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Last Interglacial changes in sea level on Aldabra, western Indian Ocean

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ABSTRACT

The Pleistocene limestones on the island of Aldabra in the western Indian Ocean preserve a detailed record of the Last Interglacial interval. Sedimentological analysis has revealed that this interval, formerly regarded as reflecting rapid sea-level rise, during global warming, followed by a more gradual fall towards the low sea level of the Last Glacial Maximum, in fact shows much greater variation. Although data do not support an accurate chronology, there is evidence that reversals in sea-level trend caused both pauses in deposition and concurrent erosion during sea-level rise, and both stillstands and erosion during sea-level fall. Data include sea-level related variations in coral morphology, discontinuities and boundaries within depositional sequences, and changes in biofacies. These may explain inconsistencies in the radiometric ages of deposits within the unit, but question the nature of the interglacial cycle, the mechanisms driving it and, in particular, whether comparable variation occurred elsewhere.

Keywords Last Interglacial, Pleistocene, sea level, western Indian Ocean.

INTRODUCTION

Deposits from the Last Interglacial interval are common throughout the tropics, and are of special importance today, both for the record they retain of sea-level variations during a relatively warm (high sea level) interval, and the insights they provide regarding ice sheet dynamics during a period of global warming. Holocene sea-levels have varied in response to ice sheet unloading and the redistribution of water masses in the global ocean (Pluet & Pirazzoli, 1991), but data for the Last Interglacial are sparse. Such changes are best illustrated in so-called 'far-field' sites, like Aldabra, remote from glaciated regions, which can be used to constrain estimates of eustatic changes and variability (Fleming *et al.*, 1998; Lambeck *et al.*, 2000).

The western Indian Ocean, including the African coast, the Seychelles Bank, the island of Aldabra and other high limestone islands, appears to have experienced a prolonged period of regional crustal stability (Camoin *et al.*, 2004). However, recent work by Stephenson *et al.* (2019) indicates that Madagascar, 420 km to the south-east, has been on the northern margin of a Neogene crustal flexure, active since the Last Interglacial, with the elevations of deposits from this interval decreasing from 9.3 to 2.8 m over a distance of only 80 km. Aldabra provides one of the best known Late Pleistocene sequences, dominated by deposits of the Last Interglacial interval. The island is famous as the last refuge for an estimated *ca* 152 000 Old World giant tortoises (Fryer, 1911; Arnold, 1979), but is also home to over 400 other endemic species (Stoddart & Wright, 1967; Peake, 1971; Renvoise, 1971). The first descriptions of the geology of the island were by Abbott (1893; with only scanty reference) and Fryer (1911), with a more detailed survey by Baker (1963). However, in 1967, The Royal Society of London mounted an expedition to the 'atoll', to record details of the flora (Stoddart & Wright, 1967; Fosberg, 1971) and in particular, the endemic fauna (Peake, 1971; Taylor *et al.*, 1979). In support of these aims, in 1969 it sponsored new geological observations to describe the stratigraphy and depositional history of the island (Braithwaite *et al.*, 1973). Geology proved to have had a profound influence on the origins and dispersal of the Aldabra biota throughout the western Indian Ocean. The presence or absence of terrestrial species provides important evidence of repeated drowning and recolonization of the island, orchestrated by sea-level change (Braithwaite, 2016a). The expedition laid the foundations for the establishment of a research station on Aldabra by the Seychelles Islands Foundation (inaugurated in 1979), and for the recognition of the site as a UNESCO World Heritage Centre in 1982.

Regrettably, pervasive diagenetic alteration has hampered attempts to date these rocks, and deposits of the Last Interglacial episode provide the only materials so far to have generated ages considered 'reliable'. Thompson & Walton (1972), using $^{230}Th/^{234}U$ ratios, obtained ages from this unit ranging from 136 to 118 ± 9 ka. Veeh (1966), using Th^{230}/U^{238} and U^{234}/U^{238} ratios, dated samples of raised limestones from Mahé and Praslin on the Seychelles Bank at 9 m and 6 m respectively above present sea level. These provided $^{230}Th/^{238}U$ ages for fossil corals ranging from 90 ± 20 to 160 ± 40 ka and $^{234}U/^{238}U$ ages from 80 ± 50 to 180 ± 60 ka. Little of these deposits remain, but ages are broadly comparable to those from Aldabra. Dutton *et al.* (2015) dated raised limestones from La Digue and Curieuse, near Praslin, which provided ages ranging from 143.0 ± 1.0 to 86.0 ± 0.4 ka. Reef deposits of similar ages occur throughout the Indian Ocean and indeed the entire tropics. Here they signal a protracted period of climatic warming (potentially nearly 60 ka!) and relatively high global sea levels, otherwise indicated by isotopic analyses of polar ice cores and deep-sea sediments (Marine Isotope Stage, MIS, 5).

Aldabra 'atoll' (latitude 9°24′S, longitude 46°20′E), lies *ca* 420 km north-west of Madagascar. Approximately 34 km long, the current land area is *ca* 155 km^2, less than half of the total area (*ca* 365 km^2) of the atoll (Fig. 1), commonly referred to as the second largest in the world. However, the term 'atoll' is misleading because, in contrast to the low sand cays typical of most active atolls, the four main islands, consisting of Pleistocene limestones, currently rise *ca* 8 m above present sea level and, in contrast to Darwin's model, depositional units older than MIS 5 apparently did not form in reef environments. Like several other 'high' islands in the Western Indian Ocean, they were originally deposited on a volcanic peak that, for Aldabra, is now *ca* 0.3 km below the sea surface (Williams, 1971), a position that belies the apparent lack of tectonic subsidence in their more recent history (Camoin *et al.*, 2004).

METHODS

Apart from the north-western island of Picard, cliffs and attendant waves generally bar landing on the outer coast of the atoll. Within the lagoon, small boats provide access to sites around the inner margins, commonly limited by dense mangroves, and restricted to periods of high tides because, with a tidal range approaching 3 m, much of the lagoon dries during low water. Land-based surveys extended from landing points, locally, but not always, through dense vegetation. Navigation in these relied on transects of existing paths and excursions from them using a conventional compass. Positions were recorded on a DOS 304 1 : 25 000 (1964) map of Aldabra, cross-referenced against stereo pairs of air photographs from a survey in June 1960. This appeared to provide reliable location, but ultimately it became clear that the maps differed in detail from the photographs. For this reason, so far as possible, locations from maps have been fixed relative to current satellite images (United States Geological Survey; Earth Explorer: https://earthexplorer.usgs.gov/). These have good resolution, subject to patchy cloud cover, but unfortunately, both maps and air photographs differ in some details. Nevertheless, with caveats regarding precision, they provide widely understood coordinates for the features described (listed in Table 1 and Fig. 1). The names applied to sites are those in use during the 1969 survey, but subsequently also proved open to doubt regarding both the names applied and the locations of the features to which they refer (see Stoddart, 1971) underlining the need for more accurate coordinates.

STRATIGRAPHY

As in other areas, the stratigraphy preserved in the outcrops on Aldabra is limited to intervals in which sea level was close to or a little above the present datum. The five periods in which this occurred, possibly extending to MIS 9 or 11, are represented by a stratigraphical sequence

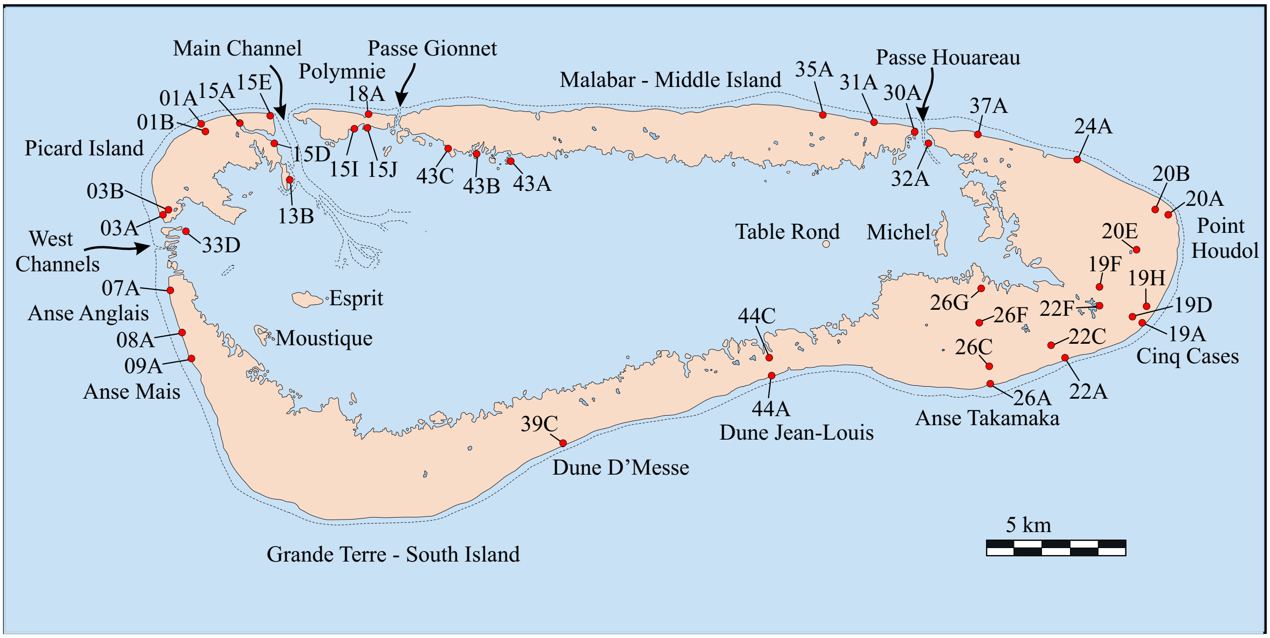

Fig. 1. Map of Aldabra showing positions of locations (red dots) referred to in the text and principal place names.

of units (Fig. 2; Braithwaite *et al.*, 1973): the Esprit Limestone, Esprit Phosphorites, Picard Calcarenites, Takamaka Limestone and Aldabra Limestone. Although these all indicate deposition near or above present sea level, their histories were separated by falls of sea level from tens to more than 100 m, accompanied by subaerial erosion and local deposition.

The focus here is on the Aldabra Limestone, representing the Last Interglacial interval, MIS 5. Scarce deposits of similar age are present in the granitic Seychelles (Montaggioni & Hoang, 1988; Dutton *et al.*, 2015) with extensive outcrops on the Kenya coast (Braithwaite, 1984) and Madagascar (Battistini, 1969). It is important to consider the lower boundary of these deposits because the surface on which they rest might be regarded as defining the beginning of this interval. The undated Takamaka Limestone provides the substrate on which the Aldabra Limestone rests. It was deposited (Braithwaite *et al.*, 1973) in an environment interpreted as 'meadows' of the marine grass *Thalassodendron*. Similar grassy tracts are common on many present western Indian Ocean Banks of ≤20 m depth, and extend into the intertidal. In such environments, red calcareous algae and *Halimeda* are common beneath the leaf canopy, but diversities of other organisms, including both molluscs and corals are low (Taylor, 1978). The deposits are typically carbonate mudstones, with coarser variants locally reflecting shallower or more exposed situations. The thickness of these deposits (3 to 4 m), and the environment required for their production, implies deposition when sea level was at least 4 to 5 m above the present position. Recession of some tens of metres would have been required to develop the subaerial erosion surfaces and terrestrial deposits (Braithwaite *et al.*, 1973) together with the diagenetic environment that would have lithified these deposits. However, the largely marine erosion surface that now defines the top of the unit implies that sea level was once more only about a metre above the present position. This might suggest a brief interval with little fall in sea level, implying that the Takamaka Limestone represented an early phase of MIS 5, or, alternatively, that it was associated with MIS 7. Deposits of MIS 7 have been reported on the Kenya coast (Accordi *et al.*, 2010) where two distinct marine transgressions have been identified in late Pleistocene deposits (Caswell, 1953; Braithwaite, 1984) and on Madagascar [Battistini (1969); with new dates in Stephenson *et al.* (2019)]. However, MIS 7 deposits do not appear to be common although they have been described at +4.5 to +6.0 m above present sea level in Bermuda [Rowe *et al.* (2014); although Hearty (2002) had reached

Table 1. Coordinates of localities referenced in the text.

