANS, 2008). The Köppen-Geiger climate classification varies from Cfa (Warm temperate, full humid, hot summer) along the east coast to Cfb (Warm temperate, full humid, warm summer) along the south coast to Csb (Warm temperate, summer dry & warm) in the south-west (Conradie, 2012). As such, the east coast receives most of its approximate 1 000 mm rainfall during summer, whereas the southern coast receives most of its more variable 350 - 1 000 mm rainfall during winter – thus experiencing a Mediterranean climate. Winds vary from site to site but overall are generally coast-parallel, i.e. north-east and south-west in roughly equal proportions on the east coast; however in the south-western Cape, north-west and south-east winds predominate.

The southern African coast is wave-dominated. Evidence suggests that the KwaZulu-Natal (KZN) coast is impacted by very large swells (Hs > 8m) approximately every 20 years (Smith et al., 2013). Wave power and swell heights generally increase southwards from Tofo to Cape Point (Fig. 1). Few rivers debauch into the ocean; those that do form wave-dominated deltas or lagoons in the case of the smaller rivers. This results in an environment which is generally low in silt. The coast comprises both rocky and sandy reaches. Beachrock and aeolianite outcrops are also present. Competent, discordant rocky reaches commonly form the headlands of log spiral-, headland-bound- and pocket- bays. Sandy beaches are often located within these coastal embayments, many of which are associated with contemporary river valleys. Rocky reaches are characterized by shore platforms which are associated with SPS (Fig. 1; Table 1).

The southeast African coastline is tectonically passive. The sea level has risen 125 m since the end of the last glacial maximum (Ramsay & Cooper, 2002) and is subject to thermal-expansion sea-level rise (SLR), currently measured at 2.7mm (Mather et al., 2009) and 1.23 mm/yr (http://tidesandcurrents.noaa.gov/sltrends/sltrends.html) for Durban, and 2.39mm/yr for Port Elizabeth, on which both references agree (Fig. 1). Overall the effect of SLR is masked by seasonal and multi-annual high water line position variation (Smith et al., 2016).

A number of SPS locations have been reported along the southeast African coastline (Smith & Uken, 2003; Perissinotto et al., 2014; Rishworth et al; 2016). They form within the peritidal zone where suitable (carbonate-rich) terrestrial runoff is present (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016). The supratidal/ high intertidal zone experiences extreme changes, which partially excludes Metazoans (Perissinotto et al., 2014; Rishworth et al., 2016) and enables prokaryotes to dominate. SPS location coordinates and source data are given in Table 1.

3 Methodology

In this paper a description of the physical, oceanographic and climatological setting is followed by an account of the lithological and geomorphological setting in which SPS grow. Various extant and sub-fossil peritidal SPS sites were sampled and analyzed using a Zeiss, Ultra Plus FE SEM (field emission scanning electron microscope).

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We compare SPS to the stromatolites from Hamelin Pool, W. Australia (Logan et al., 1964), those from Kuwait (Alshuaibi et al 2015), the Bahamas (Reid et al., 2000), the Dutch North Sea (Kremer et al., 2008) and the Giant's Causeway, N. Ireland (Cooper et al., 2013). We then discuss SPS preservation potential in the geological record. Then we compare SPS with Precambrian examples from the literature. On the basis of our findings we also make recommendations as to where stromatolites might be found on Mars.

4 Results

The entire coastline has not been surveyed but most of the rocky stretches investigated contain SPS to varying degrees. We add several new SPS colony locations (Table 1). SPS occur discontinuously along a 2 300 km stretch of coastline. They are climatically independent and grow in Tropical to Mediterranean environments. SPS are often associated with tufa but the proportions vary with the coastal geomorphology. If the coastline is cliffed or dominated by vertical surfaces, tufa dominates (Fig. 2A), whereas SPS occurs within rock pools on competent shore-platforms. There is a clear horizontal gradation from tufa to stromatolites. SPS occurs as both the trapped and bound variety (very rare) and the mineral precipitated form.

The colonies (Table 1; Fig. 1) are growing in shallow potholes, chemically- or mechanically- produced pools and barrage pools (see: Forbes et al., 2010) constructed by stromatolite growth on shore platforms (Fig. 2), and in rare instances on unconsolidated beach sediment. The water in the shore-platform pools varies from fresh to hyper saline (Smith et al., 2011; Perissinotto et al., 2014) depending on the wave climate and weather conditions operating at any given time. Elevated water temperatures, as much as 10º C above ambient environmental, have been recorded from Cape Morgan, Luphatana and Richards Bay, indicating warm thermal spring activity (Smith et al., 2011) and proving a groundwater source component. When unmixed, these warm waters occur at the base of pools, separated from the overlying water by an obvious thermocline. SPS growth is absent below the thermocline (Smith & Uken, 2003). Tufa and three depth-controlled, stromatolite morphologies are present (Fig. 3D) (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016). These zones consist of the following:

- I Tufa curtains often coat vertical rock surfaces. These are 1-3m high and vary from a few centimetres to a metre thick (Fig. 2A).
- II Partially emergent pustular stromatolites occur in the subareal wet area around pools and seeps (Fig. 2B). This form may occur as mounds up to a few centimetres above pool rims and in very shallow water. At some localities (eg Luphatana and Mtentu: Fig. 1) the pustular stromatolite variety is not present. This stromatolite form appears to be a link between stromatolites and tufa (Fig. 2B, C & D).
- III Subaqueous laminar and columnar stromatolites (1-10cm high) occur in shallow water (Fig. 2B). The laminar stromatolite morphology is particularly common in the wind-shadow margins of pools.
- IV In deeper pools (20 – 30 cm depth) colloform stromatolite morphology is present (Fig. 2B).

No growth occurs in pools below the thermocline, if one is present.

4.1 Trapped & Bound Stromatolites

Trapped and bound stromatolites are very rare and have only been observed at Cape Morgan (Fig. 2C). This type occurs at points of strong groundwater input (Smith et al., 2011). Three varieties of trapped & bound stromatolites are observed:

- Rare examples of trapped and bound stromatolites are found in beach gravel between rocky reaches. The grains involved vary from fine to coarse.

