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Topographic zonation and polycyclic pedogenesis in the northern atolls of the Chagos Archipelago, Indian Ocean

I.C. Baillie [a,*], C.N. Floyd [b], S.H. Hallett [a], R. Andrews [a]

[a] School of Water, Energy and Environment, Cranfield University, MK43 0AL, UK
[b] 1 Belfontaine, La Roque, Jersey JE3 3FP, UK

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ABSTRACT

We conducted soil surveys on two islands in the Peros Banhos and Salomon atolls of the northern Chagos Archipelago, Indian Ocean. We found muted but consistent topographic and soil zonation from the ocean shores to the lagoons. The main elements of the zonation are: berms of coral boulders and rubble along the heads of the ocean-side beaches; rubble-strewn soils inland of the berm; and pale sands with shallower topsoils and few coral clasts on slight rises and declivities over the rest of the islands. The ocean-side rubbly soils have interstitial coarse sand and are the most fertile on the islands, with dense tangled stands of unmanaged coconuts, profuse litter, and deep humic topsoils. Topsoils are shallower and less humic in the pale sands inland. Sand size decreases from ocean to lagoon, but increases with depth in most profiles. Water tables are often <2 m deep, and many soils have faint pale brownish mottling in the lower subsoils. There is a low tabular outcrop of bare Holocene coral sandstone on one of the islands. It is incised by shallow grikes that are partly infilled with silty muck, as are some small depressions in the central parts of both islands. The pedogenic environment appears to be dynamic, with storm surges depositing fresh sand, eroding coastlines, and infilling inter-island channels. Some soils have buried humic topsoils, stone layers, sand size inversions, and slight changes in sand colour, which are attributed to polycyclic pedogenesis. Some topsoils have elevated levels of total Zn, which is thought to be derived from long distance volcanic ash. Our data indicate that the soils are of low nutrient fertility. Total N and available P do not attain the strikingly eutric levels found in some atoll soils. The low fertility is attributed to the predation of seabirds by inadvertently introduced black rats. This precludes soil enrichment with marine-derived nutrients by guano deposition.

1. Introduction

Youth and the predominantly carbonatic mineralogy limit soil development on low coral islands. The weathering of coral sand and clasts generates little clay and silt, and soil textures are coarse. Cation exchange and water retention capacities are low, and mainly reside in the soil organic matter. The limited cation exchange complexes are saturated by calcium, and some of the soils have low and imbalanced nutrient fertility. The soils are highly permeable and drought-prone, even though water tables are often <2 m deep (Stone, 1953). Most of the soils have humic loam topsoils and very pale, often white, sandy subsoils that are weakly structured and variably compacted (Intes and Caillart, 1994; Kepler and Kepler, 1994; Morrison, 1990; Twyford and Wright, 1965; Wall and Hansell, 1979; Woodroffe and Morrison, 2001).

As many coral atolls lie in latitudes between 5° and 15°, they are prone to intense cyclonic storms. Single storms can be extremely powerful and can have rapid and dramatic effects on atoll configurations, island landscapes, and soils. Maragos et al. (1973) attributed the sudden appearance of an 18 km long rampart of coral rubble at Funafuti Atoll in Tuvalu to a single typhoon in 1972. Albert et al. (2016) used aerial photographs and satellite imagery to examine changes in the configurations of 33 vegetated islands in the mid-Solomons over a period of about half a century. They found that five islets had disappeared completely, and that the coastlines of six other islands had changed substantially. Storms create land, as well as remove it, and islets can be extended and fused by channel infill (Fosberg and Carroll, 1965).

The topographic activity affects soil development. Blumenstock (1958) noted almost complete gravel cover at Jaluit Atoll in the Marshall Islands after a single typhoon. Former topsoils have been buried by storm surges in the Marshall Islands (Fosberg, 1990). The occurrence of some soils with poor and apparently interrupted accumulation of total nitrogen in the northern Marshall Islands has also been attributed to storm surges (Gessell and Walker, 1992).

The wholly carbonatic mineralogy and youth of atoll regoliths can give rise to low and imbalanced nutrient fertility (Baillie et al., 2018). Thomas (2020, p3) described soils in Kiribati as ‘among the poorest in the world’. Nutrient fertility gradually improves as the soils mature on

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[*] Corresponding author.
E-mail address: i.baillie@tiscali.co.uk (I.C. Baillie).

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stable sites. Soil organic matter accumulates with time, giving concomitant increases in nitrogen status. However, the unbalanced cationic nutrient stoichiometry inherited from the coral does not change significantly, and the exchange complexes continue to be saturated with Ca, which induces deficiencies in K and possibly in Mg. However, on many coral islands the inherent infertility is partially offset by soil enrichment with N and P from seabird harvesting of marine nutrients from large areas of ocean, and their deposition in droppings under their densely gregarious roosts.

Compared with the Pacific, there are few studies of soils on atolls in the Indian Ocean (Fig. 1a). The soils of Minicoy in the Lakshadweep (Laccadive) Islands show an increase in pedogenic maturity from West to East (Vadivelu and Bandyopdahyay, 1997). These authors propose a 'coral' sub-family in the carbonatic mineralogy family of Soil Taxonomy (Soil Survey Staff, 1999). Some subsoils on the coral islands of the eastern Seychelles been enriched with ornithogenic P and have phosphatic pans (Piggott, 1968). Rendzinas have developed in aeolian coral sands on lower slopes in Mauritius (Lionnet, 1952). However, there are only generalised accounts of the soils of the Maldives (FAO, 1994), and a few brief comments on the infertility of soils in the Chagos islands (Sheppard, 2016).

We conducted soil surveys, as part of a development feasibility study (Posford Haskoning, Ltd, 2003) on two atolls in the northern Chagos Archipelago (Fig. 1b). We use the data to relate the morphological and chemical zonation of the soils to differences in the subdued topography. The possibility that some of the soils are polycyclic was examined by noting buried topsoils, sand size inversions, stone layers, and differences in subsoil Munsell colours. We examine some pedogenic implications of the trace element chemistry of the soils. We characterise the nutrient fertility of the soils and discuss the possibility that the low levels are due to rat infestation, the consequent devastation of seabird numbers, and the curtailment of soil enrichment with guano.

2. Methods

2.1. Study area

The Chagos Archipelago is located in the central Indian Ocean (Fig. 1a). It consists of low coral islands and reefs, mostly grouped in six main atolls, and the very extensive but almost completely submerged Grand Chagos Bank (Fig. 1b). The total land area is less than 100 km^2, spread over 60,000 km^2 of ocean. The archipelago is located off major shipping routes and away from large urban and industrial centres (Fig. 1a). Its waters are less polluted and its marine ecosystems less damaged than in most Indian Ocean atolls. The isolation of most of the archipelago, except for Diego Garcia in the south, was intensified by depopulation in the 1970's. Human disturbance is further reduced by the designation in 2010 of the whole archipelago and its surrounding waters as a large no-take marine reserve (Yang and Yesson, 2012; Sheppard et al., 2012). However, the marine environment has not escaped the global and regional effects of climate change, such as sea surface warming and the consequent bleaching and mortality of corals (Head et al., 2019; McClanahan et al., 2007; Pisapia et al., 2016).