Site	Description of location	Latitude and longitude
01B	North-west coast of Picard island, inland from Anse Var	09° 22′ 32″ S 46° 12′ 56″ E
03B	West coast, south end of Picard island	09° 23′ 56″ S 46° 12′ 21″ E
07A	North-west coast Grande Terre south of Passe Midi	09° 25′ 23″ S 46° 12′ 32″ E
08A	North-west coast Grande Terre, *ca* 500 m north Anse Anglais	09° 26′ 56″ S 46° 13′ 03″ E
09A	Anse Mais, north-west coast of Grande Terre	09° 26′ 28″ S 46° 12′ 50″ E
13B	Petit Grande Poche inlet, north-east coast of Picard Island	09° 23′ 24″ S 46° 14′ 40″ E
15A	Bras Grande Poche, north-east Picard	09° 22′ 27″ S 46° 13′ 48″ E
15D	Entrance to Bras Grande Poche, north-east Picard island	09° 22′ 46″ S 46° 14′ 25″ E
15E	East coast Picard, *ca* 200 m south of Main Channel entry	09° 22′ 15″ S 46° 14′ 21″ E
15I	Entre Deux Polymnie, *ca* 2 km east of Grande Passe	09° 22′ 33″ S 46° 15′ 52″ E
15J	Palm Beach Polymnie, 4 m cliffs on lagoon coast	09° 22′ 28″ S 46° 16′ 04″ E
18A	Polymnie Headland, south of Anse Cedres	09° 22′ 17″ S 46° 16′ 06″ E
19D	Coastal ridge, Cinq Cases area	09° 22′ 17″ S 46° 16′ 06″ E
19F	Cinq Cases area, near Northern creeks	09° 25′ 40″ S 46° 30′ 53″ E
19H	Large hole, *ca* 250 m south-east of Cinq Cases Camp	09° 25′ 44″ S 46° 31′ 00″ E
20A	Point Houdol, *ca* 100 m south-west of trees	09° 24′ 03″ S 46° 31′ 21″ E
20B	Large pool, *ca* 400 m north-west of Point Houdol	09° 24′ 04″ S 46° 31′ 13″ E
22A	Coast, *ca* 3 km south-west of Cinq Cases Camp	09° 26′ 50″ S 46° 28′ 59″ E
22C	Lagoon face of 4 m Terrace, south-west of Cinq Cases Camp	09° 26′ 39″ S 46° 28′ 54″ E
22F	Shore of Creek northern end of Cinq Cases path	09° 25′ 46″ S 46° 29′ 43″ E
24A	East coast Grande Terre, *ca* 4.3 km north-west of Point Houdol	09° 22′ 59″ S 46° 29′ 25″ E
26C	Takamaka area, terrace of old lagoon floor	09° 27′ 05″ S 46° 27′ 39″ E
26F	Path north of Takamaka Grove	09° 25′ 58″ S 46° 27′ 29″ E
26G	Area north of Takamaka Grove	09° 25′ 26″ S 46° 27′ 38″ E
30A	Passe Houareau, western coast	09° 22′ 31″ S 46° 26′ 20″ E
30A	Passe Houareau palaeocliffs and ramp	09° 22′ 34″ S 46° 26′ 31″ E
31A	North coast isle Malabar *ca* 1400 m west of Passe Houareau	09° 22′ 20″ S 46° 25′ 36 “ E
32A	Passe Houareau, island east shore	09° 22′ 34″ S 46° 26′ 31″ E
33D	Islot Rose in West Channels	09° 23′ 21″ S 46° 27′ 36″ E
35A	North coast isle Malabar, west of Passe Houareau	09° 22′ 11″ S 46° 24′ 34″ E
37A	North shore, *ca* 900 m east of Passe Houareau	09° 22′ 29″ S 46° 27′ 03″ E
39C	South coast, raised beach on 4 m terrace	09° 28′ 16″ S 46° 19′ 55″ E
43A	Lagoon island, *ca* 1.9 km south-west of Au Parc	09° 23′ 09″ S 46° 18′ 46″ E
43B	Lagoon island, *ca* 2.8 km east of Passe Gionnet	09° 23′ 02″ S 46° 18′ 07″ E
43C	Lagoon shore, *ca* 1.75 km south-east of Passe Gionnet	09° 22′ 53″ S 46° 17′ 36″ E
44A	Cliffs close to Dune D'Messe	09° 27′ 02″ S 46° 23′ 38″ E
44C	Dune D'Messe path, *ca* 600 m north-west	09° 26′ 39″ S 46° 23′ 31″ E

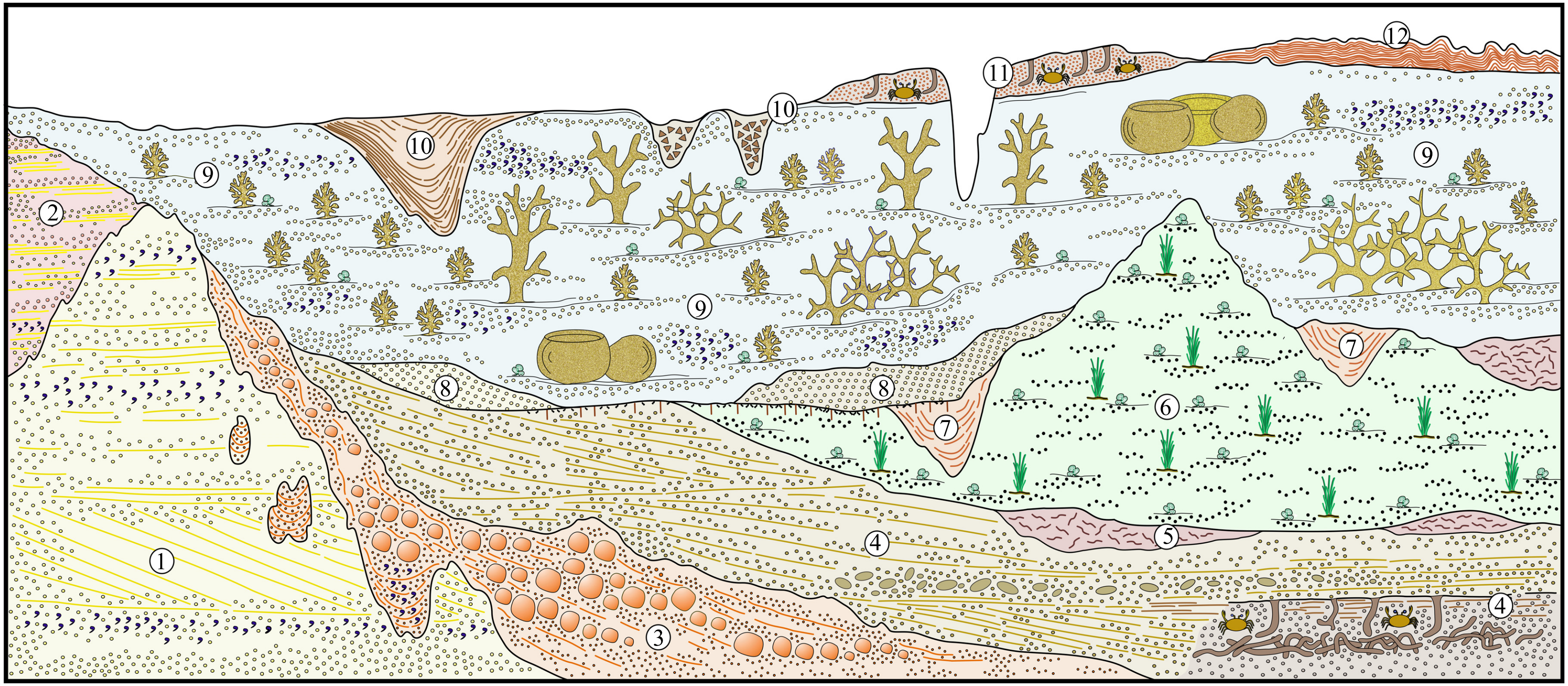

Fig. 2. Pleistocene stratigraphy of Aldabra, after Braithwaite *et al.* (1973), representing *ca* 8 m vertical thickness and 34 km lateral variation. For the purposes of illustration these are not to scale. 1 = marine Esprit Limestone. 2 = oolitic Esprit Phosphorites, formed subaerially. 3 = conglomeratic phosphate debris-flows on the flanks of Esprit Island. 4 = cross-bedded Picard Calcarenites with vertebrate remains including tortoises. 5 = palaeosols on Picard Calcarenites with terrestrial molluscs including *Succinea*. 6 = marine Takamaka Limestone with nodular red calcareous algae and *Halimeda*. 7 = palaeosols filling subaerial dissolution pits. 8 = dense well-cemented fine-grained calcarenites containing *Strombus* and *Polynices*. 9 = marine Aldabra Limestone with rich coral and molluscan fauna. 10 = dissolution pits and terrestrial deposits including a diverse vertebrate fauna. 11 = calcarenites intensively burrowed by crabs. 12 = stromatolitic laminated crusts.

different conclusions], on Henderson Island in the central Pacific (Anderson *et al.*, 2010) and on Hawaii (Sherman *et al.*, 2014) where they have been subject to tectonic uplift.

It seems unlikely that the Takamaka Limestone will provide any accurate age dates in the near future. As a consequence, it is appropriate to adopt a sequence-stratigraphic approach and argue that the association of subaerial and marine erosion surfaces defines a significant break. On this basis the shallow-water deposits of the Takamaka unit are best accommodated in MIS 7 with the overlying deposits, reflecting variations in sea level that were not significantly different, falling within MIS 5.

MARINE ISOTOPE STAGE 5 AND THE ALDABRA LIMESTONE

Notwithstanding the presence of subaerial deposits, much of the surface of the Takamaka Limestone reflects protracted marine erosion, comprising a morphological suite including low undercut cliffs, *ca* 2 m high at Passe Houareau, Site 32A (Fig. 3A). These form an embayed palaeo-coastline flanked by ramps that dip gently seaward, Site 07A, *ca* 1 km south of Anse Anglais (Fig. 3B). In many areas, (for example, Takamaka, Site 26C) borings of *Lithophaga* and clionids pepper flat areas of the truncated surface (Fig. 3C). But there is also evidence of extensive subaerial erosion, in the form of residual areas like those forming the Passe Houareau palaeo-cliffs, rising >2 m above the general surface. These would have formed low islands rimmed by the cliffs and peripheral ramps visible around the atoll. Prolonged exposure of these residuals resulted in surfaces riddled with irregular cavities, similar to those forming present 'champignon' surfaces of limestones in higher areas of the islands (Stoddart *et al.*, 1971). Commonly, the cavities formed are filled by varied red-brown earthy sediments, that include palaeosols (Sites 43A and 43B). However, the widespread marine erosion surface cuts both cavities and fillings, deeper channels are filled with supposed terrestrial deposits (Fig. 3D; Lagoon Island close to Site 43C). In some areas north of Dune Jean-Louis (Site 44C), cavity-fillings have been subject to a second marine erosion, including further boring by both *Lithophaga* and clionids, implying additional long-term but small-scale variation in sea level (Fig. 4; Braithwaite *et al.*, 1973). In many areas, dense fine-grained brown laminated crusts, interpreted as of subaerial origin, drape across eroded surfaces of the Takamaka Limestone, smoothing irregularities, but these may be significantly younger.