- A stromatolite cemented beach pebble conglomerate is recorded from Cape Morgan (Smith et al., 2011). In this case a storm beach deposit (6-10 cm thick) is "bound" between two mineralized laminar stromatolites.

- A headland conglomerate has been formed at Cape Morgan by stromatolite cementation of dolerite boulders (Smith et al., 2005). Some of these boulders have been disaggregated and re-cemented into the conglomerate (Fig. 2D).

4.2 Mineral Precipitated Stromatolites

At all localities (Table 1) thin (1-10 cm thick) crusts of mineral-precipitated stromatolites are present. All examples are developing within rock pools and potholes (Fig. 2c & D). Where vertical surfaces are present, tufa forms and conversely, where a well developed shore platform is present, such as at Mtentu and Luphatana, only SPS is present.

SPS growth zones are related to water physico-chemistry, calcification and limited to salinity values of <20 psu (generally 2– 10 psu) (Smith et al., 2011; Perissinotto et al., 2014). In areas where groundwater discharge is very strong coralline red algae may alternate with tufa growth in the lower part of the intertidal zone. Stromatolites may cease growing, desiccate, and then regrow forming erosion surfaces. Growth cessation may be due to "self" blocking of the water conduit by stromatolite growth or wave erosion.

SPS are highly colourful during bloom (Fig. 2B), but become white on desiccation to a micrite crust. Stromatolite samples from Cape Morgan, Luphatana, Mtentu, Ballito and Tofo were examined using a Zeiss, Ultra Plus FE SEM (field emission scanning electron microscope). This investigation clearly showed the presence of stromatolite lamination and Cyanobacteria filaments in both the growing and sub-fossil samples (Fig. 3). The stromatolite lamination seen in a calcified specimen is an alternation of thicker lamina characterized by vertically orientated sub-fossil Cyanobacterial filaments (Fig.3D). In contrast to the growing microbialite, no climax lamination (Reid et al., 2000; Smith et al., 2005) was observed in the calcified SPS form.

4.3 SPS Lithological & Geomorphological Assemblage

Shore platforms in the study area vary from 5 to 60 m wide and are generally backed by a boulder beach or beach ridges (Fig. 4). The SPS exposures often occur on Capes that extend into the ocean. The boulder ridges generally contain angular blocks and megaclasts, as opposed to the smaller (~ 50cm diameter) rounded boulders found within intertidal and subtidal gullies dissecting the shore-platforms. This geomorphological setting is backed by a prominent storm swash terrace (see: McKenna et al., 2012; Dixon et al., 2015) on the landward side, from which groundwater emanates (Smith et al., 2011; Rishworth et al., 2016). The storm swash terrace may partially bury older beach ridges. Storm swash terraces are constructed by marine storm deposition, but are then liable to modification and leaching by terrestrial runoff (McKenna et al., 2012). This environment may be capped by coastal dune cordons (Table 2). The geomorphology of each shore platform is controlled by lithology, jointing and bedding style. The Cape Recife to Storms River examples have been well-described in terms of biology (Perissinotto et al. 2014; Rishworth et al., 2016; 2017), but not in terms of geology and geomorphology, however perusal of the literature and geological maps suggests growth in a similar geomorphological setting to elsewhere (Table 2). Shore-platforms comprised of many competent lithologies have been observed. Where the coast comprises incompetent material no platforms can form.

- Competent Sandstones form wide shore-platforms (Fig. 4A; Table 2). Although several examples are recorded in Table 2, those of the Ordovician Nardouw Sandstone have not been adequately described in the literature. However at Cape Point this sandstone is strongly indurated. The SPS bearing shore-platforms at Mtentu and Luphatana (Fig. 1; Table 2) are formed in well-indurated Lower Devonian Msikaba Formation sandstone. The Msikaba Formation is well-bedded (more-or-less horizontal) and vertically jointed. The shore-platform has been formed by wave quarrying of large blocks, which break along bedding and joint planes. The eroded boulders have accumulated in a boulder ridge at the rear of the platform (Fig. 6). SPS occurs in pools on the shore platform.

- Tufa is the main component at Tofo and the shore-platform has been excavated into this lithology (Fig. 4C). Thin (1-2cm thick) sub-fossil stromatolites (Table 2) are interbedded. Sub-fossil mineral precipitated stromatolites are also found as upper intertidal and supra tidal pothole linings. No growing tufa or stromatolites are present. The Tofo sub-fossil stromatolites are within contemporary potholes on an active shore-platform indicating that they are Recent. The tufa is backed by an extensive coastal dune cordon, strongly impacted by urbanization.

- Dolerite Sill Shore Platforms: This type is seen at Tinley Manor (Fig. 4D), Ballito and Cape Morgan; the latter being the best example (Table 2). The dolerite is strongly jointed and forms a rugged shore platform. The platform itself tends to undulate and shows minor sea cliffs and pools. The former are produced by wave bore quarrying of blocks along joint surfaces. Pools are formed by mechanical joint widening, pot-holing and chemical weathering while barrage pools are impounded by stromatolite growth (Fig. 2C & 5). Stromatolites (of the mineral precipitation variety) and tufa (which dominates) are present.

- At Port Edward (Fig. 1) granite forms a poorly developed shore platform littered with megaclasts and backed by a storm swash terrace. Minor SPS and tufa examples were noted near the storm surge terrace and shore-platform boundary.

- At Richards Bay the coastline is marked by the semi-indurated Pleistocene Port Durnford Beds (Fig. 1). These comprise muds, silts and fine sands. The shore platform is poorly developed and backed by a retreating coastal cliff comprised of poorly-consolidated sediments. Tufa is present growing on the cliff face with only traces of SPS.

- Microbialite coatings on back-beach sands, the lower parts of marine-scarped storm swash terraces and scarped coastal dunes is relatively common. However these occurrences appear to have no preservability potential.