Peros Banhos (PB) and Salomon (S) are the two main atolls in the northern Chagos (Fig. 1b). Peros Banhos (5^0 15′–5^0 30′ S, 71^0 25′–72^0 E) consists of a circular lagoon about 25 km in diameter, ringed by 26 named islands, the areas of which range from <10 ha to 140 ha, and many islets and reefs (Fig. 1c). Salomon Atoll (5^0 10′–5^0 22′ S, 72^0 13′–72^0 17′ E) lies about 30 km to the east, and consists of an

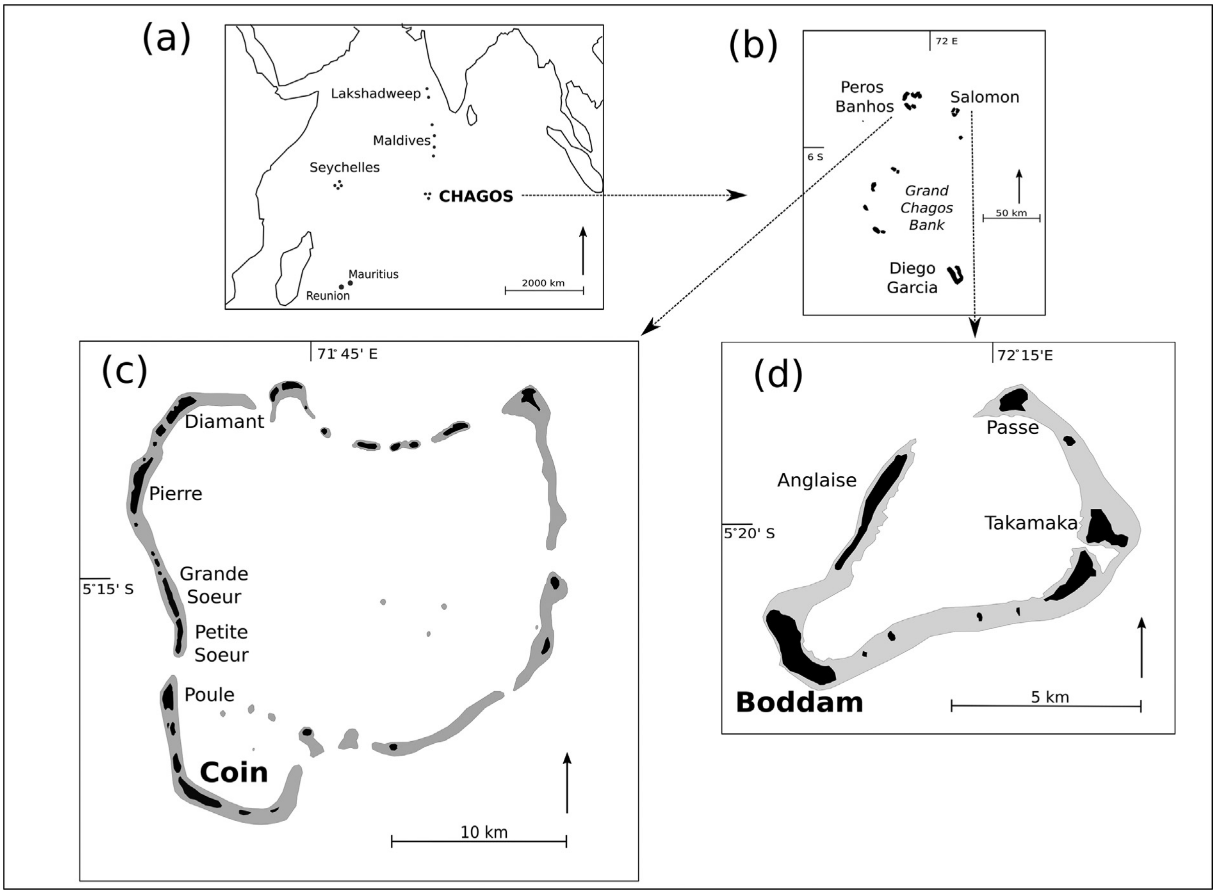

Fig. 1. Locations of: (a) Chagos Archipelago in Indian Ocean; (b) Peros Banhos and Salomon atolls in northern Chagos; (c) and (d) Islands (dark) & main reefs & shoals (light) in Peros Banhos and Salomon atolls.

8 km oval NNE-SSW lagoon, which is ringed by nine named islands, the largest of which covers about 140 ha, and many islets and reefs (Fig. 1d).

In contrast to the marine environment, human activities have severely disturbed the terrestrial ecosystems and soils on the main islands through the removal of the natural vegetation, almost total plantation with coconuts, and the inadvertent introduction of the black rat (*Rattus rattus*).

2.2. Soil survey methods

2.2.1. Field

We assessed the land resources and agricultural possibilities as part of the Posford Haskoning, Ltd (2003) multi-disciplinary study of development prospects for these atolls. We examined the soils of Ile de Coin (PB) and Ile Boddam (S), the two most promising islands (Fig. 1), at semi-detailed intensity (ca 0.3 observation.ha^{-1}) with an Edelman combination auger to depths of 1.5 m or to where stopped by rock or dense stones. The observations were sited at 50 or 100 m intervals along traverses aligned across the islands from ocean to lagoon (Figs. 2a and b). The soils of six other islands were briefly examined at <0.1 observations.ha^{-1} (Appendix C). Samples from each horizon were tested on site for electrical conductivity and pH in a 1:2.5 suspension of soil in distilled water.

2.2.2. Analytical methods

Typical soils were described in 13 pit profiles (FAO, 2001)(FAO, 2006), and samples from the main horizons were analysed at Cranfield University. Particle size distribution was determined by sieving and sedimentation after peroxidation with H_2O_2 and dispersion by sodium hexametaphosphate, and are reported on an oven-dry basis. The purity of the coral and the vigourous effervescence precluded carbonate removal with HCl. Electrical conductivity and pH were measured electrometrically in a 1:5 suspension of air-dried soil in water, and also in 1 M KCl and 0.01 M $CaCl_2$. The exchangeable cations were extracted with 1 M ammonium acetate and assayed by atomic absorption. The exchanged ammonium was extracted with potassium chloride and assayed by titration after distillation to give the cation exchange capacity. The organic carbon content was determined by Walkley-Black oxidation with acidified dichromate, and total nitrogen by Kjeldahl digestion. Calcium carbonate equivalent was determined by the volume of carbon dioxide evolved with hydrochloric acid. Available phosphorus was extracted by the Olsen method with sodium bicarbonate and assayed spectrophotometrically. Total contents of the trace elements were extracted with *aqua regia*, a mixture of concentrated hydrochloric and nitric acids, and assayed by atomic absorption (BSI, 1975, 1995; MAFF, 1986).

3. Results

3.1. Environmental setting

3.1.1. Climate

The climate of the atolls is mainly affected by the NW (December – April) and SE (June – September) trade winds. Data from Gan in the Maldives, about 500 km to the north (Fig. 1a), and from Diego Garcia, about 100 km to the south (Fig. 1b), indicate that mean air temperatures exceed 24 °C for all months, and the soil temperature regime is isohyperthermic (Soil Survey Staff, 1999). The mean annual rainfalls at both Gan and Diego Garcia are about 2700 mm (Hunt, 1997), but Peros Banhos and Salomon appear to be wetter, with annual totals possibly up to 4000 mm p.a. (Crapper et al., 2000; Posford Haskoning, Ltd, 2003). The rainfall is more or less aseasonal, and soil moisture regimes are perudic (Soil Survey Staff, 1999). The atolls lie outside the main cyclone tracks but are affected by severe storms, some of which generate surges that can overtop the islands (Posford Haskoning, Ltd, 2003).