Sequences that imply further marine influence overlap the Takamaka Limestone in some areas. West of Passe Houareau (Site 30A) the ramp surface is covered by a sequence of four thin calcarenite units (Fig. 3E), including a burrowed interval, and a molluscan fauna that suggests a beach environment. The assembly is interpreted as reflecting a cycle from shallow lagoon to beach to shallow lagoon. Locally, on the southern coast of Polymnie, on a headland extending into the lagoon (Site 43B), the Takamaka surface, again bored by *Lithophaga* and clionids (Fig. 3F), is overlain by centimetres thick sheets of medium-grained calcarenite, containing numerous *Fragum*, *Polynices*, *Strombus*, *Pyramidella* and tellinids implying a quiet, sandy shallow water environment.

Lagoon islands south of Isle Malabar (middle island) show additional evidence of an early lagoonal influence. In some areas (Site 43C), thicker calcarenites are extensively burrowed (Fig. 5A) and are overlain by the coral-bearing calcarenites of the Aldabra Limestone.

Together, these features and deposits, including those of subaerial origin (Braithwaite, 1975, fig. 22), reflect a period in which sea level varied, more than once, within a metre or so of its present position. In the absence of any reliable age date, it is argued that these deposits represent part of the MIS 5 sequence. Although the fall in sea level required to bring about lithification of the Takamaka Limestone supports a greater age, the overlying deposits and intercalated marine erosion surfaces, seem more likely related to MIS 5.

The Aldabra Limestone is locally >8 m thick, essentially rimming the entire atoll (Braithwaite *et al.*, 1973). Diverse corals and over 300 species of molluscs (Taylor, 1978) dominate a rich and varied fauna. Molluscs, consisting of calcite are typically well preserved, whereas corals, formerly consisting of aragonite, are commonly neomorphosed. The deposits are commonly *Halimeda*-bearing calcarenites, but range from carbonate muds to calcirudites. Taylor (1978) defined seven biofacies, characterized by specific faunal associations. They are: (i) *Acropora humilis* dominated facies; (ii) *Acropora palifera* dominated facies; (iii) faviid coral dominated facies; (iv) *Goniastrea* dominated facies; (v) *Halimeda* sand facies; (vi) *Porites*-coral knoll facies; and (vii) *Polynices–Fragum* facies. Each was located to a broadly defined area around the

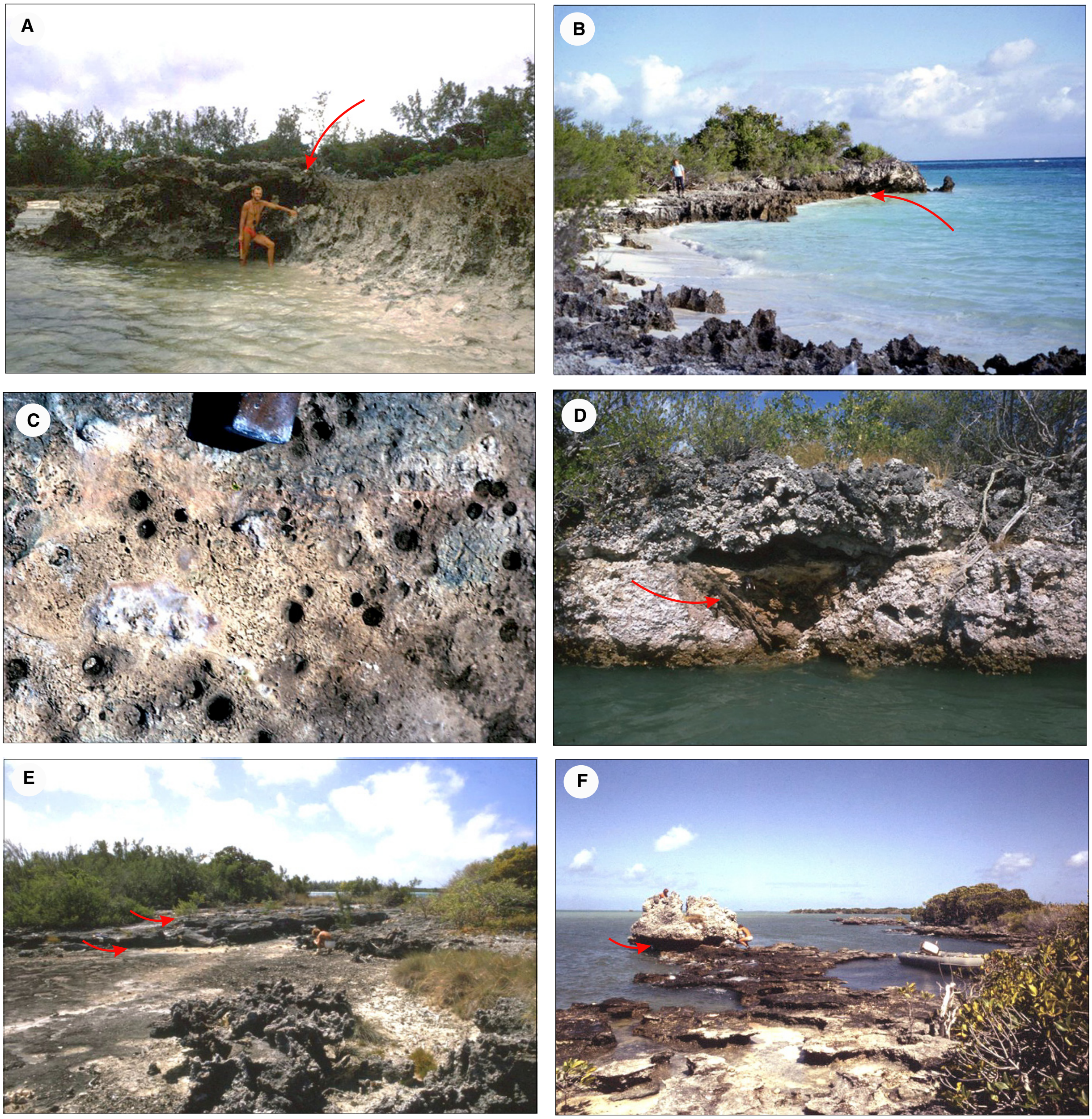

Fig. 3. (A) Palaeo-cliff *ca* 2 m high, reflecting protracted erosion of the Takamaka Limestone with Aldabra Limestone (MIS 5) banked against it to the north (left) with the boundary indicated by the red arrow. Site 32A, island off the eastern shore of Passe Houareau (9°22′34″S, 46°26″31′E). (B) Gently dipping ramp surface of Takamaka Limestone, facing west, with overlying Aldabra Limestone. The red arrow indicates the contact. Site 07A, *ca* 1 km south of Anse Anglais (south of Passe Midi) (9°25′20″S, 46°12′32″E). (C) Borings of *Lithophaga* and clionids pepper flat areas of the truncated surface of the Takamaka Limestone, overlain by Aldabra Limestone. Site 26C, Takamaka au Bord de la Mer and elsewhere (9°27′05″S, 46°27′39″E). (D) The widespread marine erosion surface cuts cavities and palaeo-channels in the surface of the Takamaka Limestone filled with supposed terrestrial deposits indicated by the red arrow. Overlain by coral-bearing Aldabra Limestone. Lagoon island close to Site 43C, *ca* 1.75 km south-east of Passe Gionnet (9°22′53″S, 46°17′36″E). (E) Sequence of four calcarenite units, forming a cycle of lagoonal and beach deposits overlying the Takamaka Limestone surface, arrows mark the base and top of the sequence. Site 30A, western lagoon shore of Passe Houareau (9°22′31″S, 46°26′20″E). (F) Surface of the Takamaka Limestone, bored by *Lithophaga* and clionids, and overlain by centimetres thick sheets of medium-grained calcarenite, containing the distinctive *Fragum–Strombus–Polynices* fauna in the position indicated by the red arrow. Overlain by a large *Porites nigrescens* colony reflecting deposition of the Aldabra Limestone. Site 43B, a headland on the southern coast of Polymnie, *ca* 2.8 km east of Passe Gionnet (9°23′01″S, 46°18′06″E).

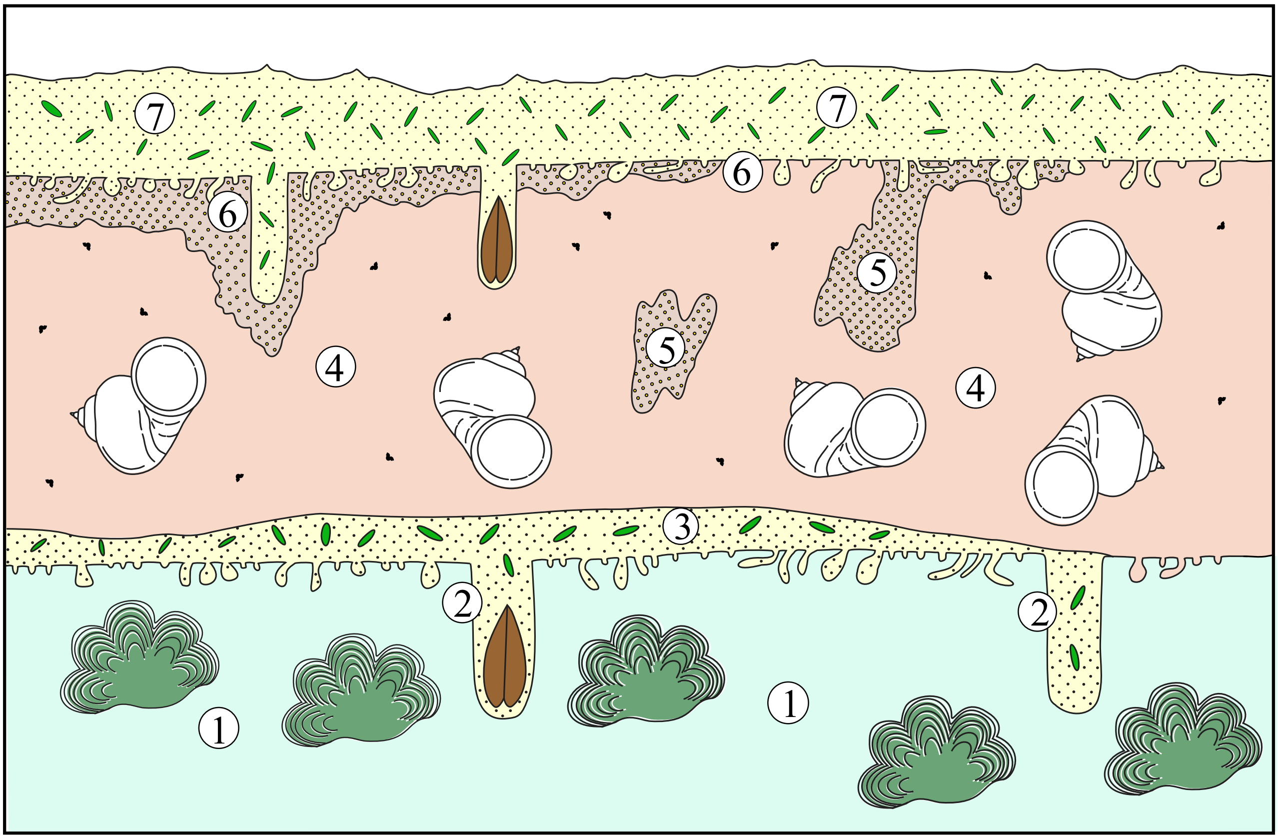

Fig. 4. Section, about 25 cm thick, through rocks overlying the Takamaka Limestone at Dune Jean Louis with multiple erosion surfaces. 1 = Takamaka Limestone with nodose calcareous algae. 2 = surface bored by *Lithophaga* and *Cliona*. 3 = calcarenite rich in *Halimeda*. 4 = earthy calcarenite containing terrestrial gastropods including *Trophidophora*. 5 = cavities in an irregular erosion surface contain well cemented calcarenite. 6 = truncated surface bored by *Lithophaga* and *Cliona*. 7 = *Halimeda*-rich calcarenite. The vertical scale is approximately 25 cm. Dune D'Messe, locality 44C 9°26′39″S 46°23′31″E.