4.4 Response to High-Swell Events

The study area is subject to modally high wave conditions. Extreme waves, however, exceed modal conditions by several metres. Extreme waves on this coast originate from extra tropical low pressure systems, tropical storms/ cyclones and, potentially, tsunamis. The coast of Mozambique is frequently impacted by Tropical Storms and Tropical Cyclones; 152 such storms were recorded during the period: 1952-2007 (Mavume et al., 2009). One of the more recent was the category 4 Tropical Cyclone Japhet which made landfall some 200km north of Tofo. The most recent was Tropical Storm Dineo (February, 2017) which produced 6m waves at Tofo (http://www.aljazeera.com/news/2017/02/tropical-storm-dineo-hits-mozambique-170216105245838.html). A swell with H_s=8.5m was generated by Tropical Storm Imboa on the KZN north coast in early 1984 (Guastella & Rossouw, 2012). Another noteworthy high swell event on 18-20 March 2007 (impacts ranged from Port Elizabeth to Maputo) (Fig. 1), was produced by a cut-off-low pressure system. This event produced swells up to 14m high (H_s=8.5m) and had run-ups of 7-11m amsl which heavily impacted the coast (Smith et al., 2007). A further high swell event between 31st August and the 1st September 2008 impacted the southern and southeast African coast, from Cape Point to Cape Morgan (Fig. 1). This swell was generated by an extremely deep low pressure system and produced swells of H_s= 10.7m (Guastella and Rossouw, 2012) with a 7-8m run-up which resulted in considerable coastal flooding at Cape Morgan, Port Elizabeth (Smith et al., 2014).

Field inspection following both the March (2007) and September (2008) high swell events indicated changes to the Cape Morgan colonies (the other colonies were unknown at this time). In the case of both storms, growing and unconsolidated microbial mat was largely removed by wave action, but stromatolites remained on the shore-platform. Large blocks of tufa

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were removed by the high swell impact. Following the March 2007 event, surface stromatolite growth at Cape Morgan had been largely restored by January 2008. Observations were not made until years after the September 2008 event by which time no wave impact was evident. In neither case do we know whether remaining Cyanobacteria recolonized this environment or whether it was re-supplied with Cyanobacteria from elsewhere.

At Ballito (Fig. 1), sub-fossil peritidal stromatolites that had been buried under coastal reclamation were exposed by erosion following the 2007 high swell event. These crusts were cemented to a dolerite shore platform 30m wide (Fig. 1). Small colonies of extant stromatolites were noted within peritidal dolerite rock pools at Tinley Manor, 10 km north of Ballito. Dolerite boulders up to 1m in diameter where deposited within a boulder beach by this event. This locality showed a thin crust of sub-fossil stromatolites extending landward under the boulder beach and storm swash terrace. As of 2016, this location now shows small colonies of growing SPS fed by active springs emanating from the highly urbanized storm surge terrace.

5 Discussion

SPS grow within shallow rock pools (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016) potholes and SPS dammed barrage pools (Forbes et al., 2010; Perissinotto et al., 2014). They are dominantly thin micritic crusts, with only rare trapping and binding stromatolite varieties. Not all localities show the complete tripartite stromatolite morphology (Fig. 3B) but the subaqueous laminar and columnar and the colloform variety (in deeper water) is ubiquitous. SPS can withstand the effect of waves in excess of 14m (Smith et al., 2007) and probably much higher. However, the gauged swell record is very short; the longest record is for Richards Bay which begins in 1979. Boulder size analysis from the northern KZN coast yielded an H_s estimate of 11.36 m, but the date and frequency of this inferred event is unknown (Salzmann & Green, 2012). Further, the Luphatana extant colony is located just in front of a boulder ridge which contains 80 ton boulders, indicative of extreme waves, the parameters of which are as yet unquantified. Similarly the St Johns Point and Giant's Causeway, N. Ireland stromatolites (Cooper et al., 2013) are both associated with very large boulders. Wave spray deposits have been found at levels of 60m amsl at Cape Morgan (Smith et al., 2014). This shows that the extant stromatolites can withstand the present wave climate extremes.

Any SPS model must take into account that they are forming at the interface of freshwater seeps and a high energy rocky peritidal zone (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016). They are carbonate due to the high pH regime (Smith et al., 2011), and growing on older siliceous rocks (Tofo is an exception) within a siliciclastic contemporary setting. Microbialites are ubiquitous in the peritidal setting but only become stromatolites if a carbonate rich groundwater plume is present (Smith et al., 2011; Rishworth et al., 2016). The following points also need to be considered, although they may, or may not, be necessary for SPS growth

SPS possess seasonal to sub-seasonal (due to storm abrasion) laminae (Smith et al., 2005). The lack of climax lamination in the calcified form may be due to storm activity or non-calcification of this lamina type. Warm thermal ground water may be present indicating a groundwater source. The SPS hinterland is very steep and supports braided streams and thin soils. Sea level rise is ongoing SLR (Mather et al., 2009; http://tidesandcurrents.noaa.gov/sltrends/sltrends.html). The stromatolites and shore-platform contact is an unconformity.

The diversity of substrates suggests that lithology is not important for SPS growth; however, the competency of the substrate is vital for potential preservation. Tufa deposits and pustular stromatolite deposits are very unlikely to survive transgression or regression as there is no accommodation space. Barrage pool build ups can form a layer of stromatolite which could then be overstepped during marine tansgression and preserved in the stratigraphy. Marine processes may break up the stromatolite and free stromatolite crusted boulders from barrage and rock pools, such as is seen at Cape Morgan (Fig. 2A), and transport them as littoral drift and deposition elsewhere. As SLR is taking place on this coast, such deposits could form as part of a transgressive coastal sequence.

The best opportunity for preservation is provided by rock pools, especially potholes, in competent shore-platform rock as this provides accommodation space. SPS growth itself could seal the SPS deposit, especially in flat bedded competent sandstone as at Mtentu and Luphatana. Thus SPS environments could be preserved as lenses on palaeo-shore-platforms. Former sea level still-stand localities should be investigated for preserved SPS deposits. The extant stromatolite regrowth which has taken place at Ballito (Fig. 1) suggests that preservation can take place. A submarine investigation of subaqueous post-last glacial maximum coastlines might resolve this issue.