3.1.2. Soil parent materials

The archipelago is underlain at depth by early Cenozoic volcanic rocks of the Chagos - Maldives - Laccadive Rise, which were emplaced by a northwards-migrating hotspot under the Indian Ocean crust (Bhattacharya and Chaubey, 2000). The Chagos section has been subsiding since the Palaeogene (Duncan, 1990) and the volcanics have been overgrown by 10^2–10^4 m of accreting coralgal reefs. Sea levels were considerably lower than at present during the Late Glacial Maximum (10^5–10^4 years BP), and the uppermost coral formations were subject to terrestrial weathering. Karstified remnants of the Pleistocene corals (Woodroffe et al., 1994; Woodroffe and McLean, 1998) form the roots of Peros Banhos and Salomon, and were encountered at depths of 8–20 m in drilling by the Posford Haskoning, Ltd (2003) groundwater team.

The clastic coralline deposits overlying the Pleistocene coral date from the mid-Holocene (7300–5600 years BP), when the sea levels were higher than at present. Holocene sea level has been estimated at about 3 m above current in southern India (Banerjee, 2000), but levels in the Chagos may have been even higher, with estimates of up to 6–9 m above the current level (Eisenhauer et al., 1999). Sea levels were also elevated to a lesser extent between 5200 and 4200 BP.

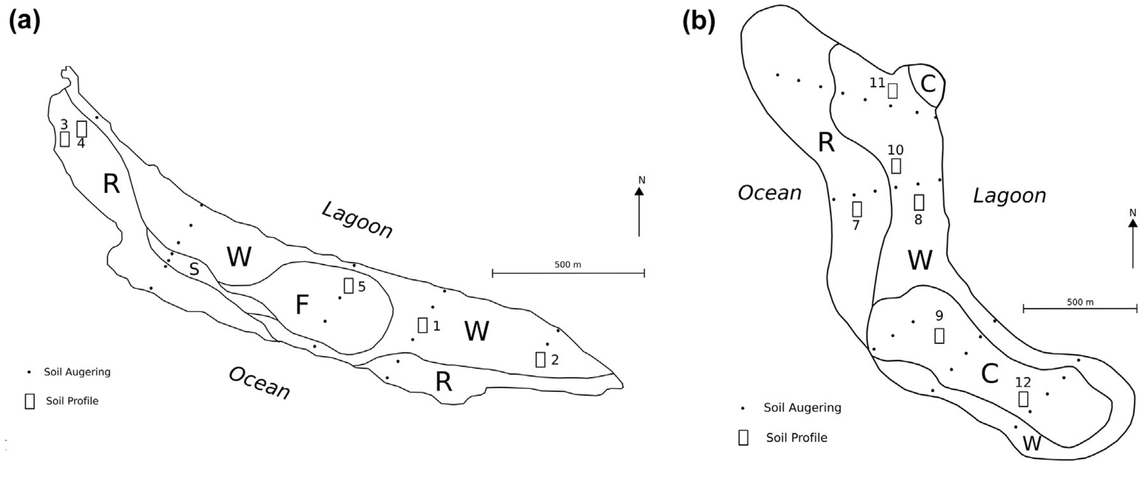

Fig. 2. a. Soil map of Ile du Coin (PB): F Deep white fine sand on mid-island rise; S Wet silty & sandy loam in mid-island depression; R Humic rubbly coarse sand inland of ocean-side berm; W Pale sand in wash deposits. b. Soil map of Ile Boddam (S): C Bare rock & shallow sandy loam on tabular coral; R Humic rubbly coarse sand inland of ocean-side berm; W Pale sand in wash deposits.

Some of the Holocene clastic deposits have been cemented by calcareous solution and reprecipitation. There is an extensive low (<3 m a.s.l.) tabular outcrop of hard coral sandstone on Ile Boddam (S). This rock is not karstified and is thought to date from the Holocene. There are similar but less extensive cemented coral flats on other islands in the Salomon atoll, and some low coral stacks on the ocean-side reef flats. Scattered surface stones occur on Ile du Coin (PB), but there are no significant outcrops.

There is a narrow but continuous clast-supported berm about 0.5–1.5 m high at the head of the ocean-side beaches of all islands. The constituent coral boulders and cobbles grade from hard, whitish, and unweathered at the surface to softer, more weathered, and reddish- and dark brown-stained at depth. For 100–200 m inland from the berm the wash deposits still contain many coral cobbles and stones. However, the deposits there are supported by the matrix of coarse to medium sand, rather by than touching clasts. The rest of the islands are mantled with pale white to creamy sands, many with faint pinkish foraminiferal tinges (more Munsell 7.5YR than 10YR). There are patchy subsoil layers of coral stones and gravel, a few of which may block deep augering. The sands become gradually finer towards the lagoon but coarsen with depth within profiles.

There is a low mid-island rise on Ile du Coin (PB) (Fig. 2a), which has fine and very fine sands to depths of almost 2 m. These are thought to be aeolian deposits that were deflated from wash sediments that were sparsely vegetated during dry periods in the Holocene. There are patches of fine sand on Boddam (S), but these are not extensive enough to be mapped separately (e.g. Profile 11 in Fig. 2b & Table 2). The Iles du Coin and Boddam are the only large islands that are aligned roughly NW-SE (Fig. 1c and d), parallel to the prevailing trade winds. The other islands lie more or less cross-wind, and any deflated sand is likely to be deposited offshore. Aeolian sand and even substantial dunes have been noted on atolls and coral reefs elsewhere in the tropics, including in the Indian Ocean (Piggott, 1968; Stoddart and Steers, 1977). The high and aseasonal rainfall, dense vegetation, and moist topsoils reduce the likelihood of deflation at present in the northern Chagos.

There are a few pumice stones on the ocean-side beaches and berms on several islands. The limited quantities of the silt and clay found in depressions, channels and grikes are thought to be at least partially derived from long distance volcanic ash (Sachet, 1955).

3.1.3. Land use and vegetation

The islands had no permanent human inhabitants until the late eighteenth century when the French occupied them, administered them from Reunion, and established coconut plantations. The islands passed to the British in 1814, who retained the plantations (Durup, 2013). The plantation workforce relied mainly on food imports and coconuts for their carbohydrate needs, and fishing for their protein. They did not practice subsistence cultivation of taro or other aroids to any extent, in contrast to many Pacific islanders and the inhabitants of the coral islands of the Seychelles (Piggott, 1968).

Coconut management and harvesting ceased with depopulation in the 1970's, and the main islands are now mostly covered with untended stands of coconuts of mixed ages. There were probably natural coconuts on the coasts prior to the establishment of the plantations. However, there were also areas of mixed broadleaf forest in the interiors of some islands (Sheppard, 2016; Sheppard and Seaward, 1999). We saw a remnant of this forest in the eastern part of Ile Takamaka (S). In comparison with most tropical lowland forests, it is of modest stature and low diversity, as is to be expected from the disturbed topography, harsh soil conditions, and ecological isolation. The main tree species are: *Barringtonia asiatica*, *Calophyllum inophyllum*, *Ficus* sp. cf. *avi-avi*, *Ficus benghalensis*, *Guettarda speciosa*, *Hernandia peltata*, *H.ssonora*, *H.a* sp., *Hibiscus tilliaceus*, *Morinda citrifolia*, *Neiosperma oppositifolia*, *Pisonia grandis* and *Terminalia catappa.* There are discontinuous areas of specialist plant communities around the shores. These include *Scaevola taccada, Argusia argentea*, *Hibiscus tiliaceus*, *Hernandia* sp. and *Suriana maritima*. *Canavalia cathartica, C. rosea*, and *Ipomea pes-caprae* (Posford Haskoning, Ltd, 2003; Topp and Sheppard, 1999).