circumference of the atoll. However, although these reflect important variations in the distribution of elements of the biota of the Aldabra Limestone, they encourage the view that they were collectively contemporaneous, representing the distribution of contrasting environments around the atoll at some 'geological moment'. This overlooks information on the nature of the processes of deposition, but also the fact that the unit represents a time *interval*. There is of course evidence for contemporary variation, with massive and generally smaller corals more common in what was probably a lagoonal environment, whereas branching corals and framework areas are typically closer to the present outer margins of the islands. The surfaces exposed, only preserve the outer parts of the environmental systems represented, but there are real differences, underlined by the contrasting environments implied by different faunal elements. Viewed from a sedimentological perspective, observations reflect variations in depths of deposition and hydrodynamics that are not easily resolved as 'contemporary'. The base is defined by the subaerial and marine erosion surfaces (and deposits) bounding the Takamaka Limestone (regarded as products of MIS 5), whereas the top is truncated by marine terraces, modified by subaerial erosion, that collectively imply the loss of some unknown thickness of limestone. Thus, limited by these relatively planar features, the deposits form an apparently unified stratigraphical unit, assumed to represent a finite period. The question, therefore, is whether they were strictly 'contemporaneous'. Do these deposits represent a traditional sequence, theoretically 'layered' from base to top, with time-based variation expressing the superposition of Nicholas Steno (1669), or are they the cumulative result of what can be

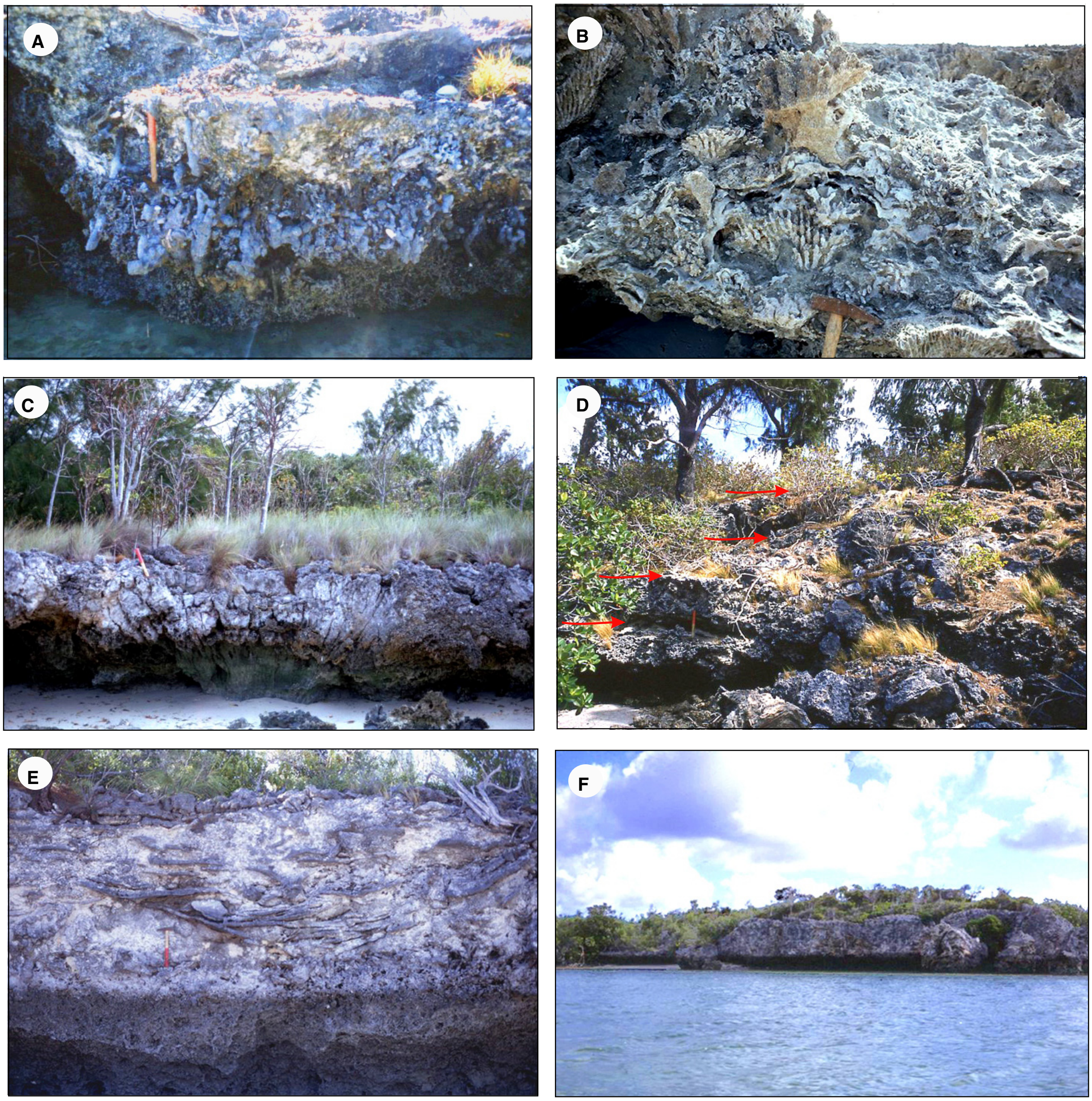

Fig. 5. (A) Extensively burrowed calcarenites overlying the Takamaka Limestone suggest a stronger lagoonal influence in some areas. Site 43C, lagoon shore *ca* 1.75 km south-east of Passe Gionnet (9°22′53″S, 46°17′36″E). Here and in other images in the group the scale is indicated by a 2 kg hammer with a shaft of *ca* 30 cm. (B) Coralgal growth frame with *Acropora* and repeated crusts of calcareous algae. Site 03B south end of Picard island 9°23′56″S, 46°12′21″E). (C) Massive *Porites* microatoll. Although growth on the margins of this colony was apparently continuous, successive surfaces within the centre bear small *Pocillopora*, *Favia* and calcareous algae that define relatively long-lived pauses in deposition. Site 13B, Petit Grande Poche north-east coast of Picard (9°23′24″S, 46°14′40″E). (D) The Aldabra Limestone rests on the ramp-like marine erosion surface of Takamaka Limestone, here forming cliffs 4 to 5 m high. A series of discontinuous 'bedding' surfaces, indicated by red arrows, is locally present within the sequence. Site 30A, western lagoon shore of Passe Houareau (9°22′31″S, 46°26′20″E). (E) In some areas, corals form the main structural elements. Among these, *Acropora hyacinthus* is conspicuous, with relatively thin, concave-up, sheets up to *ca* 2 m in diameter, some of which are *in situ*. Site 15J, Palm Beach, Polymnie (9°22′28″S, 46°16′04″E). (F) At the entrance to Bras Grande Poche, the largest inlet on the eastern shore of Picard Island, and at Bras Grande Poche and Bras Tanguin, areas of coral frame, heavily bored and encrusted by calcareous algae, form extensive knolls rising >2 m above the background calcarenites. Site 15D (*ca* 9°22′46″S, 46°14′25″E).

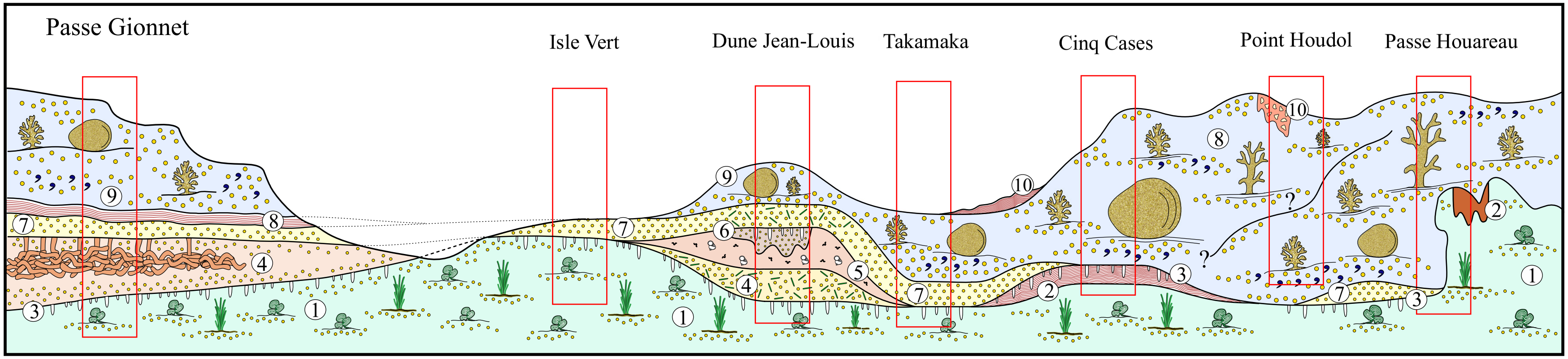

Fig. 6. Schematic illustration comparing variations in sequences of the Aldabra Limestone and their supposed relationships, with approximate positions. For the purposes of illustration, these are not to scale. 1 = Takamaka Limestone, muddy calcarenite with nodose red calcareous algae and *Halimeda* but few corals. 2 = terrestrial laminated crust and earthy terrestrial cavity fillings. 3 = marine erosion surface with borings by *Lithophaga*, *Cliona* and sipunculids. 4 = intensively burrowed muddy calcarenite, locally up to 1 m thick but represented elsewhere by up to six successive thinner units. These may equate to fine-grained calcarenites with *Halimeda* at Dune Jean-Louis. 5 = earthy deposit, ?palaeosol, with terrestrial snails including *Trophidophora*. 6 = well-cemented fine-grained calcarenite filling irregular erosion surface. Upper surface is bored by *Lithophaga* and clionids, details in Fig. 4. 7 = well-cemented calcarenite with *Halimeda*, locally with *Strombus–Polynices* molluscan community. 8 = laminated, ?terrestrial crust. 9 = Aldabra Limestone *sensu stricto*, calcarenite with rich coral and molluscan fauna, locally with microatolls and traces of bedding. 10 = dissolution pits filled with terrestrial soils and locally containing abundant bone fragments. Stromatolitic laminated crusts may be contemporary or overlying these.

regarded as 'cells of lateral accretion'? Evidence falls into four broad categories: (i) modifications in coral forms, implying pauses in deposition; (ii) boundaries within the stratigraphical sequence; (iii) changes in facies; and (iv) changes in the nature of deposition. The locations given for these features (Table 1) commonly include multiple examples and are not exclusive. A schematic illustration of the variations in the sequences described and their possible relationships is provided in Fig. 6.

Modifications of coral form

Patterns of coral growth reflect local variations in conditions during growth, including changes in water depths. North of the research station on Picard Island at Anse Var (Site 01B), *in situ* colonies of *Acropora* show repeated intervals in which a laminar encrusting growth habit is replaced by projecting branches that rise vertically from the successive sheet-like extensions of the colony, (the phenotypic plasticity of Todd, 2008). Interpretations of similar morphologies elsewhere have taken them to indicate periodic inhibition by surf action. Similarly, encrusting sheets of *Millepora* and calcareous algae separate alternating increments of growth frame and calcarenite, forming transient 'bedding' surfaces in which growth was punctuated by periods briefly dominated by algal growth or sedimentation (Fig. 5B; Site 26A). Some corals are encrusted by calcareous algae, and contribute to limited areas of growth frame, but interstitial sediments form a disorganized mass with randomly oriented larger bioclasts. At Grande Poche (Site 15A) on the north-east coast of Picard, a 40 cm high colony of *Acropora humulis* reflects repeated stages of growth and recolonization, with each stage encrusted by calcareous algae.