5.1 Global Extant Stromatolites

There are several important differences between the SPS described here and other, well known extant stromatolite occurrences (Table 3). Variations on the Hamelin Pool theme are generally used for artists' conceptions of the *Archaean*, however this instance is unusual as it has restricted ocean access, high evaporation and is consequently hypersaline (Logan et al., 1964). The Highborne Cay, Bahamas sub-tidal model is characterized by columnar stromatolites within an ooid shoal (Reid et al., 1995; Visscher et al., 1998; Baumgartner et al., 2009). Both of these extant stromatolite settings contain stromatolites produced by trapping and binding within a soft coastal setting. These may leave traces such as MISS (Noffke and Awramik, 2013) but are unlikely to be preserved in the long-term.

Kremer et al (2008) found calcium carbonate being precipitated within annual Cyanobacterial mats in beaches of the Dutch North Sea, but again these were of the trapped and bound form, as opposed to mineral precipitation. The Kuwait examples (Alshuaibi et al., 2015), however, are of the mineral precipitation form, but as they are developed on beachrock are unlikely to be preserved. In the case of stromatolites growing on soft sediment coastlines, very rapid induration would be required for preservation.

5.2 Precambrian Stromatolites

Precambrian stromatolites are commonly found to have developed in transgressive settings on varying substrates (Table 4). Erosion surfaces are common within them (Kranendonke (2011; Nutman et al., 2016) as is the case with SPS. In the case of Strelley Pool (Australia), stromatolites formed initially on a rocky shore-platform (Allwood et al., 2006), which compares well with SPS (Table 4). It remains possible that tufa was associated with Precambrian examples, but has not been preserved due to a lack of accommodation space. Most Precambrian stromatolites formed on soft coastlines (Table 4). This would have required both extremely rapid microbial growth and very rapid sediment induration for preservation, processes that do no not respond fast enough on the present southern African coastline. It is doubtful whether a simple absence of Metazoans in the Precambrian, as has recently been questioned (Rishworth et al., 2016b), could accomplish this. Perhaps the Precambrian marine climate was markedly less aggressive than at present.

It has been suggested that no adequate marine extant stromatolite analogue exists for the marine Precambrian mineral precipitated stromatolites, as most modern marine extant stromatolites are of the trapped and bound variety (Awramik & Grey., 2005).The micrite SPS deposits close this gap. Most Precambrian stromatolites formed in a transgressive setting, similar to the SPS (Table 4). Further, SPS are thin micritic crusts, similar to most Precambrian stromatolites (Awramik & Riding, 1988). In the Strelley Pool case, Member- 1 (boulder conglomerate associated with stromatolite) rests on a palaeo-shore platform (Table 4) suggesting this to be a palaeo-SPS example. The peritidal stromatolite setting is a common theme for Precambrian stromatolites; although intertidal and subtidal components are also present (Table 4). The SPS setting shows only a stunted intertidal and no subtidal component. Microbialite develops in this crack between terrestrial and marine influence where Metazoans are reduced by the extreme nature of this setting. If the ground water chemistry is suitable, SPS can form. It is easy to imagine how the SPS environment would unfold if Metazoan activity was reduced or not present, as was the case in the Precambrian; this would allow large subtidal stromatolites, such as those in the Malmani Dolomite (Sumner & Grotzinger, 2004) (Table 4) to develop. SPS are growing during a mild transgression, thus their preservability at the present time is probably low. However, should SLR accelerate in the future, it is possible that this environment could be overstepped and preserved as rock pool and pothole fills. The lower colloform and laminar stromatolite variety are more likely to be preserved and the tufa not at all.

5.3 Extraterrestrial Implications

Phosphorous on Mars is commoner than on Earth (Greenwood et al., 2007) so it is reasonable to expect that stromatolites would have formed if life (as we know it) was ever present and the water chemistry was suitable. On Mars, marine and lacustrine flooding surfaces should be investigated. Palaeoshore-platforms, especially if associated with megaclast fields or ridges should be investigated. Although none have ever been reported (Banfield et al., 2015) as yet, the terrain at Chryse Planitia and Arabia Terra, which bordered the postulated Vastitas Borealis ocean, (Wilson et al., 2016, Rodriguez at al, 2016), could be shore platform candidates and should be targets for stromatolite investigation. Recently Ruff & Farmer (2016) suggested that structures in the Ma'Adim terraces within the Gusev Crater are siliceous stromatolites. These terraces may have been formed by wave action in the *Gusev Palaeolake* or at the margin of the *Great Northern Ocean*. The proposed siliceous stromatolites around "Home Plate" (Ruff & Farmer, 2016) were previously interpreted as hydrothermal deposits (Squyres et al., 2008), but this does not preclude them being stromatolites. It is possible that these features are extraterrestrial palaeo-SPS.

6 Conclusions

Extant and sub-fossil mineral-precipitated stromatolites are present on rocky reaches of the very high energy, southern African coastline from Mozambique to Cape Point. This environment extends from a Tropical to a Mediterranean climate. Stromatolites are found on contemporary shore-platforms produced in highly competent lithologies, generally backed by boulder ridges and storm swash terraces. If vertical surfaces (metre-scale sea cliffs) are present on the shore platform, tufa forms. SPS are growing within shallow pools on shore-platforms. They are growing within a transgressive coastal setting, as was the case with many Precambrian stromatolites. The preservability of these micrite stromatolites is probably low, but will improve with stromatolite cementation to competent substrate rock. Contemporary rocky and Quaternary coastlines should be investigated globally for the SPS environment. The SPS setting is a valid analogue for the Archaean Strelley Pool Archaean stromatolite occurrence, however most Precambrian stromatolites appear to have formed on soft coastlines, but this seems improbable under the present wave climate. Shore-platform settings should be targets in the search for Martian stromatolites.