There is yellowing of coconuts and inter-venal chlorosis in broad leaf species on the pale sands of most islands, particularly on the lagoon sides. Chlorotic specimens of *Calophyllum inophyllum* on pale sands on the lagoon-side of Ile Boddam contrast with the healthy-looking trees on humic loam on Takamaka. Chloroses are also widespread in the few survivors of the introduced food crops such as *Artocarpus altilis*, *Carica papaya*, *Citrus* spp., *Mangifera indica*, *Zea mays* and *Ziziphus mauritiana*, irrespective of their location. The chloroses are attributed to deficiencies of iron, magnesium, and manganese, but probably not zinc (Lucie-Smith, 1959). No signs of boron deficiency were observed in *Casuarina equisetifolia*, which can be susceptible (Orwa et al., 2009).

3.2. Topographic zonation and dynamics

Although the islands are low and have subdued relief, with no land more than 4 m above mean sea level, there is systematic zonation in the topography. On Ile de Coin (PB) the cross-island toposequence from the ocean to lagoon is: ocean coral flat; ocean beach; coral rubble berm; peri-berm rubble flat; sandy wash flat; mid-island freshwater depression; mid-island rise; sandy wash flat; lagoon beach; lagoon coral flat; lagoon (Fig. 2a). This sequence is similar to zonations noted on other coral islands (FAO, 2001; Fosberg, 1951). Parts of the mid-island rise appear droughty, with sparse vegetation and patches of bare whitish topsoils, probably because their surfaces are well above the water table for long periods. The mid-island depressions are intermittently below the water table and are swampy in places, as also noted on Diego Garcia (Stoddart and Steers, 1977).

The topography is different in the southern part of Ile Boddam (S), where much of the interior consists of a low tabular platform of hard coral at 2–3 m a.s.l (Fig. 2b). It is thought to be derived from cementation of Holocene sands. The coral is slightly weathered and is incised by solution grikes up to 2 m wide and 70 cm deep, which are partly filled with coral debris, sand from storm surge overwash, and some silt and clay, possibly of volcanic origin. The platform is flanked on both lagoon and ocean sides by clastic pale sandy flats. There are similar but less extensive platforms on some other islands in the Salomon atoll. An outcrop on Ile Anglaise (S) (Fig. 1d) is incised by substantial channels and basins, up to 3 m deep and 30 m across. Some of these are connected to the sea, and their ponds are saline or brackish *barrachois* (Stoddart and Steers, 1977). Others have been cut off by the recent storm ridges on the ocean side or sand banks on the lagoon side, and now have small ponds and swamps of low salinity.

As found in many large atolls, the main islands of the northern Chagos have rainfed freshwater lenses (Falkland and Woodroffe, 1997; Werner et al., 2017), the centres of which bulge up to 2 m above sea level (Posford Haskoning, Ltd, 2003). As most of the land is <3 m metres above sea level, water tables may intermittently rise to within a metre of the ground surface. The water tables are dynamic, and rise and fall in a rhythm that follows, but lags after, the tides. Prolonged heavy rainfall can also temporarily raise the water table, but it is below 1 m for most of the time, and the upper rooting zones in most soils are freely or excessively drained for long periods. However, the intermittently high water table give faint pale brownish mottles in many lower subsoils (Figs. 3 and 4c).

The islands are young and probably date from no earlier than 7 ka BP (Eisenhauer et al., 1999). Their development appears to be ongoing, with growth and removal of terminal sand spits, closure of inter-island channels, and the amalgamation of islets (Fosberg and Carroll, 1965). There are no obvious topographic depressions to mark recent islet amalgamations, but there are places where the ocean-side berms are less pronounced, possibly because they are younger and have developed only after recent channel infill and islet amalgamation. Behind these, there are strips running across the island to the lagoon, in which the coconuts tend to be more chlorotic than elsewhere,

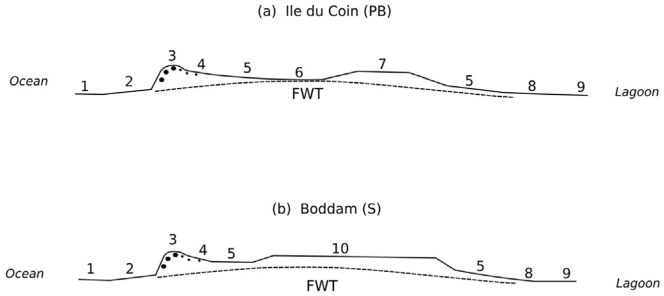

Fig. 3. Schematic ocean-lagoon transects of land forms on Isle du Coin (Peros Banhos) and Isle Boddam (Salomon). 1 Ocean-side coral reef; 2 Ocean-side beach; 3 Coral rubble berm; 4 Rubble wash; 5 Ocean-side sandy flat; 6 Mid-island depression; 7 Mid-island rise; 8 Lagoon-side flat; 9 Lagoon-side beach; 10 Mid-island tabular coral flat with grikes (Southern Boddam). FWT fresh water table.

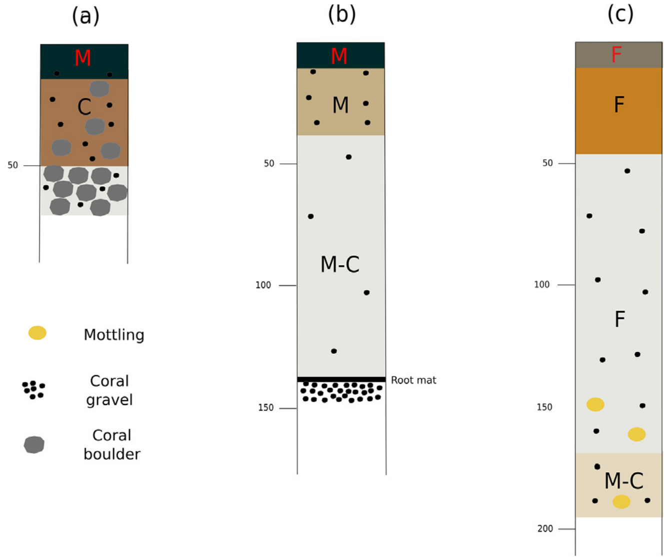

Fig. 4. Profiles of main soil types: (a) Profile 3, R dark rubbly sandy loam inland of ocean-side berm. (b) Profile 2, W pale sand on mid-island flat; (c) Profile 5, F deep white fine sand on mid-island rise. F, M & C refer to dominant sand sizes. Sands coarsen with depth. See Fig. 3 for locations & Appendix A for descriptions and analyses.

suggesting an as yet incomplete build-up of soil fertility. If these features do indicate areas of recent channel infill, Ile du Coin (PB) appears to have been formed by the amalgamation of several previous islands, whereas Boddam (S) appear to have been a single island for some time. The configurations of Iles Diamant (PB), Pierre (PB), Les Souers (PB) (Fig. 8), and Anglaise (S), suggest that they were also formed by amalgamations of islets.

3.3. Soil morphology and zonation

The main morphological features of the study soils are similar to those reported in soils on coral atolls elsewhere, i.e. humic silty loam topsoils; pale coloured and weakly structured coral sand or loamy sand subsoils; and wet and moderately compact pans, in the lower subsoils. Most soils are rooted down to and below the water table. Since the abandonment of the plantations, some soils have developed 5–15 cm deep litter layers of coconut fronds and unharvested nuts. This gives rise to topsoils that hand texture as humic silty loam.

The soils vary consistently with topography (Table 1, and Fig. 3a, b). The ocean-side berms support vigorous stands of coconuts, and have deep litter layers and humic staining, making the lower clasts blackish and reddish brown. The interstitial coarse sands are also dark and humic to several decimetres, but the soils are raw and have no other horizonation. These are equivalent to the ‘brown soils’ noted at the heads of the eastern ocean beaches on Diego Garcia (Purkis et al., 2016). The clasts in the adjacent rubbly humic coarse sands are fewer and smaller than in the berms, and are mostly cobbles and gravels. These soils also support dense stands of mixed-age coconuts, and have profuse litter and deep dark humic topsoils (Fig. 4a). The subsoils are light brownish stony coarse sands.