South of Passe Femme, on the west coast at Anse Anglais (Site 07A), corals are typically massive rounded forms >1 m in diameter with some *Porites ca* 4 m in diameter. Branching corals are less common and many of the *Porites* colonies have flattened upper surfaces with raised rims, forming microatolls. One example includes a small *Galaxaea* colony grown on the upper surface of the *Porites* and subsequently embedded in coarse coral and algal debris. A *ca* 1 cm thick layer of calcareous algae encrusts the vertical sides of the *Porites*. As Scoffin & Stoddart (1978) demonstrated, microatolls are generated by growth and are not simply truncated surfaces, but in either event they reflect a specific relationship to the air–water interface and thus to sea level (or sea levels). In these examples, it is implied that sea level at the time of growth was much lower than that indicated by the total thickness of the depositional unit, with a number of pauses in growth. Their structural position requires a sea surface below that necessary to support the frame areas at Anse Var (Site 01A). However, a short distance to the south (Site 07A), and inland from the present cliff, a *Millepora* colony >3 m in diameter, with plate-like branches oriented at right angles to supposed principal current directions (normal to the present coastal margin), is at the same structural level. This would also have required significantly deeper water than that responsible for the microatolls and therefore reflects a higher sea level. Species associated with this include *Platygyra*, *Goniastrea* and *Hydnophora*.

Groups of *Porites* microatolls, together with colonies of *Galaxaea*, *Stylophora*, *Millepora*, *Tubipora* and *A. palifera* dominate the fauna at Petite Grande Poche (Site 13B) on the north-east coast of Picard Island, but there is no evidence in the surrounding coarse calcarenite/calcirudite of any break in deposition. However, a 2.5 m colony of *Porites* (Fig. 5C) contradicts this observation. Although growth on the margins of the colony was apparently continuous, successive surfaces within the centre bear small *Pocillopora*, *Favia* and calcareous algae, defining a series of relatively long-lived pauses in deposition. Although many colonies in this area have microatoll surfaces, these are at different levels and are not contiguous. However, individually they represent low tide levels during numerous relative stillstands and the sizes of colonies imply that these extended over periods of *ca* 200 years. Although there is one well-defined break in deposition that has a small *Porites* colonizing the new surface, there is typically very little modification of the sediment surface before deposition was resumed. Alternatively, the same observations might simply indicate that coral and sediment surfaces were not contemporary. The molluscan fauna typically includes species reflecting sandy shallow-water environments (Taylor, 1978).

The critical point that these features demonstrate is that deposition was not a 'continuous' process and, although in general terms sea level would have been rising, this was not achieved by a gradual progression but in a series of small-scale surges punctuated by periods of relative stasis or even regression. Similar punctuated sequences were recorded by Montaggioni & Hoang (1988, fig. 8) in the granitic Seychelles. The meltwater pulses recorded more recently in Caribbean successions (Fairbanks, 1989; Braithwaite, 2016b) reflect a similar punctuated rise on a larger scale. The apparent disparities between shallower and deeper water on Aldabra can be resolved by regarding features at the same structural level as having formed at different depths, and therefore at different times.

Boundaries within the Aldabra Limestone

In addition to boundaries within the depositional sequences beneath the Aldabra Limestone, illustrated in Figs 3E, 3F and 5A, there are also discontinuities within the unit. Inland from Anse Var (Site 01B), colonies, typically of massive corals, appear to have settled on an irregular low-relief surface within the sequence, and are interpreted as reflecting an intraformational pause in deposition. Associated calcarenites show wide variations in grain size, implying differing hydrodynamic conditions, and although they occupy spaces between frame areas, they locally define distinct surfaces bound by crusts of *Millepora*, calcareous algae and alcyonarians. The associated molluscan faunas sample both sand crevice and coral-living communities. Some corals, like *Millepora*, are active surf seekers, whereas others, including *Acanthastrea* and *Stylophora*, favour sheltered spots within the wave-beaten environment implied, that seems unlikely to have been a reef edge.

High cliffs (3 m) at Entre Deux (Site 15I) on the south-eastern extension of Picard Island include a well-defined erosion surface. The lower 150 cm of the cliff contains massive corals including *Porites* and *Goniastrea*, typically with flattened tops bored by *Lithophaga* and with *Chama* cemented to surfaces. By contrast, the upper unit comprises massive *Porites* knolls, surrounded by calcarenite including molluscan and coral debris and a sand-dwelling molluscan community.

On Polymnie, on the lagoon coast south of Anse Cèdre (Site 15J), 4 m high cliffs of Aldabra Limestone rest on an eroded surface ramp of Takamaka Limestone, but include at least two 'low tide' levels, reflected in groups of *Porites* microatolls. The best-defined surface, *ca* 3 m above the present lagoon floor is nearly contiguous with an intraformational surface bored by *Lithophaga*. A parting at a comparable level elsewhere in the succession includes red-brown putative terrestrial material. The relief on these surfaces is at least a metre. Fragmented areas of *Galaxaea* and stagshorn *Acropora* (cf. *formosa*), the last >6 m across, indicate breakage in place, but with growths of encrusting calcareous algae re-forming a framework.

On the southern coast of Main Island, *ca* 250 m south-east of Cinq Cases Camp (Site 19H), cliffs of Aldabra Limestone, *ca* 5 m high, consist largely of coral and calcareous algal calcirudite, with a sandy carbonate mud matrix, locally rich in *Halimeda*. Poorly-defined layers resemble bedding, but do not form any consistent pattern. Numerous spray-like *Acropora* with one patch of a small stagshorn, (*Acropora* cf. *formosa*), are associated with large colonies of *A. palifera,* a 1.5 m *Porites* microatoll, faviids and *Goniastrea*.

Like those at Cinq Cases, the limestones at Point Houdol (Site 20A) are predominantly calcarenites, locally coarsening to calcirudites in which *Halimeda* forms up to 80% of bioclasts. Poorly defined layers again resemble bedding. However, there is a significant difference in the greater numbers of corals here, which include massive *Porites* and *Platygyra* (commonly 1.0 to 1.5 m diameter), and large colonies of *Acropora palifera*, *Favia* spp., *Goniastrea* and *?Acropora hyacinthus*. Many of these are in the growth position, accompanied by rhodoliths and algally encrusted cobbles. The molluscan fauna associated with these deposits includes *Turbo*, *Tridacna* and *Conus* spp. However, there is a clear stratigraphical break *ca* 2 m below the top of the cliff, with the lower limestone containing large colonies of *Acropora palifera*. About 400 m north-west of Point Houdol, around a large pool (Site 20B), an irregular erosion surface separates two essentially similar *Halimeda*-bearing limestones, with small spray-like *Acropora* common locally, together with small massive corals including *Platygyra*, *Acropora* spps. and *Pocillopora*.

At Passe Hoareau (Site 30A), the Aldabra Limestone rests on the surface ramp of Takamaka Limestone, and forms cliffs 4 to 5 m high. A series of 'bedding' surfaces is present locally within the sequence (Fig. 5D), but are not, unfortunately, laterally continuous. The two lowest are simply sediment defined, but above these the third incorporates the truncated top of a massive *Porites* colony >4.5 m in diameter and *ca* 1.0 m high. *Porites* is common here, with *Favia* spps., *Goniastrea* and *Pocillopora*.

Borings, including *Lithophaga*, are common on the surfaces of the massive colonies. A small area of the cliff consists almost entirely of separated calyces of *Galaxaea*, remnants of a large colony broken *in situ*, with sprays of *Acropora* spps., *Millepora* and *Platygyra*. Areas of growth frame are comparatively small, but may be persistent, with colonies linking upward through the calcarenite that supports them laterally. Both massive and branching corals are associated with thin sheets of encrusting calcareous algae. Similar bedded Pleistocene sequences are recorded elsewhere, including examples in MIS 5 limestones in Nyali Quarry in Mombasa, Kenya, with multiple layers (Braithwaite, 2016b, fig. 12). Local variations in Aldabra stratigraphy are illustrated schematically in Fig. 6.

Facies changes

On the east coast of Picard Island, *ca* 200 m south of the entrance to Main Channel (Site 15E), there is a facies transition. Biofacies change from an area characterized by small coral knolls to one dominated by coral frame, with parallel changes in coral composition. Locally, corals include branching and plate-like *Millepora* and *Acropora* spps. including large stagshorn *Acropora*. *Millepora* is more common here than further south, whereas stagshorn *Acropora* is generally less so. Branching *Porites* and *Galaxaea* are associated with massive *Porites* several metres in diameter, Faviids *Goniastrea* and *Pocillopora* spps. with extensive nodular and encrusting calcareous algae. Molluscs are relatively sparse but include *Turbo* spps., *Tridacna*, *Spondylus* and *Cerithium* that imply an environment in which sea level was >5 to 10 m above the present datum.

Corals form the dominant structural element at Palm Beach, Polymnie (Site 15J), but among these, *Acropora hyacinthus* is conspicuous, forming relatively thin, concave-up, sheets up to *ca* 2 m in diameter. Some of these are *in situ* (Fig. 5E), but disoriented and inverted colonies are also present and imply growth on a relatively steep slope where they could have been more easily overthrown. *Acropora hyacinthus* is typical of deeper calmer waters on reef fronts, and one of the less common elements in the associated fauna is a small dendrophyllid. This genus is also typical of deeper waters but occurs today on Aldabra in water 5 to 15 m deep, facing strong tidal currents in both Gionnet Channel and Passe Hoareau. North of Palm Beach, the upper part of the *ca* 8 m high seaward cliff consists largely of boulders of massive corals, including *Favia*, *Goniastrea* and a few upright *Porites*. These occur in a poorly stratified sandy-rubble matrix with fragments of *Acropora* spps., *Seriatopora* and *Millepora*. There is no obvious sedimentological break between lower and upper portions of the cliff here, but contrasts between the seaward margin and the lagoon shore of the island reflect a dramatic facies change, noting that the supposed ‘deeper’ species apparently lie inboard from the faunas in rocks forming the present seaward cliffs. A similar contrast occurs in Palm Beach Bay, where *A. hyacinthus* is common on the west side but relatively rare to the east, although both areas include growth frame with many species in common.