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LOCATION	COORD (S)	COORD (E)	STATUS	SOURCE
Cape Point	34º 20' 48.42"Ss	18º 27' 48.16"E	Extant	This study
Storms River	34º 10' 34"	24º 39' 46" E	Extant	Perissinotto et al. (2014)
Oyster Bay	34º 11' 25.07" S	24º 41' 43.76" E	Extant	Perissinotto et al. (2014))
Cape St Francis	34º 12' 49" S	24º 50' 04" E	Extant	Perissinotto et al. (2014)
Seaview	34º_01' 03.16" S	25º_21' 56.48" E	Extant	Perissinotto et al. (2014))
Skoenmakerskop	34º_02' 28.23" S	25º_32' 18.60" E	Extant	Perissinotto et al. (2014)
Cape Recife	34º_02' 42.13" S	25º_34' 07.50" E	Extant	Smith et al (2011)
Cape Morgan	32º 41' 36" S	28º 22' 27" E	Extant	Smith & Uken (2003)
Luphatana	31º 25' 10" S	29º 51' 30" E	Extant	This study
Mtentu	31º 14' 30" S	31º 03' 22" E	Extant	This study
Port Edward	31º 02' 55.26" S	30º 13 '47.79" E	Extant	This study
Ballito	29º 32' 15" S	31º 13' 20" E	Sub-fossil	Smith et al. (2011)
Tinley Manor	29º 26' 43.98"S	31º 17' 26.99"E	Extant	This study
Richards Bay	28º 46' 15.20"S	32º 08' 00.32"E	Extant	This study
Tofo	23º 41' 26" S	35º 33' 04" E	Sub-fossil	Smith et al. (2011)

Table 1: SPS occurrences in southeast Africa, see Figure 1 for locations.

LOCATION	# SST °C	SHORE PLAT	ROCK POOLS	STROM	TUFA	*SP LITHOLOGY	*SP AGE	BEDROCK STATUS	BOULDERS PRESENT	STORM-SURGE TERRACE	COASTAL DUNES
Cape Point	8-15	√	√	√	√	Sandstone (Nardou)	Ordovician	v.indurated	Boulder beach	√	√
Storms River	15.5-19.5	√	√	√	?	Sandstone (Nardou)	Ordovician	v.indurated	Boulder Ridge	N/R	√
Oyster Bay	16-18	√	√	√	?	S/Stone (Nardou)	Ordovician	v.indurated	N/R	N/R	√
St Francis	16-20.5	√	√	√	?	S/Stone (Nardou)	Ordovician	v.indurated	N/R	N/R	√
Seaview	16-20	√	√	√	√	S/Stone (Nardou)	Ordovician	v.indurated	N/R	N/R	?
Skoenmakerskop	16-23	√	√	√	√	S/Stone (Nardou)	Ordovician	v.indurated	N/R	N/R	?
Cape Recife	16-23	√	√	√	?	S/Stone (Nardou)	Ordovician	v.indurated	N/R	N/R	?
Cape Morgan	17.5-20.5	√	√	√	√	Dolerite	Jurassic	Fresh	Boulder Ridge	√	√
Luphatana	19-22.5	√	√	√	X	S/Stone (Msikaba)	L Devonian	v.indurated	Boulder Ridge	√	√
Mtentu	19-22.5	√	√	√	X	S/Stone (Msikaba)	L Devonian	v.indurated	Boulder Ridge	√	√
Port Edward	19.5-23	√	√	√	X	Granite	1.1 Ga	Fresh	Boulder Ridge	√	Urbanised
Ballito	20.5-24.5	√	√	√	X	Dolerite	Jurassic	Fresh	Storm Beach	√	Urbanised
Tinley Manor	20.5-24.5	√	√	√	X	Dolerite	Jurassic	Fresh	Storm Beach	√	Urbanised
Richards Bay	20-24.5	X	X	X	√	Pt Durnford Fm	Pleistocene	muds, silts, F/sst	Storm Beach	X	√
Tofo (sub-fossil)	22-29	√	√	√	X	Tufa	Pleistocene	Tufa	Storm Beach	X	Semi-urbanised
[1]SW W.Australia	15-22	√	?	√	√	Limestone/ Granite	Pleistocene Limestone/ Granite (540-780 Ma)	Fresh	Storm Beach	?	?
[2]Giants Causeway, N. Ireland	7.9-15.3	√	√	√	X	Basalt	Cretaceous	Fresh	Storm Beach	√	√
St John's Point, N. Ireland	7.4-15.4	?	√	√	?	Limestone	Lower Carboniferous	Fresh	Storm Beach	√	?
[3]Kuwait	13.3-32.3	√	?	√	X	Beach Rock	Late Quaternary	Fresh	No	X	?
[4]N. Sea	?	X	X	√	X	X	Beach Sand	none	X	X	?

*SP: Shore Platform; # Smit et al. (2013); [1] Forbes et al. (2010); [2]Giants Causeway, N. Ireland; [3]Alshuaibi et al. (2015); [4]Kremer et al. (2008); N/R not recorded.

Table2: SPS assemblage physical aspects compared with other global occurrences.

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LOCATION	SOURCE	SETTING	ENERGY LEVEL	STROM TYPE
Hamlin Pool	Logan et al. (1964)	Carbonate, Sub-supratidal, Soft substrate	Low	Trapping/Binding
Highborne Cay	Reid et al. (1995)	Carbonate, Subtidal, Soft substrate	Low	Trapping/ binding
Kuwait	Alshuaibi et al. (2015)	Carbonate, Intertidal, Crusts on beach rock	Low	Mineral precipitation
Dutch North Sea	Kremmer et al. (2008)	Soft siliiciclastic shoreline	High	Trapping/ Binding
SPS	Smith & Uken (2003)	Shore-platform (Table 2)	Very high	Mineral precipitation

Table 3: Comparison of SPS with other extant stromatolites.

ROCK UNIT	AGE (Ga)	ENERGY	TIDAL REGIME	COAST	SUNSTRATE	TRANSGRESSION	SOURCE
Isua Group Greenland	3.7	?	Shallow marine	Soft?	Metacarbonate	?	Nutman et al. (2016)
Strelley Pool Chert	3.43	Hi	Peritidal	Rocky (SPS)	Jasper banded black chert; potholes	Transgression	Allwood et al., (2006)
Josefsdal Chert	3.5-3.3	Hi	peritidal	Soft?	Volcanic seds / Hydrothermal spring source	?	Westall et al (2006)
Moodies Group	3.22	Med	Inter to subtidal	Soft (gravelly)	Sand	Transgression	Gamper et al (2011) Ericksson et al (2006)
Pongola Group	2.9	Low	Inter-to-subtidal	Soft?	Sand	Transgression?	Mason & Von Bruun (1979) Bolhar et al. (2015)
Malmani Dolomite	2.56-2.52	Low-Hi	Peritidal to deep subtidal-	Soft?	Variable	Transgression?	Sumner & Grotzinger (2004)
Turee Creek Group, Western Australia?	2.45–2.22 Ga	Hi	Sub-tidal	Soft?	Sandy siliciclastic/ carbonate	Progradation	Martindale et al (2015)
Ferriman Group	1.88	?	Peritidal	?	?	?	Edwards et al. (2012)
SPS	Extant	Very Hi	Peritidal	Rocky (SPS) Soft (gravelly: v. rare)	Dolerite, Sandstone, Tufa Granite Sand & Gravel (v. rare)	Transgression	Smith & Uken (2003) Perisotimo et al. (2014)

Table 4: Comparison between SPS and Precambrian Examples. ? indicates that the specific information is not known.