Inland from the rubbly areas, the most extensive soils are deep pale sands that are developed in wash deposits. Some are topped by profuse litter, giving rise to dark silty loamy topsoils, but these are not as pronounced as in the rubble soils. The subsoils are sands, which tend to coarsen with depth. They are mainly off-white to light greyish cream, and many have faint pale pinkish or orange tinges, thought to be inherited from foraminifera. Many subsoils are compact. Many lower subsoils have faint pale orange and brownish mottles, and are moist-wet below one metre(Fig. 4b).

The fine sands on the low mid-island rise on Ile du Coin are bright white, and unmottled to well below one metre, as the water table is deeper than elsewhere (Fig. 4c). Coconuts regenerate poorly on these soils and there are patches where *Casuarina* is dominant and even some that are bare of trees and have only sparse grass and sedge cover. The less vigorous vegetation gives thin litter layers and thin pale topsoils with low contents of organic matter (Table 2). The poor cover and bare patches are weakly protected against rain splash erosion, and there are small (ca 5 cm high) earth pillars under clumps of sedge (Profile 11, Table 2 and Appendix A).

The marshy patches and ponds in the mid-island depressions have wet, light grey, moderately mottled silty loams and sands with wet mucky silty topsoils that smell faintly of H_2S. These are more extensive on Ile du Coin than on Ile Boddam.

The surface of the coral platform on Boddam is mostly bare, with a few patches of humic stony sandy loam, which are rarely more than 40 cm deep. The grikes are partially filled, with up to 50 cm of wet, dark silty loam and muck.

3.4. Soil chemistry

The soils have pH (H_2O) values greater than 7.5, with some subsoils as alkaline as 9.5. CEC values are high for the textures, but are lower than exchangeable Ca, presumably because the ammonium acetate is leaching some structural Ca from the coral. The exchange complexes are almost saturated by exchangeable Ca, and there are low contents of exchangeable Mg, K and Na (Table 2 and Appendix A), and the soils have low overall nutrient fertility.

As with soil morphology, there are systematic chemical variations which parallel the topographic zonation. The dark topsoils of the humic rubble soils have higher organic C (mean 80 g.kg-1) than those of the pale sands (mean 57 g.kg-1). Available P is also substantially higher (mean 373 vs 93 mg.kg-1), but total nitrogen contents are similar (3500 vs 3621 mg.kg-1). The subsoils of the pale sands have low contents of all nutrients, except exchangeable Ca. All of the soils seen are non-saline, except for small areas around a channel on Ile Anglaise (S).

The topsoils of the eroded patches of white sands on the mid-island rise of Ile du Coin have moderate contents of organic carbon but are low in total N and available P (Table 3). The wet mucky soils in the marshy area in the mid-island depression and in the grikes on the coral platform on Ile Boddam have high organic C and total N but available Pis not correspondingly elevated.

The predominantly carbonatic mineralogy gives rise to low contents of trace elements (Table 4). The subsoil values for Cu, Mn, and Mo are similar to those reported for intact corals elsewhere in Asian waters (Li et al., 2016). Values for Cu, Fe and Zn tend to be higher, particularly in the humic rubble soils. The contents of these elements in the humic loam topsoils are many times higher than in the subsoils. The loam in the grike on Ile Boddam has relatively high content of Cu and Fe, but not Zn.

Table 1
Topography, morphology and international classifications for soil classes of Peros Banhos and Salomon atolls.

Soil class	Topographic location	Morphological summary	Profiles (Fig. 3 & Appendix A)	World reference base (FAO., 2015)	Soil taxonomy (Soil Survey Staff, 2014)
Rubble	Berm at head of ocean-side beach	Deep humic stony silty loam; over touching coarse rubble of small coral boulders, stones and gravel, with interstitial loose white (10YR) coral sand.		Calcaric Regosol	Lithic Udorthent
Humic rubble	Rubble wash flat inland of berm	Humic silty loam; over stained slightly weathered stones and gravel; over pinkish white (7.5YR), moist, loose medium and coarse sand; over compact, wet, pale (10YR or 7.5YR) gravelly coarse sand.	3, 4, 7	Mollic or Calcaric Cambisol *Or* Humic or Calcaric Regosol	Humic Eutrudept *Or* Typic Udorthent
Pale medium sand	Sandy wash flats on ocean side & centre of island	Brown, single grain, moist, loose fine or medium sand or loamy sand; over pinkish white (7.5YR), moist, loose medium grading to coarse sand; over pale, compact, wet, gravelly coarse sand.	2	Humic Cambisol *Or* Calcaric (Mollic) Arenosol	Typic Fragiudept (compact horizon at <100 cm) *Or* Typic Udipsamment (compact horizon at >100 cm)
Pale fine sand	Wash flats on lagoon side of island centres	Very dark brown, (humic) silty or fine sandy loam; over pinkish white (7.5YR), moist, loose fine grading to medium sand to >1 m; over compact, wet, pale (10YR) gravelly coarse sand at >1.5 m.	8,10	Humic Cambisol *Or* Calcaric (Mollic) Arenosol	Humic Eutrudept *Or* Typic Udorthent
White sand	Mid-island rise	Thin whitish, dry, singe grain, loose sand, alternating with small earth pillars of brown loamy sand; over brown, single grain, moist loose sand or loamy fine sand; over white (10YR or 7.5YR) moist, loose, fine grading to medium sand; over compact, wet, pale gravelly coarse sand at >1.5 m.	5, 11	Calcaric (possibly Fragic) Arenosol	Typic (possibly Fragic) Udipsamment
Bare coral	Coral platform	<10 cm litter and lichen on tabular coral slabs.		Calcaric Leptosol	Lithic Udorthent
Coral loam	Coral platform	10–30 cm dark brown, humic loam/silty loam; over solid coral slabs	13	Leptic Cambisol or Regosol	Humic Eutrudept *Or* Typic or Lithic Udorthent
Grike loam	Deep cracks between coral slabs,	Black mucky or humic loam; over pale (hue 10YR) wet-moist loose sand.	12	Gleyic or Humic Regosol	Typic or Aquic Udorthent
Wet sand	Declivities and pond margins	Thin, dark, slightly mucky, wet humic loamy sand; over brown single grain wet loose sand or loamy sand; over pinkish white(7.5YR), wet, loose medium grading to coarse sand; over compact, wet, light grey, gravelly coarse sand.	6	Gleyic *or* Calcaric Arenosol	Aquic Udipsamment
Lake muck	Ponds and channels	Shallow (<50 cm) peat or muck; over wet humic loam; over wet (10YR), sand & gravel		Humic or Gleyic Regosol	Humaqueptic Psammaquent
Channel brackish sand	Ponds and channels	Non-humic, pale (10YR), wet, brackish gravels & sands		Calcaric Regosol (some Salic)	Aquic Udorthent (some Halic) *Or* Aquic Udipsamment (few are Halic)

3.5. Pedogenic discontinuities

Monocyclic pedogenesis in these parent materials proceeds mainly by the gradual accumulation of organic matter, which leads to increasingly deep and dark topsoils. Total nitrogen and other nutrients also slowly accrue. The Holocene tabular coral sandstone on Ile Boddam indicates that there is limited cementation of subsoils by illuvial Ca, which may contribute to the moderate levels of compaction in many lower subsoils. There are no other indicators of eluvial/illuvial processes such as argilluviation or podozolisation. The faint mottling subsoil in many subsoils is incipient gleization. The tendency for sand size to decrease from ocean to lagoon and to increase with depth (Figs. 4 and 5) is attributed to parent material sedimentation, rather than pedogenesis, with finer particles deposited later and further from the source as energy levels subside within a single surge.