The eastern headland at Anse Cèdres, Polymnie (Site 18A), provides further examples of contrasts. The cliffs expose >6 m of limestone with predominantly branching corals including *in situ Acropora palifera* >2 m high, encrusting sheets of *Echinopora*, large numbers of *Acropora* spps., *Goniastrea*, *Platygyra* and *Galaxaea*. Knobbly rhodoliths are scattered in areas of debris rather than contributing to any framework. However, across Main Channel, near the entrance to Bras Grande Poche, the largest inlet on the eastern shore of Picard Island (Site 15D), and in Bras Tanguin, areas of coral frame, extensively bored and heavily encrusted by calcareous algae, form knolls up to 2 m high (Fig. 5F). Between the knolls, bioturbated calcarenites locally include patches of shelly and coral-rich debris. Within Bras Grande Poche, north of the main beach, cliffs of calcarenite/calcirudite *ca* 7 m high include large areas of broken, but mainly *in situ* stagshorn *Acropora* at the top. Concave sheets of *Acropora hyacinthus* >2 m in diameter appear at intervals, with *Galaxaea*, *Millepora*, *Acropora* spps., *Porites* and *Platygyra*. Most seem ‘freshly’ broken, lacking algal encrustation, although there are exceptions associated with knobbly free-living rhodoliths. Large *Acropora palifera* and *Lobophyllia* appear to be *in situ*, but contrast with much greater proportions of unsorted coral debris than of massive corals. Near the base of the cliff a massive *Porites*, *ca* 4 m in diameter but only 30 to 40 cm high, is associated with encrusting calcareous algae and *Goniastrea*. A single colony of *A. humulis*, also about 40 cm high, occurring in an area of sandy carbonate mud, shows successive stages of growth and recolonization capped by

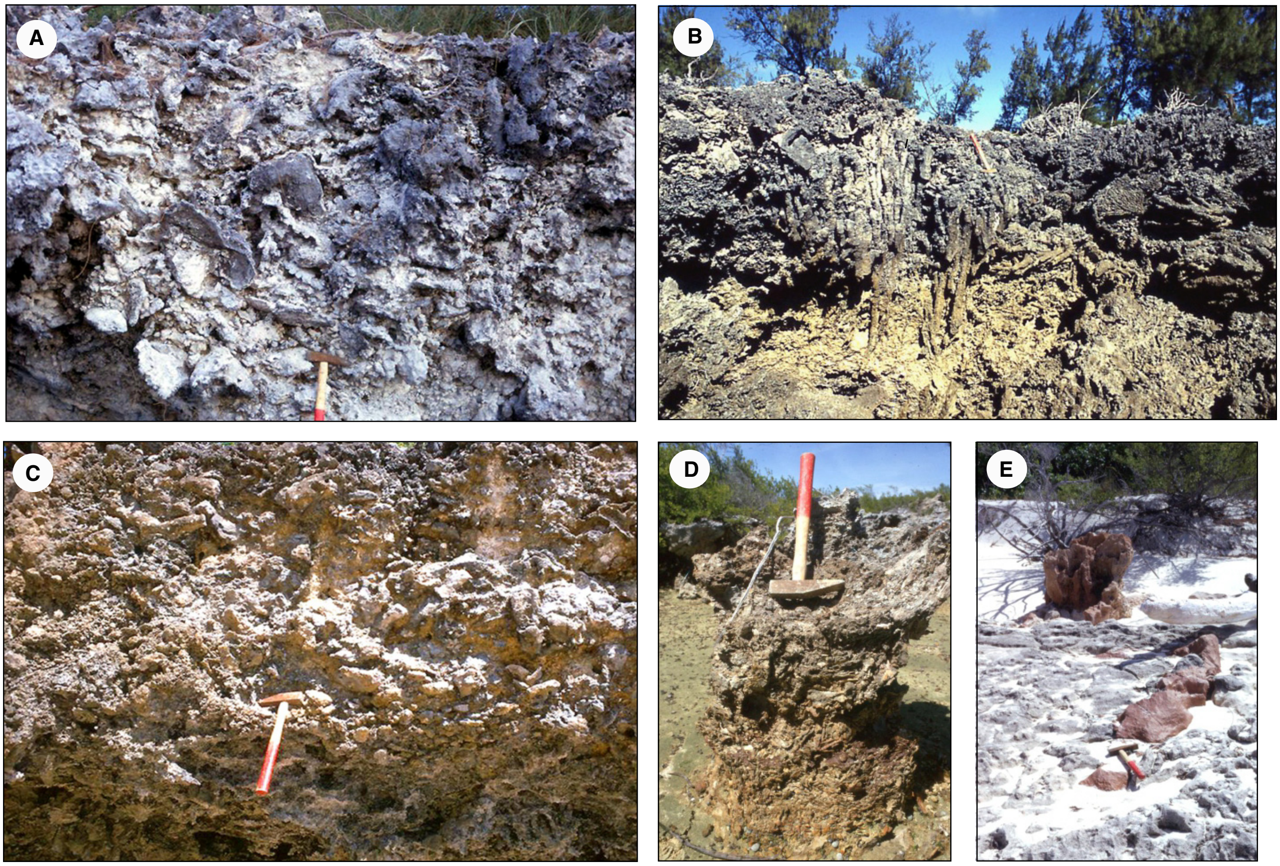

Fig. 7. (A) Areas of 'fresh' coral and calcareous algal debris suggest rapid burial without reworking, potentially indicating storm deposition. Similar debris is present on the shore of Palm Beach, Polymnie, Site 15J (9°22′28″S, 46°16′04″E). The hammer used for scale in this and subsequent images in this group is 2 kg with a shaft *ca* 30 cm long. (B) On the northern coast of Middle Island (Isle Malabar), *ca* 1.4 km west of Passe Houareau, cliffs *ca* 5 m high consist of *Halimeda*-bearing calcarenites with a prolific coral fauna. The dominant frame elements are large (some >2 m high) colonies of *Acropora palifera* associated with both massive *Porites* (>2 m diameter) and *Porites nigrescens*. Site 31A (9°22′20″S, 46°25′36″E). (C) Coarse calcirudites, locally interspersed with areas of coral frame, consisting of rounded pebbles and cobbles of coral, encrusted by calcareous algae, reflecting protracted reworking. Site 35A, *ca* 3.5 km west of Passe Houareau (9°22′11″S, 46°24′34″E). (D) Large numbers of dissolution pipes are scattered across the surface of the Aldabra Limestone. Many of these contain deposits of bones (mainly of tortoises), as at Point Houdol, Site 20A *ca* 100 m south-west of trees (9°24′03″S, 46°31′21″E). (E) Red fine-grained deposits also fill fractures across the atoll, with a good example *ca* 500 m north of Anse Mais, north-west Grande Terre, Site 08A (9°26′28″S, 46°12′50″E).

encrusting calcareous algae. Associated molluscs include *Barbatia*, *Tridacna*, *Strombus* and *Conus* together with *Heterocentrotus* spines. Approximately 2 m above the lagoon floor, a well-defined break in deposition is traceable for some tens of metres, fading southward. A relative sparsity of large corals below this surface provides the only distinguishing feature. In some areas, 'fresh' coral and calcareous algal debris imply breakage and rapid burial, without reworking, potentially indicating storm deposition (Fig. 7A; Site 15J). Similar debris is present locally on the opposing shore of Polymnie.

For 200 to 300 m on the coast south of Bras Grande Poche, plate-like corals are comparatively common, but small massive species increase in numbers and there is a marked facies change near Petit Grande Poche (Site 13B). The fauna here is dominated by *Porites* microatolls, with *Galaxaea*, *Millepora*, *Tubipora* and *A. palifera*. Locally, coarse detritus between coral heads comprises stick-like *Acropora* fragments, together with overturned *Stylophora*, *Acropora* and rhodoliths. Varied molluscs include *Cerithium* spps., *Cypraea* and *Turbo*.

On the northern coast of Middle Island (Isle Malabar; Sites 31A and 35A), west of Passe Houareau, cliffs *ca* 5 m high, consist of *Halimeda*-bearing calcarenites with a prolific coral fauna. The dominant frame elements are large (some >2 m high) colonies of *Acropora palifera* (Fig. 7B; Site 31A), associated with both massive *Porites* (>2 m diameter) and *Porites nigrescens*. Small *Acropora* spp. are common, with one *Goniastrea* microatoll towards the top of the sequence. Other species include *Favia* spps., *Platygyra*, *Millepora, Pocillopora* spps., *Galaxaea* (one *ca* 1.5 m diameter)*, Pocillopora eydouxi* and *Platygyra*. Encrusting sheets of calcareous algae are associated principally with areas of growth frame. Well-defined areas packed with fragments of stagshorn *Acropora* reflect *in situ* breakdown of colonies that appear 'fresh', lacking algal encrustation. Corals are relatively sparse in the lower parts of the cliffs but are typically large 'massive' forms, separated by areas that are mostly calcarenite. They become more common upward, including in particular small *Favia* spps. At intervals, associated calcirudites consist of rounded pebbles and cobbles of coral encrusted by calcareous algae (Fig. 7C; Site 35A), reflecting extensive reworking. Molluscs include *Turbo*, *Lambis*, cowries, *Tridacna*, *Cerithium*, *Spondylus* and a few small *Conus* sp., with scattered spines of *Heterocentrotus*. Interpretation of this biota suggests that it reflects a position close to an active edge but not breaking the surface, with moderately rough water probably several metres deep. At times sea level would have been >10 m above the present datum but parts of the sequence may have shallowed upward to a tide limited position.

East of Passe Houareau, on the north coast of Grande Terre (South Island; Site 37A), the lower portions of the cliffs generally contain fewer corals, but those present include massive *Porites*, and scattered large *Acropora palifera*. Small 'massive' colonies become more common upward, where the limestones are typically coarse coral gravels with patches of calcarenite, locally rich in *Halimeda*. In these areas few corals are in place, and some >1 m diameter are overturned, but patches of corals and calcareous algae locally form knolls *ca* 1 m high.

North of Point Houdol, on the east coast of Grande Terre (Site 24A), cliffs 6 to 7 m high contain numerous large corals in growth position; some are encrusted with calcareous algae whereas others appear relatively 'fresh', lacking either borings or encrustation, and again imply rapid burial. The topmost metre of the cliff consists of numerous closely packed knobbly calcareous algae, locally forming a contiguous loose frame.

On the coast south-west of Cinq Cases (Site 22A) on Grande Terre, the Aldabra Limestone includes large areas of growth-frame separated by calcarenite that includes scattered *Halimeda*, and knobbly and encrusting calcareous algae. Some areas are relatively coarse, comprising colonies of *Acropora* spps., *Favia* spps.*, Goniastrea* and *Porites*, some of which are relatively large. The sparse molluscan fauna includes *Turbo* spps. and *Tridacna*. Inland to the north, and overlying these deposits, patches of fine-grained calcarenite form a 30 to 40 cm thick sheet packed with calcareous algae.

Changes in facies occur both geographically and within vertical successions. It seems unlikely that these represent the distribution at a specific time, comparable to the biozones of a Holocene reef. They can, however, be explained if they formed at different times, partitioned by their relative positions on a surface with up to 10 m local relief. The latter point is important because it implies that samples collected near the base of the unit may be younger and, conversely, those at the top potentially older than the mean age.

Changes in the nature of deposition

Debris encrusted by calcareous algae is widespread inland from the cliffs at Anse Var on Picard Island (Site 01B), and elsewhere, but in some areas, delicate branching corals like *Pocillopora*, lack algal crusts and appear freshly broken and, by inference, rapidly buried. Well-preserved molluscs in these areas include *Turbo* that retain operculi, also supporting a rapid burial. However, the scattered appearance of patches of rounded coralgal cobbles implies erosion of a framework and extensive reworking, with debris probably transported during storms into what appears to have been a palaeo-back-reef lagoon. Massive corals, including *Goniastrea* up to 2 m diameter, occur towards the top of the succession, surrounded by calcarenite, but inland from the present cliffs, these become less common and of lower diversity. Clusters of molluscs include *Turbo* spps. (many with operculi), *Conus*, *Cypraea* spps., *Chama* spps., *Spondylus* and *Nerita* spps. (Taylor, 1978). Most imply a sandy back-reef environment although *Nerita* spps. are typical of the high intertidal zone.

Cliffs close to Dune Jean-Louis (Site 44A) on the south coast of Grande Terre consist of poorly sorted calcarenites with prominent *Halimeda* and large quantities of coral gravel, including fragments of *Galaxaea* and *Heterocentrotus* spines. Overturned colonies are common, including several large (>1 m) *Platygyra* on the west side of the beach, with comparatively little material that is *in situ*. However, what there is includes scattered large *Acropora palifera*, small *Acropora*, and alcyonarians, *Goniastrea*, *Favia* spps. and *Symphyllia*. *Acropora* is common at the tops of the cliffs, apparently representing local growth areas, but there are also numerous displaced and disoriented specimens. Collectively, these features imply a net accretion characterized by significant local relief.