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Figure 1: Locations of known Shore-Platform Extant Stromatolites.

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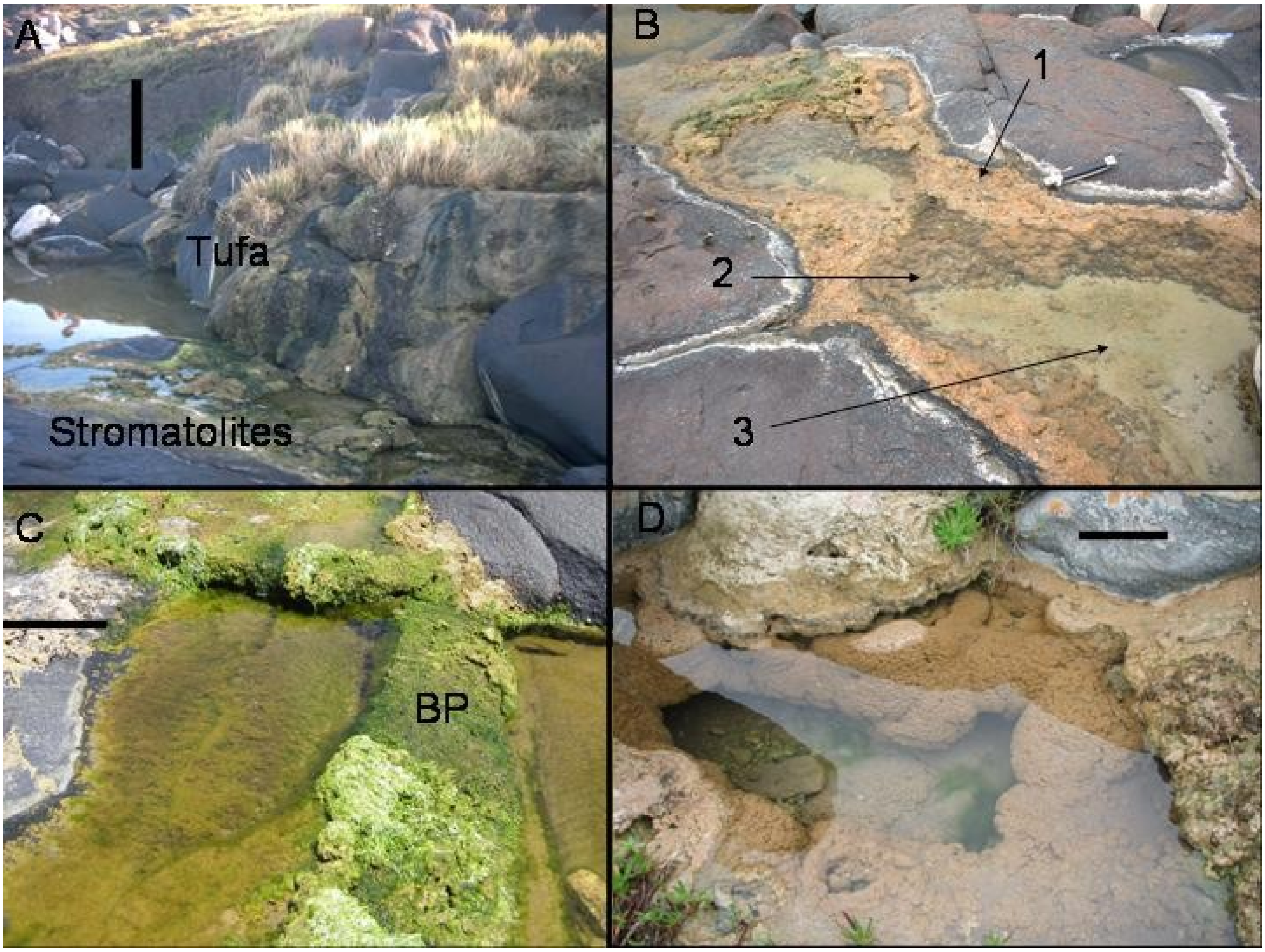

Figure 2: A: Tufa curtain grading down into stromatolites (scale bar is 1m); B: Stromatolite pool, 1: Pustular stromatolite, 2: laminar and columnar stromatolite forms and 3: Colloform stromatolites. Knife for scale is 39 cm; C: Barrage pool (BP) constructed by stromatolite growth (scale bar is 20cm) and D: Rock pool being filled by columnar stromatolites (scale bar is 20cm).