However, some soil features appear to have developed polycyclically in sands that were deposited at different times. Dark coloured subsoil horizons with moderate organic matter are thought to be former topsoils that were buried by subsequent overwash (Profile 7, Fig. 6b). Similar horizons have been reported in abandoned aroid cultivation pits on Pacific atolls (Weisler, 1999a), but this mode of formation can be discounted in the northern Chagos, as there is no evidence that the inhabitants ever practised pit agriculture on a substantial scale. Buried organic horizons can also arise by litter infill of old treefall pits, so these horizons need to be interpreted with care.

Inversion of the coarsening of sand size with depth is another feature thought to indicate polycyclic pedogenesis, and is attributed to the upper, coarser sand being deposited later and coming from a different source. Profile 8 (Fig. 6a) shows such an inversion at 100 cm, with medium over fine sand. The change is accompanied by a slight change in soil colour. Pale subsoils with high chromas and values within Munsell hue 7.5YR sometimes grade to similar chromas and values on the 10YR page. These differences (e.g. Fig. 6c) are probably due to differences in foraminiferal contents of the wash from different parts of the reef, and to deposition at different times. Subsoil coral stone layers are attributed to deposition in the initial powerful surges, with later and gentler flows depositing the overlying sands (Fig. 6b).

4. Discussion

4.1. Polycyclic sedimentation and pedogenesis

Although not in a major cyclone belt, there are storms in the Chagos that are capable of altering island configurations (Kench and Maclan, 2004). Purkis et al. (2016) found that there have been many small changes to ocean-side coastline of eastern Diego Garcia over half a

Table 2
Analyses of soil profiles on Peros Banhos and Salomon atolls.

Soil class	Profile	Sample depth	Fine earth granulometry			pH	EC	Organic C	Total N	Available P	Exchangeable				
	(App. A)		Sand	Silt	Cla	1:5 soil:water					Ca	Mg	K	Na	CEC
		cm		%			mS.cm^{-1}	g.kg^{-1}	mg.kg^{-1}				cmol.kg^{-1}		
Humic rubble	3	0–14	46	29	25	7.9	0.17	80	7610	415	58	4.5	0.3	0.4	35
		25–3	nd			8.5	0.12	23	1890	350	nd				
	4	0–6	48	26	26	8.1	0.19	7.2	1911	414	55	4.7	<0.05	0.4	34
		80–90	92	5	3	9.4	0.06	nd							
	7	0–10	45	36	19	8.1	0.22	8.7	980	290	62	2.6	0.04	0.5	30
		60–70	90	6	4	9.0	0.14	0.6	385	168	56	6.5	<0.05	0.4	15
Pale medium sand	1	0–4	79	11	10	8.2	0.14	6.5	3982	47	68	4.7	0.1	0.3	27
		16–60	91	5	4	9.2	0.06	0.5	518	33	69	6.2	<0.05	0.3	24
	2	0–11	79	11	10	8.5	0.12	3.4	2317	42	54	4.6	0.1	0.5	25
		75–85	98	1	1	9.2	0.09	0.3	308	37	25	4.0	0.1	0.4	22
Pale fine sand	8	0–1	74	14	12	8.3	0.14	4.7	3858	92	59	3.5	0.1	0.4	26
		40–50	98	1	1	9.0	0.04	<0.05	434	35	37	6.0	<0.05	0.3	23
	10	0–12	79	15	16	8.1	0.14	7.1	4950	114	62	1.0	0.2	0.4	28
		45–5	94	3	3	8.9	0.05	0.2	406	80	46	4.5	<0.05	0.3	18
White sand	5	0–12	81	11	8	8.7	0.08	1.3	1239	73	66	6.4	<0.05	0.3	16
		80–90	97	2	1	9.3	0.05	0.1	140	46	63	6.9	<0.05	0.3	17
	11	0–6 (sedge)	65	19	16	7.9	0.09	8.7	3276	88	61	0.8	0.1	0.4	36
		0–4 (bare)	65	19	16	8.3	0.09	4.5	2764	99	67	1.1	0.1	0.4	20
Humic coral loam	9	0–12	66	5	29	7.8	0.23	9.5	8217	277	64	4.2	0.3	0.5	42
Grike loam	12	0–8	81	9	10	7.6	1.14	36.3	12,666	124	43	32.3	0.8	19.9	56
Wet wash sand	6	0–	59	18	23	7.8	0.44	26.6	6448	46	62	8.1	0.5	0.6	70
		3–16	68	17	15	8.5	0.12	2.1	1841	10	48	2.6	<0.05	0.1	14

See Appendix A for full data.

Table 3
Effects of terrestrial erosion on sandy wash topsoils, Ile Boddam (S).

Profile Appendix A)	Horizon	pH	Organic C	Total N	C:N	Available P	Exch. K	Exch. Mg
	(cm)		%			mg. kg^{-1}	cmol^{+}.kg^{-1}	
P11	0–6 Non-eroded brown sand	7.9	8.7	0.33	27	88	0.1	0.8
	0–4 Eroded light grey sand	8.3	4.5	0.28	16	99	0.1	1.1

Table 4
Trace element totals in soil profiles on Peros Banhos and Salomon atolls.

Soil class	Profile	Sample depth	Co	Cu	Fe	Mn	Mo	Zn
					ug.kg-1			
Humic rubble	3	0–14	0.5	11	386	21	0.1	357
	4	0–	0.5	14	878	31	0.1	426
	7	0–10	3	19	514	11	0.1	440
		60–70	0.3	4	169	2	0.1	16
Pale medium sand	1	0–4	1	0.5	129	18	0.2	35
		16–60	1	0.5	92	4	0.2	14
	2	0–11	0.5	1.4	85	11	0.1	54
		75–85	0.4	0.2	62	2	0.1	25
Pale fine sand	5	0–12	0.3	1	41	6	0.1	66
		80–90	0.4	1	34	2	0.1	63
	8	0–12	0.3	8	537	14	0.4	100
		40–50	0.3	1	31	1	0.1	5
	10	0–12	0.8	12	753	19	0.4	192
		45–55	0.2	2	59	1	0.3	14
White sand	11	0–6 (sedge)	0.7	5	215	9	0.8	97
		0–4 (bare)	0.5	5	133	9	0.1	102
Coral loam	9	0–12	0.6	11	308	46	0.4	121
Grike loam	12	0–8	1	24	1048	85	0.2	25
Wet sand	6	0–3	0.5	2	92	12	0.1	62
		3–16	0.4	1	75	2	0.1	48

century, and sediment is still infilling the Diego Garcia lagoon (Stoddart, 1971). We found similar rapid changes in the northern Chagos. The coast line of the northeastern end of Ile Diamante (PB) has undergone significant modifications in less than a decade, with truncation of the promontory and some infilling of the bay (Fig. 7). Aggradation is also occurring in the on-going closure of the channel (Fig. 8) between Iles Grande and Petite Souer (PB).

Topographic disturbances are likely to accelerate in the Chagos and throughout the tropics as future climate change leads to fiercer and more frequent storms. The increase in temperature will give more intense and extensive coral bleaching and mortality, which could reduce the capacity of reefs to protect shores against the increasing wave energies (Brown, 1997; Sheppard et al., 2005, 2017).