FEATURES YOUNGER THAN THE ALDABRA LIMESTONE

Following deposition of the Aldabra Limestone a series of erosional events and deposits reprise features on the surface of the Takamaka Limestone. The 'final' thickness of the Aldabra Limestone is unknown but there is no evidence of a terminal depositional surface, or of how high sea level may ultimately have been (≥+15 m?; see below and Korotky *et al.*, 1992). The 8 m and 4 m terraces imply erosion, potentially of several metres, of lithified material, and unless they formed *after* the Last Glacial Maximum their diagenesis would have required a substantial retreat of sea level before a return to a position about +8 m above the present datum. The correlation of these features to similar elevations in Kenya and the granitic Seychelles argues that these changes reflect eustatic variation in sea level and, notwithstanding data from Madagascar (Stephenson *et al.*, 2019) do not reflect tectonically induced uplift.

A key feature of the present surface of the Aldabra Limestone is the presence of large numbers of dissolution pits reflecting subaerial exposure. Two distinct suites of fillings are recognized. Laminated rusty red-brown fillings may be a metre thick, with laminae steeply draped from cavity margins, suggesting that the contents may have shrunk after deposition. Fine-grained orange-red earthy fillings are typically structureless and packed with fragments of bones and older limestones, as at Point Houdol (Fig. 7D; Sites 20A and 20B). Some, like Islot Rose in the west channels area (Site 33D), occupy areas as large as 40 m^2. The remains recovered from them include tortoises, a crocodile, six species of lizard and a bird (Taylor *et al.*, 1979; Hume *et al.*, 2018). Locally, angular blocks of neomorphosed limestone up to 30 cm in diameter, with some surfaces coated with flowstone, represent areas of the walls of extensive cavities that may have been cave systems, like Caverne Patate on Rodrigues, Mauritius (Braithwaite, 1994). Parts of similar cavities, lined with fibrous brown 'stalagmitic' deposits, are present on cliff faces. Structureless red deposits containing bones are found filling fractures in the limestones north of Anse Mais, Site 08A.

The continuity of the 8 m and 4 m terraces around the atoll implies large-scale (marine) erosion events, but there is little evidence of the details of these. Commonly, present coastal erosion has removed much of the seaward surface of the 4 m terrace. However, there are areas on the south coast where shallow channels are preserved and small areas of raised beachrock include probable *Ocypode* burrows (Fig. 8A; Site 39C). On the landward margins, the terrace slopes gently towards the present lagoon floor (Fig. 8B). A dark-brown laminated crust coating the limestone surface on the shore of Cinq Cases Creek (Site 22F), contains *Melampus* and *Terebralia* (Fig. 8C). These imply an environment dominated by mangroves, whereas the overlying calcarenite includes *Fragum*, *Strombus*, *Cerithium* and *Chama*, suggesting reversion to a shallow lagoon (Taylor, 1978). Laminar crusts overlying the Aldabra Limestone in the Takamaka area (Site 26F) form conspicuous stromatolitic bodies from centimetres to metre sizes (Fig. 8D). These seem to be relatively young, but contemporary stromatolites on Aldabra (Braithwaite *et al.*, 1989) are morphologically distinct. These deposits and the laminated crusts in particular, seem comparatively fresh, although not presently active. Similar crusts appear to have formed, with cavity fillings, several times in the past. Although probably not deeply submerged, the stromatolites would have required a sea level marginally above its present position. Thin discontinuous sheets of burrowed calcarenite locally rest on the eroded surface of the Aldabra Limestone (Fig. 8E) in the Cinq Cases area (Site 19F) but similar calcarenites are apparently interleaved with extensive earthy cavity fill deposits [Fig. 8F; Cinq Cases (Site 19D)]. The relative ages of these deposits are unknown, but, together with the terraces, they point to three or

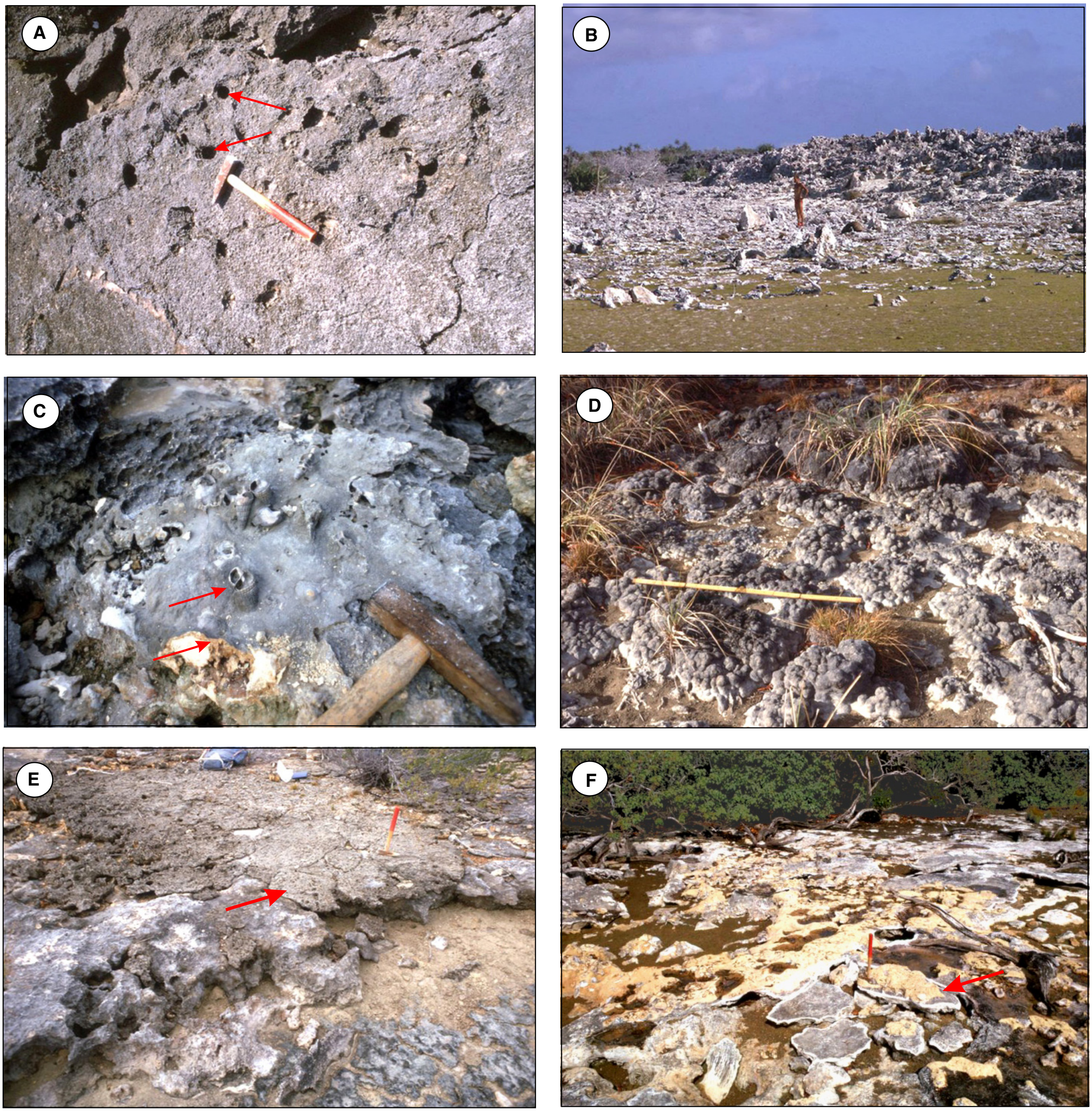

Fig. 8. (A) Raised beachrock perched on the edge of the 4 m terrace with open *Ocypode* burrows (two indicated by red arrows). Hammer for scale, 30 cm. Site 39C, coast *ca* 500 m east of Dune D'Messe (9°28′16″S, 46°19′55″E). (B) Little remains of the seaward surface of the 4 m terrace, cut away by coastal erosion, but it is obvious on the landward margins, with a transition to the north (right) to an old lagoon floor, sloping gently towards the present lagoon in the Cinq Cases area, Site 22C (9°26′39″S, 46°28′54″E). Figure for scale *ca* 1.85 m tall. (C) A dark-brown laminated crust (red arrow), coating the limestone surface on the shore of Cinq Cases Creek. Contains scattered *Melampus* and *Terebralia* (red arrow), implying a terrestrial environment, whereas the overlying calcarenite includes a diverse *Fragum–Strombus* fauna reflecting a shallow lagoonal environment Hammer for scale, 30 cm. Site 22F (9°25′46″S, 46°29′43″E). (D) Laminated crusts north of Takamaka Grove (Basin Ibis), Site 26F, form conspicuous stromatolitic bodies ranging from centimetres to metre in size (metre rule for scale) (9°25′58″S, 46°27′29″ E). (E) Thin discontinuous sheets of burrowed calcarenite rest on the eroded surface of the Aldabra Limestone (red arrow; 30 cm hammer for scale). Cinq Cases area, Site 19F (9°25′48″S, 46°29′49″E). (F) Calcarenites apparently interleaved with extensive earthy cavity fill deposits (red arrow; 30 cm hammer for scale). Cinq Cases, Site 19D (9°25′40″S, 46°30′53″E).

more stillstands or oscillations of sea level before it began its descent towards that of the Last Glacial Maximum.

EVIDENCE FROM ASSUMPTION ISLAND

The island of Assumption, *ca* 45 km south of Aldabra provides additional evidence. Given the relative sizes of the islands, with a total area of *ca* 365 km^2 on Aldabra against 11.6 km^2 on Assumption, it might be expected that the stratigraphy of Aldabra would be more complete, with sequences on Assumption, resulting from a parallel sea-level history, abbreviated to some extent. However, the stratigraphy of Assumption, briefly described by Korotky *et al.* (1992), appears to be radically different.

The oldest deposits on Assumption, dated using ^{230}Th/^{234}U, are younger than the oldest on Aldabra and form 'Marine Terrace II' (at 4 to 8 m *sic*) of Korotky *et al.* (1992). The base comprises light coloured limestone with: "coarse cross-laminations, containing abundant poorly-rounded large coral detritus". In fig. 2 of Korotky *et al.* (1992), these deposits, described as 'Lagoonal', are about 1 m thick. The age attributed to them, and presumably obtained from one of the corals, is 127 ± 2.7 ka, relating to MIS 5. Confusingly, the authors' fig. 2 implies that this lies below high water mark. However, the diagram shows the top as an irregular erosion surface, overlain by 'Reef Limestone' dated at 115 ± 1.8 ka. This is approximately 2 m thick with *in situ* corals and lenses of coarse calcarenite at the base and top. It is truncated by a well-defined 'bench' with a carbonate ('chemogenic or algal' *sic*) crust 0.1 m thick. Overlying this sequence, 1.5 m of weakly lithified cross-bedded calcarenite includes branching structures 'suggestive of roots' and interpreted as representing possible mangrove marsh. The latter deposits are dated at 96 ± 3.0 ka (Korotky *et al.*, 1992, fig. 2). The youngest age, of 82 ± 2.7 ka, relates to the fill of a fissure in the older limestones. The authors regard aeolian sands resting on these deposits to be of early Holocene age.