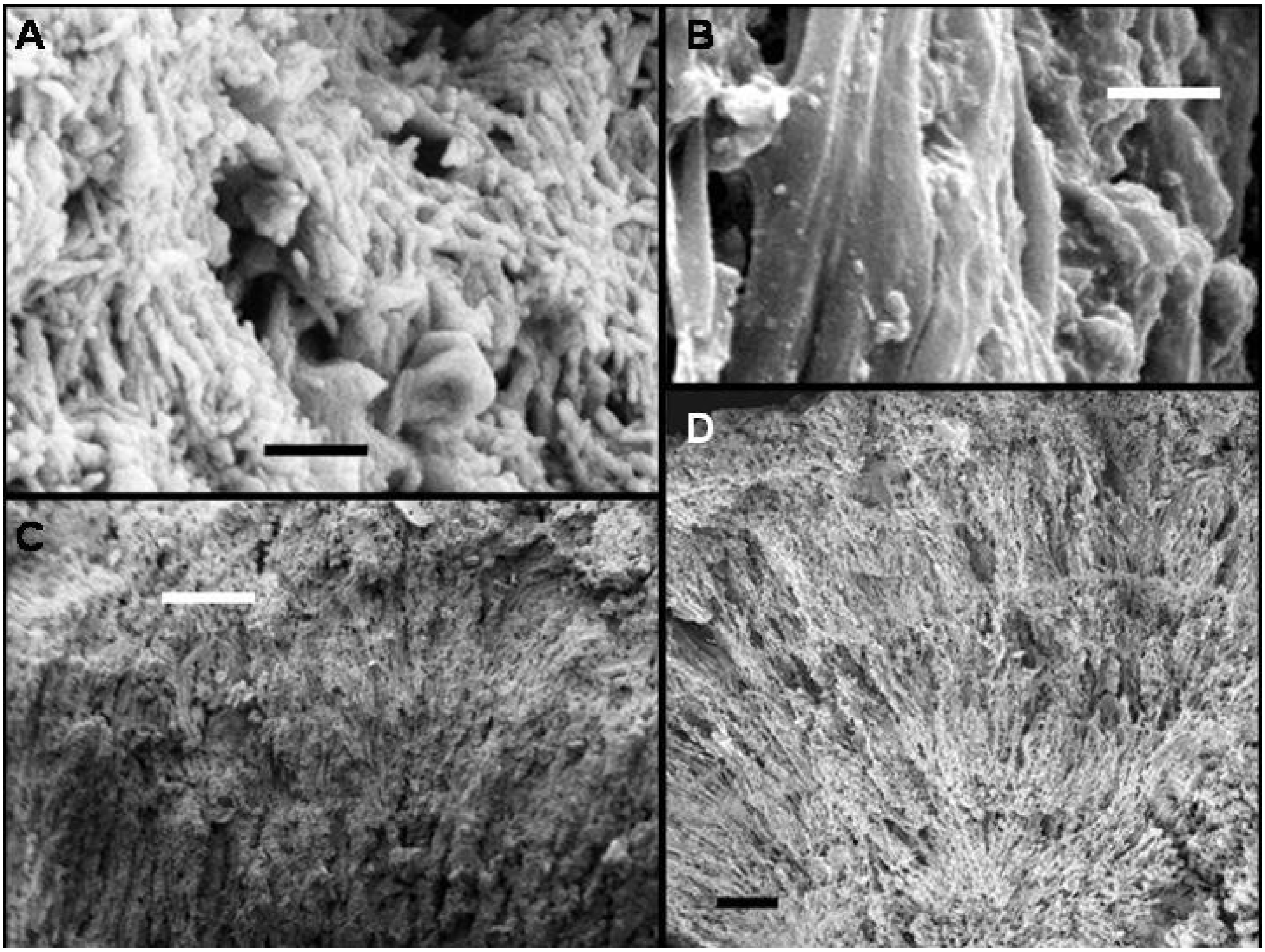

Figure 3: A: Tofo: SEM image showing fossil Cyanobacterial vertically-orientated filament bundles (scale bar is 1µ); B: Cape Morgan – showing a vertical bundle of live Cyanobacteria filaments (scale bar is 10µ); C: Ballito: Vertical filament bundles from SPS exposed following a high swell event (scale bar is 200µ); and D: Cape Morgan: Radiating cyanophyte filament fans which form part of a desiccated domical stromatolite. Scale bar is 0.6mm). Note the millimetre-scale lamina composed of sub-fossil filaments of the pioneering stage alternating with the significantly thinner (light coloured lines) representing desiccation and calcification. These laminae are seasonal or sub-seasonal (if interrupted by storm abrasion).

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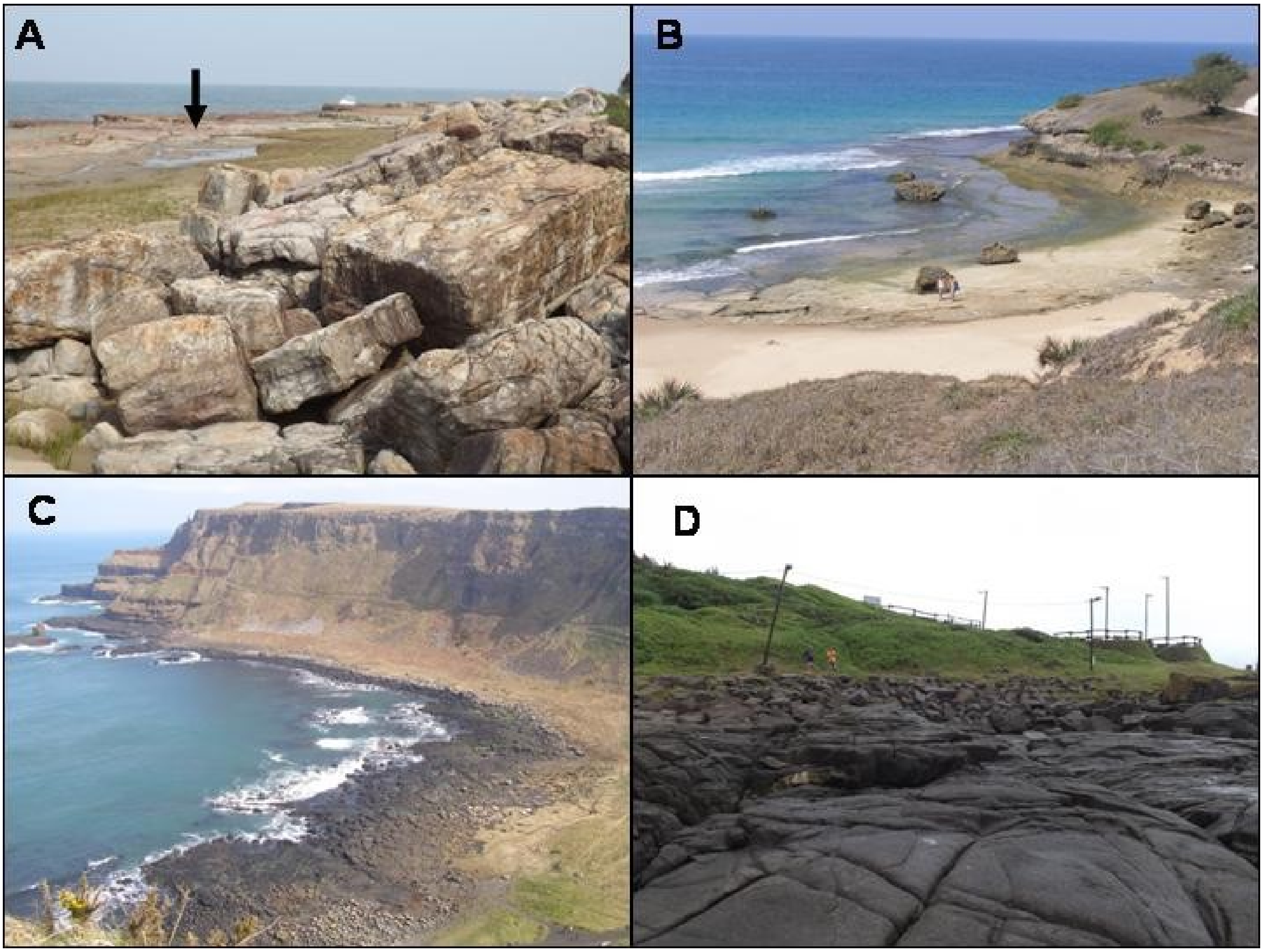