Polycyclic pedogenesis is to be expected in such dynamic environments. The deposition of raw sand over a developed profile means that pedogenesis has to restart more or less from scratch. The new profile is affected by the nature of the new cover, which may come from a different part of the reef from the original, giving changes in sand granulometry, inversions of sand sizes, and colour changes. The accumulation of organic carbon, nitrogen and the build-up of nutrient fertility have to restart in the new and raw sand, and natural vegetation is less vigorous in the early stages of the development of a new soil.

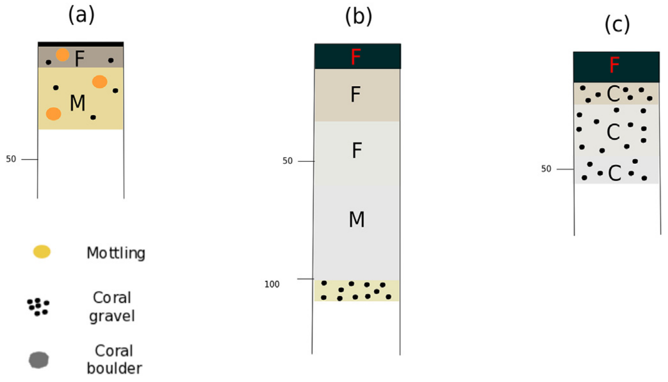

Fig. 5. Profiles of monocyclic soils: (a) Profile 6, Shallow and slightly gravelly pale sand. (b) Profile 8, Deep pale sand. (c) Profile 9, Very gravelly pale sand. F, M & C refer to dominant sand sizes. Sands coarsen with depth. See Fig. 3 for locations & Appendix A for descriptions and analyses.

4.2. Trace elements

The trace element contents of most of the subsoils (Table 4) are similar to those recorded for in situ corals elsewhere in Asian waters (Gopinath et al., 2010; Li et al., 2016). However, the topsoil contents of Zn and, to a lesser extent, Fe and Mn of the rubbly humic loam are considerably higher. They are also much higher than in their own subsoils. These enrichments appear greater than can be attributed to simple recycling by the vegetation, especially as even the oldest soils have developed only since the mid-Holocene, and the polycyclic soils are younger. Another possibility is deposition from air pollution. The nearest and most probable source would be the Indian subcontinent. However, trace element pollution levels in corals close to the Indian coast are only slight and no higher than our soils (Gopinath et al., 2010; Krishna Kumar et al., 2010).

Volcanic ash or floating pumice are also possible sources. There have been major volcanic eruptions, such as at Krakatoa, Tambora, Taal and Pinatubo, in Southeast Asia, upwind of the Chagos, during the Holocene. Most of the tephra were andesitic-basaltic, but the 1991 Pinatubo eruption included some dacite (De Maisonneuve & Bergal-Kuvikas, 2020). The Zn levels found in the topsoils of fhe rubbly humic loam are similar to those found in volcanic soils in Sabah (Musta et al. 2008). Distance does not disqualify Southeast Asia as a possible source, as the volumes and wide dispersion of ash from these eruptions were sufficient to affect global for months and years.

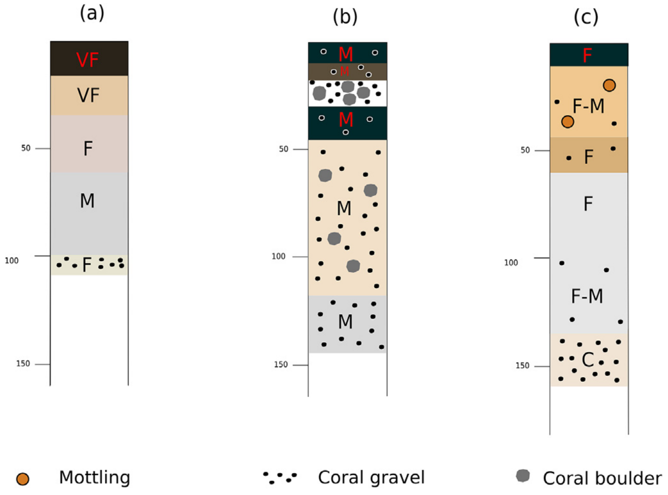

Fig. 6. Soil profiles with indicators of polygenesis: (a) Profile 8, Sand size inversion, stone concentration, and hue change at 100 cm; (b) Profile 7, Buried topsoil, stone line, and contrasting subsoil hues; (c) Profile 10, Contrasting subsoil hues. F, M & C refer to dominant sand sizes. Sands normally coarsen with depth. See Fig. 3 for locations & Appendix A for descriptions and analyses.

4.3. Rats and soil fertility

The soils of the Chagos have been characterised as 'poor and thin' (Sheppard, 2016, p4). These low fertility levels reflect the inherent limitations of the carbonatic soil parent materials and the youth of the regoliths. Some aspects of the nutrient infertility improve as the soils mature, with gradual increases in soil organic matter, N and P. However the unbalanced cationic nutrient stoichiometry (Baillie et al., 2018) inherited from the coral does not change significantly, and the exchange complexes continue to be saturated with Ca. This induces deficiencies in K and possibly also in Mg.

However, on many coral islands the inherited infertility is substantially offset by soil enrichment by seabirds harvesting marine nutrients and recycling them as droppings under gregarious roosts. Deposition rates of such guano are estimated to reach up to 2 $t.ha^{-1}.y^{-1}$ (Gessell and Walker, 1992). This pathway has been invoked to account for the very high P contents in many atoll soils (Fosberg, 1957; Fosberg and Carroll, 1965; Piggott, 1968). Total P levels in soils under roosts may be as high as 10%, and can exceed the 'change point', above which the P becomes mobile and liable to leaching into subsoils and aquifers (Blake et al., 2002, Aharon and Veeh, 1984; Albert et al., 2016; Baillie et al., 2018; Banerjee, 2000; Bhattacharya and Chaubey, 2000; Blake et al., 2002; Blumenstock, 1958; BSI, 1995). In many subsoils in the Pacific (Fosberg, 1959) and the Seychelles (Piggott, 1968), illuvial P can form a brownish, indurated, phosphatic pan. The illuvial P sometimes crystallises with age to form the carbonate-hydroxyapatite mineral dahllite (Niering, 1956; Rodgers, 1992).

Soils with phosphatic pans are often designated as *Jemo* series. (Fosberg, 1954, 1957). The name originated in the northern Marshall Islands (Fosberg, 1954, 1990) but has now been applied as far afield as the Seychelles (Hill et al., 2002; Piggott, 1968). Given the stringent criteria for defining soil series (Clayden and Hollis, 1984), the extraterritorial use of series names is problematic, as it risks taxonomic grouping of dissimilar soils and the loss of potentially useful discriminant information.

Formation of phosphatic pans appears to be particularly associated with the tree species *Pisonia grandis*, because of the water-soluble P-complexing leachates coming from the decomposition of its litter (Shaw, 1952). Some studies conclude that *Pisonia* is an absolute prerequisite for the formation of phosphatic pans and vice versa (Hatheway, 1953; Fosberg, 1994) but this has been queried for soils in Tuvalu (Rodgers, 1992).

Nothing like these P levels were observed in the study soils. Even the most fertile humic rubble soils have maximum P contents of <400 $mg.kg^{-1}$, and most of the others have <100 $mg.kg^{-1}$ (Table 3 and Appendix A). The low fertility can be attributed to infestation by black rats *(Rattus rattus)* and their predation of seabird fledglings. This leads to the adults seeking safer alternative roosts for breeding. Rat infestation affects soil N as well as P (Drees and Manu, 1996; Kazama, 2019). Graham et al. (2018) examined $\delta 15N$ levels on six rat-free and six rat-infested islands in the northern Chagos over a period of six years. The rat-free islands had mean bird densities 760 times higher than on the infested islands, and the ornithogenic input of N differed by about 250-fold. Topsoils on the non-infested islands had total N contents greater by an order of magnitude than those with rats.