The highest parts of Assumption, form the 'Marine Terrace III' of Korotky *et al.* (1992), and extend from 10 to 14 m above present sea level characterized by large-scale karst relief. The base of this sequence consists of 'Reef Limestone' containing large corals, and overlying deposits include coarse limestone breccias with horizontal seams (*sic*) of calcarenites. The surface of this has been 'intensely corroded' and phosphorite has accumulated in the depressions formed. The upper part of the section consists of shallow 'lagoonal' calcarenites overlain by 'algal limestones' with a pronounced carbonate crust at the top providing a ^{230}Th/^{234}U date of 110 ± 4 ka. However, the exact stratigraphical position of the phosphorite is not clear. All of this material lies above the level of the well-defined 8 m terrace surface on Aldabra and raises the question of whether a similar extension had ever been present there. The younger ages obtained suggest that sea level was significantly above its present position until about 80 ka. These results indicate that in a period broadly equivalent to that in which the Aldabra Limestone was deposited, sea level varied, with Assumption experiencing at least three intervals of erosion, interpreted as reflecting relative falls in sea level, leading to the expectation that these should also be expressed on Aldabra. The Pleistocene succession on the Kenya coast (Braithwaite, 1984) more closely resembles that on Aldabra and it is not clear how the Assumption sequence fits with these. One explanation, mooted by Pratt *et al.* (2017), is that differences in the sequences reflect the marginal influence of the crustal movements on Madagascar described by Stephenson *et al.* (2019).

DISCUSSION

The position of sea level during the Last Interglacial interval has been a matter of some contention. The superposition of the units described here provides relative ages but the precise chronology of events depends on the reliability of the ages obtained. The spurious ages initially generated by radiocarbon methods were rejected, but there remain issues regarding uranium/thorium dates, where techniques have seen significant advances in recent years (Cheng *et al.*, 2013). A critique of the various models is provided by Scholtz & Mangini (2007) that also raises the important issue of replication. Thermal ionization mass spectrometry (TIMS) measurements of subsamples from the same coral, screened to eliminate diagenetic changes, may nevertheless vary. This is in part a result of undetected diagenetic changes but also of changes in methods, underestimating errors. It might be argued that the redistribution of undetectably small amounts of uranium, with a profound effect on the ^{230}Th/U age would render any results useless. However, when it is not possible to replicate and revise existing analyses, it is difficult to reject them. For this reason, the ages quoted here are published results. Some (e.g. Dutton *et al.*, 2015) use more advanced methods, such as multicollector – inductively coupled plasma – mass spectrometry (MC-ICP-MS; Cheng *et al.*, 2013) but for the most part other ages do not appear to be wildly divergent. Although their accuracy may be questionable, they seem to provide credible guides to relationships.

Chen *et al.* (1991), using $^{234}U/^{230}Th$ data, argued that in the Bahamas a high sea-level stand (*ca* 6 m above present low water), began about 132 ka (possibly 129 ka) but stayed in the same position until *ca* 120 ka, when it fell rapidly. However, Sherman *et al.* (1993) found evidence in corals on Oahu, Hawaii, for two distinct sea-level highstand intervals during the Last Interglacial (substage 5e), using both electron spin resonance and uranium-series dates (152 ± 25 to 122 ± 8 ka and 160 ± 15 to 115 ± 10 ka, respectively) to determine age. Similarly, Aharon (1983) recorded reef crests on the coast of New Guinea at 133 ± 4 ka and 120 ± 3 ka, when sea level was $+8 \pm 3$ m and $+5 \pm 5$ m above the present datum. Yokoyama *et al.* (2018) recorded two pauses in the fall of sea level on the Great Barrier Reef approaching the Last Glacial Maximum that are considerably younger than the pauses considered here but were thought to relate to exceptionally rapid growth of ice sheets.

Hearty *et al.* (2007) examined data from Bermuda, the Bahamas and West Australia and concluded that there was evidence for several sea-level intervals. These were marked by:

1 The post-glacial MIS 6/5e Termination, before 130 ka, with a later rise above the present level.
2 Relative stability at +2 to 3 m for several thousand years (130 to 125 ka), in which fringing reefs were established.
3 A brief fall to near or below present sea level around 125 ka.
4 A rise to +3 to 4 m (*ca* 124 to 122 ka).
5 A period of instability at *ca* 120 ka.
6 A rapid rise to +6 to 9 m marked by the formation of benches, followed by a rapid descent after 119 ka.

These variations (upward surges) were explained as reflecting the unstable melting of grounded ice sheets. Barlow *et al.* (2018), modelling proxy data derived largely from high latitudes, suggested that during the Last Interglacial, MIS 5e *ca* 129 to 116 ka, sea level reached 6 to 9 m higher than its present position, but argued that any variation could only have been small (<4 m). Thus, although there is general support for a higher sea levels, they found no evidence for ice sheet regrowth, and no explanation for falling sea-level fluctuation within this period. Nevertheless, variation is implied by geological observation and ice sheets must have regrown as the climate cooled, but so far there does not seem to be direct evidence that this was other than a gradual process.

The deposits on Aldabra formed during the Last Interglacial and are at similar elevation to rocks of equivalent age in many other areas. However, the deposits demonstrate that there is unlikely to have been any overarching pattern to deposition like 'shallowing-up'. There is local evidence of shallow water, both earlier and later during deposition, but no continuous record. Pauses in deposition are equally inconsistent in relation to position. As in many present reefs, debris forms a very large proportion of the net aggradation, commonly filling low-lying areas of a substantial relief. The distribution of elements of the Aldabra biota can be viewed in terms of such relief. Thus, within the period represented by the entire unit, 'contemporary' growth was separated topographically at relatively high or low levels. Conversely, although areas may now be at broadly similar elevations relative to present sea level, they nevertheless represent deposition at different depths and/or different times. Many of the examples described show growth of corals with specific relationships to sea level.

The uranium series ages of Thompson & Walton (1972) on Aldabra support this hypothesis. They were obtained from nine separate localities (one was rejected as unreliable) mostly from the north-eastern corner of the atoll. Three gave ages of 136 ± 9 ka, with one each at 134 ± 9 ka, 126 ± 8 ka, 124 ± 8 ka, 123 ± 8 ka and 118 ± 7 ka, potentially a spread of at least 18 ka between the beginning and end of deposition. The present author can reasonably add to these, dates from poorly described but separate intervals of deposition on Assumption, ranging from 127 ± 2.7 to 110 ± 4 ka. Investigations elsewhere (Braithwaite, 2016b) have shown significant differences in the ages of reef rocks that purport to be from the same depositional unit.

Vyverberg *et al.* (2018), principally on La Digue in the granitic Seychelles group, also recorded episodic growth during this period. Age dates for La Digue obtained by Dutton *et al.* (2015) show material ranging from 143.0 ± 1.0 to 86.0 ± 0.4 ka only a few metres above present sea level, with no clear correlation between elevations of samples and age. Their calculations suggested a gradual rise in sea level but noted that a +5.9 ± 1.7 m eustatic sea-level position at 128.6 ± 0.8 ka required the partial collapse of the Antarctic ice sheet. These broadly correspond to the $^{230}Th/^{234}U$ ages of 139 ± 11 ka (+2 m), 135 ± 10 (+2.5 m), 133 ± 10 ka (+7 m) and 123 ± 8 ka (+5 m) obtained by Montaggioni & Hoang (1988) from Praslin, La Digue and Curieuse, respectively, and interpreted as reflecting separate, high sea-level stands at 139 to 133 ka and *ca* 123 ka. Other results from La Digue, provided by Israelson & Wohlfarth (1999), interpreted TIMS $^{238}U/^{234}U/^{230}Th$ ages of corals as reflecting a period of coral build-up until 131 ka BP, followed by a drop in sea level between 131 ka and 122 ka BP.

On the Kenya coast, Accordi *et al.* (2010) recorded a series of U-Th dates based on the analysis of the dense aragonite shells of *Tridacna*, expected to provide reliable ages. Assuming a closed system, most ages grouped in MIS 5, with one in MIS 7. An attempt to provide an open system isochron identified three groups: (i) a southern high-level group of 120 ± 4 ka; (ii) a low-level group also in the south, of 100 ± 4 ka; and (iii) a northern group of 118 ± 7 ka, interpreted as reflecting a single transgressive–regressive cycle. However, although the diagrams provided by Accordi *et al.* (2010, fig. 4) recognize important discontinuities within the sequences described, there is no attempt to correlate these, treating each locality as a separate entity.

The typically small numbers of accurately dated samples in Quaternary sequences may conceal greater depositional variation than has been apparent. Edinger *et al.* (2007) sampled terrace cliffs along 29 km of the New Guinea coastline, collecting corals on 15 to 40 m transects in areas lacking clear sedimentary breaks. Ages [^{14}C, accelerator mass spectrometry (AMS)] were corrected to calendar years, and within each transect the age range, from the oldest to the youngest coral, typically varied between 810 years and 1060 years, with one transect including an age unrelated to any around it. Edinger *et al.* (2007) referred to these groups as 'time-averaged', rightly suggesting that the material in any one transect reflected the conflation of separate cohorts of fossils. These results can be restated as indicating that samples currently within the same interval above sea level reflect different ages. The results of Thompson & Walton (1972) imply that transects on Aldabra could be expected to produce similar results, supporting the present interpretation of the sequences exposed.

It seems most likely that surges in rising sea level reflect the relatively rapid collapse of particular areas of ice sheets, like those recorded in the meltwater pulses of Fairbanks (1989), Blanchon & Shaw (1995); see also Braithwaite (2016b) and others in the Caribbean. Of these, Meltwater Pulse 1A (MWP-1A) seems well-established, but although data from Tahiti provide evidence for a rapid increase in sea level, believed to also represent MWP-1A (Bard *et al.*, 1996; Deschamps *et al.*, 2012), there was no support for either MWP-1B or MWP-1C (Montaggioni *et al.*, 1997; Camoin *et al.*, 2012). However, whereas surges of this kind can be used to explain the varying sea levels during deposition of the Aldabra Limestone (and underlying rocks), it is hard to see how they could be a driver for the stillstands responsible for the formation of terraces and deposits as sea level was falling. Melting and selective ice-shelf collapse produce rapid and significant changes in a rising sea level, but there is no equivalent when sea level is falling, and no obvious reason for prolonged pauses or sudden surges in the accumulation of ice. Yokoyama *et al.* (2018) recorded surges in falling sea level of 40 m at 31 000 years and 20 m between 21 900 years and 20 500 years, on the Great Barrier Reef, leading to the Last Glacial Maximum. These authors refer to a 'very rapid' build-up of global ice volumes but note that these: "do not appear to be explicable in terms of processes attributable to any specific climate-change dynamic".

CONCLUSIONS

Deposits from the Last Interglacial interval are of special importance for the insights they provide regarding variations in relatively high sea level during a period of global warming. Holocene sea levels have also varied, and it is important to look at sites remote from glaciated regions, to constrain estimates of eustatic changes and variability in earlier interglacial intervals. The Seychelles Bank and the island of Aldabra in the western Indian Ocean have experienced a prolonged period of crustal stability (Camoin *et al.*, 2004), with Aldabra providing one of the best-known Pleistocene sequences.

The Pleistocene limestones of Aldabra preserve a record of the Last Interglacial interval. Previous interpretations suggested that this was the result of a rapid rise in sea level, concurrent with global warming, and succeeded by a more gradual descent towards the low of the Last Glacial Maximum. However, the results presented here suggest that, although it is not possible to define stages, the geological evidence indicates that there were pauses or reversals during both sea-level rise and the subsequent fall. Variations in coral morphology, discontinuities and boundaries within the sequence, and changes in biofacies, indicate the influence of surges in melting, like the meltwater pulses of recent post-glacial warming. Divergences in radiometric ages reflect differences in the times of deposition within the unit. However, the stillstands forming terraces in the early phases of sea-level fall are currently unexplained.

In many areas, descriptions of the deposits of the Last Interglacial lack detail and are interpreted too simplistically. Research has been, and is likely to remain, hampered by the paucity and difficulty of age dating. More observations and more ages are required that should be distributed over wider areas within depositional units.

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