Figure 4: A: Luphatana: Stromatolites are growing in the pool (arrowed). This shore platform has been constructed by wave action unpicking the blocks and depositing them in a boulder ridge. Boulders > 80 tons are present. B: Tofo: A shore-platform has been cut in tufa. At present it is partially covered by a thin layer of sand, note the large boulders on the shore-platform. Only desiccated stromatolites were found here. C: Giant's Causeway: Extant stromatolites were recorded here by Cooper et al. (2013) and D: Tinley Manor: A small colony of stromatolites is growing on this dolerite shore-platform.

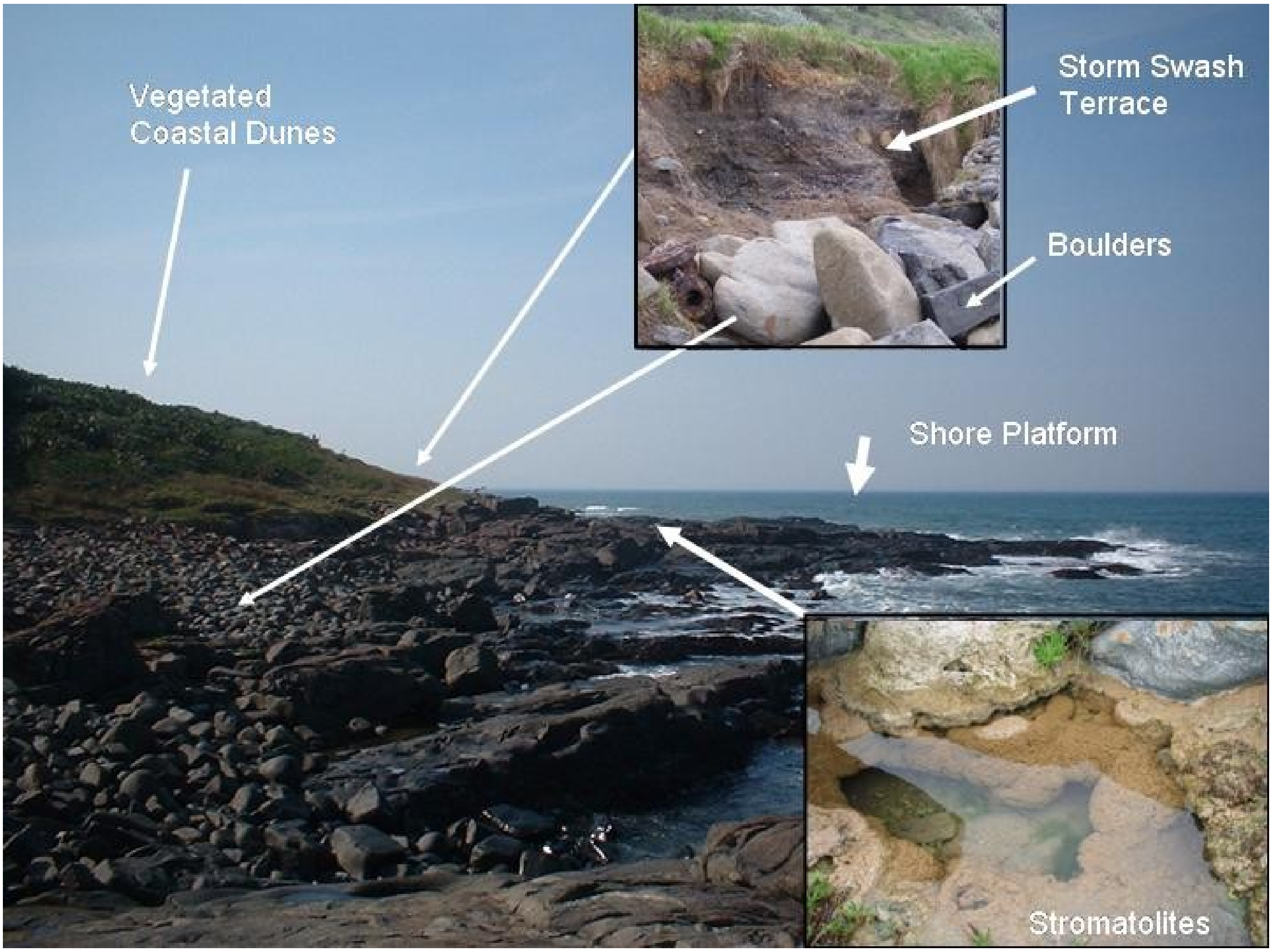

Figure 5: Cape Morgan (SPS Type Locality) showing the SPS geomorphological setting. The shore platform, boulder beach and vegetated coastal dunes are shown in the main image. The upper inset shows the storm surge terrace exposed behind the boulder beach. The lower insert shows a shallow rock pool containing growing stromatolites. Tufa, pustular, laminated and colloform varieties are present at this location.