The rats were probably inadvertently introduced at about the time of the first human settlement (Sheppard, 2016; Vogt et al., 2014). They are not ubiquitous and are concentrated on the islands that were used as plantations. Rat densities are higher in coconut areas than in mixed forest and coconut is a major ingredient of their diet (Vogt et al., 2014), and we saw many rat-gnawed nuts. Our remit was to survey the islands with the best agricultural prospects, and these had been formerly used

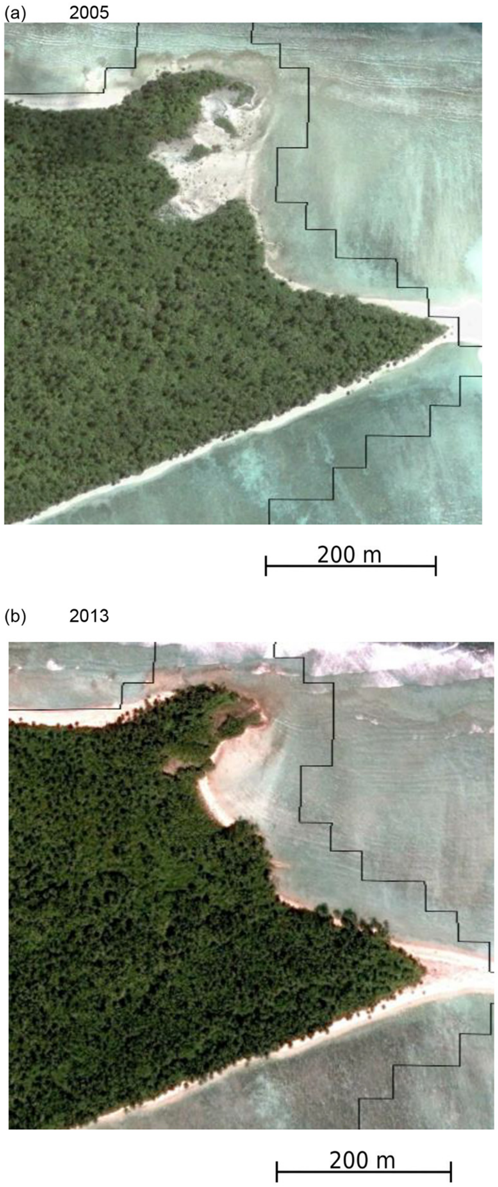

Fig. 7. Coastline changes between 2005 and 2013 at northeastern end of Ile Diamant (PB), with truncation of promontory and some infill of bay.

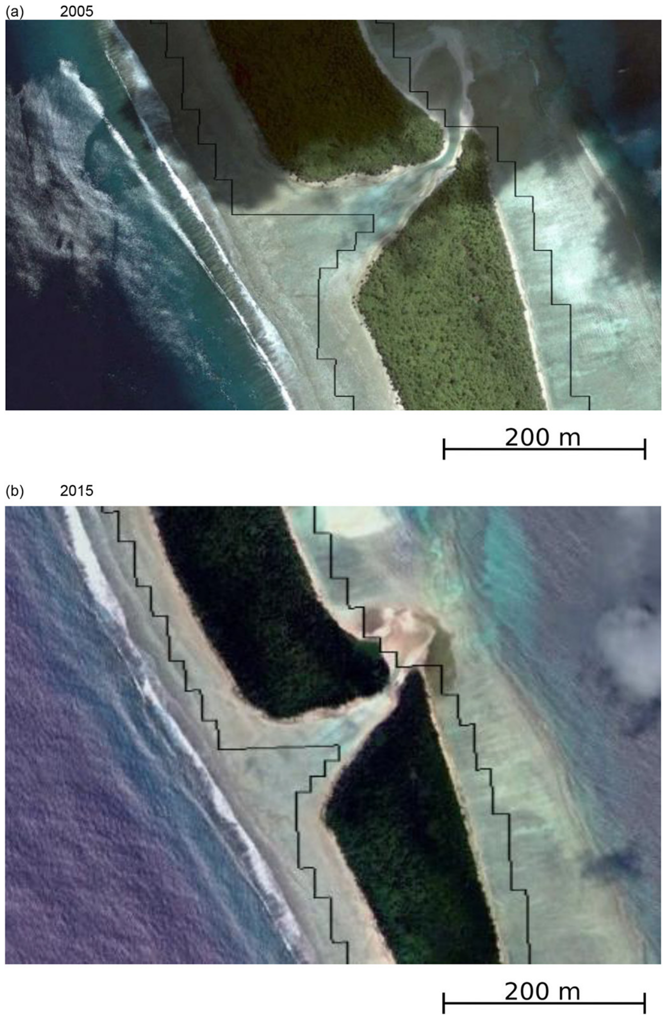

Fig. 8. On-going closure and reduced scouring between 2005 and 2013 in the channel between Iles Grande Souer and Petite Souer (PB).

for plantations and were infested with rats, and now have low densities of seabirds and roosts.(Aharon and Veeh, 1984)

The one rat-free island (Carr et al., 2020) we saw was Ile de la Passe (S) (Fig. 1d and Appendix C). Composite topsoil samples from under, and away from, a roost (Table 5) show substantial ornithogenic enrichment of C, N and P, but the effects are modest compared with some atoll soils elsewhere (Fosberg, 1959), and there was no sign of a phosphatic pan (Woodroffe and Morrison, 2001). Pans may require a substantial dry season (Aharon and Veeh, 1984), which would preclude their formation in the aseasonal climate of the northern Chagos.

4.4. Agricultural potential of North Chagos soils

The cropping potential of atoll soils is limited. Krishnan et al. (2004) concluded that rainfed coconuts, possibly intercropped with fruit and vegetables, is the only sustainable use for such soils in the Lakshadweep Islands. However, sustainable agricultural systems based on aroids, especially taro (*Colocasia esculenta),* have long supplied the carbohydrate needs of isolated populations in the Pacific, with their protein coming from fishing. The aroids are planted in pits that are dug down to moist subsoils or the water-table and backfilled with plant litter. The crop grows in pockets of wet and eutric anthropogenic Histosols in soilscapes of drought-prone Arenosols and Regosols (Mason, 1960; Piggott, 1968; Stone, 1951; Weisler, 1999b). Pit agriculture is very labour intensive and does not appear to have been practised in Peros Banhos and Salomon when they were inhabited.

Table 5
Guano effects on topsoils, Ile de la Passe (S).

Analysis	Roost soil	Non-roost
pH	7.3	8.1
EC (mS cm^{-1})	1.05	0.18
Organic C (%)	7.2	3.2
Total N (%)	0.67	0.24
Available P (mg/kg)	251	35

5. Conclusions

The soils of the Peros Banhos and Salomon atolls in the northern Chagos archipelago are developed in dynamic clastic coral sands. They show limited pedogenic development, with subtle variations related to the topographic zonation. Storm surges periodically overtop the islands and the regoliths are dynamic, with addition, removal, and resorting, and many of the soils show signs of disturbance and polycyclic pedogenesis. The source of elevated Zn contents in the humic rubble topsoils is not clear but it may have been imported in long distance volcanic ash. The generally low fertility of the soils is attributed to rat predation of seabirds and the consequent disruption of soil enrichment by guano deposition under their roosts.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2021.e00391.

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