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Reef development at high-latitudes during multiple interglacial cycles: new evidence from Lord Howe Island, Southwestern Pacific

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Abstract

Reef development during past Interglacial periods, when sea level and sea surface temperatures were higher than today, provide unique insights into how reef systems may respond to projected human-induced global warming. Lord Howe Island currently represents the southernmost limit of reef development in the Pacific. Reef growth of Pleistocene age has been inferred to have occurred around the island, and this paper provides the fi rst detailed descriptions on the character of this development. Two phases of reef growth are identifi ed, which occurred as isolated fringing reefs along the edge of the basaltic hills of the island. Uranium-series dating indicates that the upper part of the sequence is of Last Interglacial age, however extensive calcite recrystallisation meant the lower part of the sequence does not yield reliable ages. Calcite cements suggest that several phases of recrystallisation have occurred meaning the lower part of the sequence is most likely to represent reef of Penultimate Interglacial age. Component analysis of the sedimentary matrix within the reef indicates coralline algae dominated sands which are very similar to the modern reef environment. This suggests that the environment at Lord Howe Island has remained at or close to the environmental limits for reef growth during the past few interglacials, despite lithospheric plate motion moving this island further north into reef building seas.

Keywords

Reef, development, high, latitudes, during, multiple, interglacial, cycles, evidence, from, Lord, Howe, Island, Southwestern, Pacific, GeoQUEST

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REEF DEVELOPMENT AT HIGH-LATITUDES DURING MULTIPLE INTERGLACIAL CYCLES: NEW EVIDENCE FROM LORD HOWE ISLAND, SOUTHWESTERN PACIFIC

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ABSTRACT: Reef development during past Interglacial periods, when sea level and sea surface temperatures were higher than today, provide unique insights into how reef systems may respond to projected human-induced global warming. Lord Howe Island currently represents the southernmost limit of reef development in the Pacific. Reef growth of Pleistocene age has been inferred to have occurred around the island, and this paper provides the first detailed descriptions on the character of this development. Two phases of reef growth are identified, which occurred as isolated fringing reefs along the edge of the basaltic hills of the island. Uranium-series dating indicates that the upper part of the sequence is of Last Interglacial age, however extensive calcite recrystallisation meant the lower part of the sequence does not yield reliable ages. Calcite cements suggest that several phases of recrystallisation have occurred meaning the lower part of the sequence is most likely to represent reef of Penultimate Interglacial age. Component analysis of the sedimentary matrix within the reef indicates coralline algae dominated sands which are very similar to the modern reef environment. This suggests that the environment at Lord Howe Island has remained at or close to the environmental limits for reef growth during the past few interglacials, despite lithospheric plate motion moving this island further north into reef building seas.

INTRODUCTION

Coral reefs are important climatic indicators, their development being constrained by a narrow range of environmental parameters. Sea surface temperature is the most important of these, limiting reef growth to areas where temperatures exceed 18°C (Guilcher 1988; Hopley 1982). Coral reefs appear threatened by global warming with more frequent coral bleaching as temperatures exceed coral thermal tolerances, and with weaker skeletons as a result of acidification of the oceans (Kleypas et al. 1999; Buddemeier et al. 2004). Whereas there have been dire predictions of coral decline within the tropics, at high latitudes, where reefs are at or very close to the temperature limit of development, warming trends may have a more positive impact on reef systems. Recent evidence suggests that scleractinian coral growth may expand poleward in response to global warming (Precht and Aronson 2004). This is supported by evidence for enhanced reef growth during the mid-Holocene optimum, at which time reefs developed beyond their current limits in Western Australia (Marsh 1992) and Japan (Veron 1992).

Reef systems close to their environmental limits are likely to be the most sensitive to climate change. Investigations into the character and extent of reef development during past interglacial periods are important because sea levels and sea surface temperatures were hypothesised to have been higher at the peak of several interglacials (Daly 1915; Overpeck et al. 2006). Lord Howe Island represents the contemporary southern limit of reef development in the Pacific (Veron and Done 1979; Harriott et al. 1995). The island is, however, moving north into reef building seas, and therefore during past Interglacial periods the oceanographic environment would have been even more marginal for coral reef development. Despite this, recent evidence suggests that substantial coral growth has occurred in the past (Brooke et al. 2003a, 2003b; Woodroffe et al. 2006). This paper sets out to examine the character of Last Interglacial and older reef limestones on Lord Howe Island and assess the implications for future coral productivity at the southernmost limits to reef development.

STUDY AREA

Lord Howe Island (31° 33'S, 159° 04'E) is located in the central Tasman Sea, approximately 500km due east of the Australian coast **(Fig. 1)**. It has a spring tidal range of 1.5m and mean significant wave height of 2.0 - 2.9m (Allen 1984). Mean sea surface temperatures range between 18 and 23°C (Veron and Done 1979) and the island receives approximately 1500mm of precipitation per year. It is composed of Tertiary basaltic volcanics (McDougall et al. 1981), is 10km long and 3km wide, and rises to an elevation of 942m. The island sits on a planated shelf, on average 50m deep, with a radius of 20km. It occurs at the southern limit of the poleward flowing, tropical, East Australian Current which has resulted in waters warm enough to support development of the southernmost coral reef in the Pacific Ocean. The fringing reef is located on the western side of the island; it is 6km long and encloses a shallow lagoon up to 2km wide (Guilcher 1973; Slater and Phipps 1977).

At present the island lies at the transition between tropical and temperate sedimentation. Although the modern reef and lagoon are dominated by tropical biota, such as corals and coralline algae, sediments are more temperate in character on the shelf (Kennedy and Woodroffe 2004; Kennedy et al. 2002). Carbonate sedimentation on Lord Howe Island

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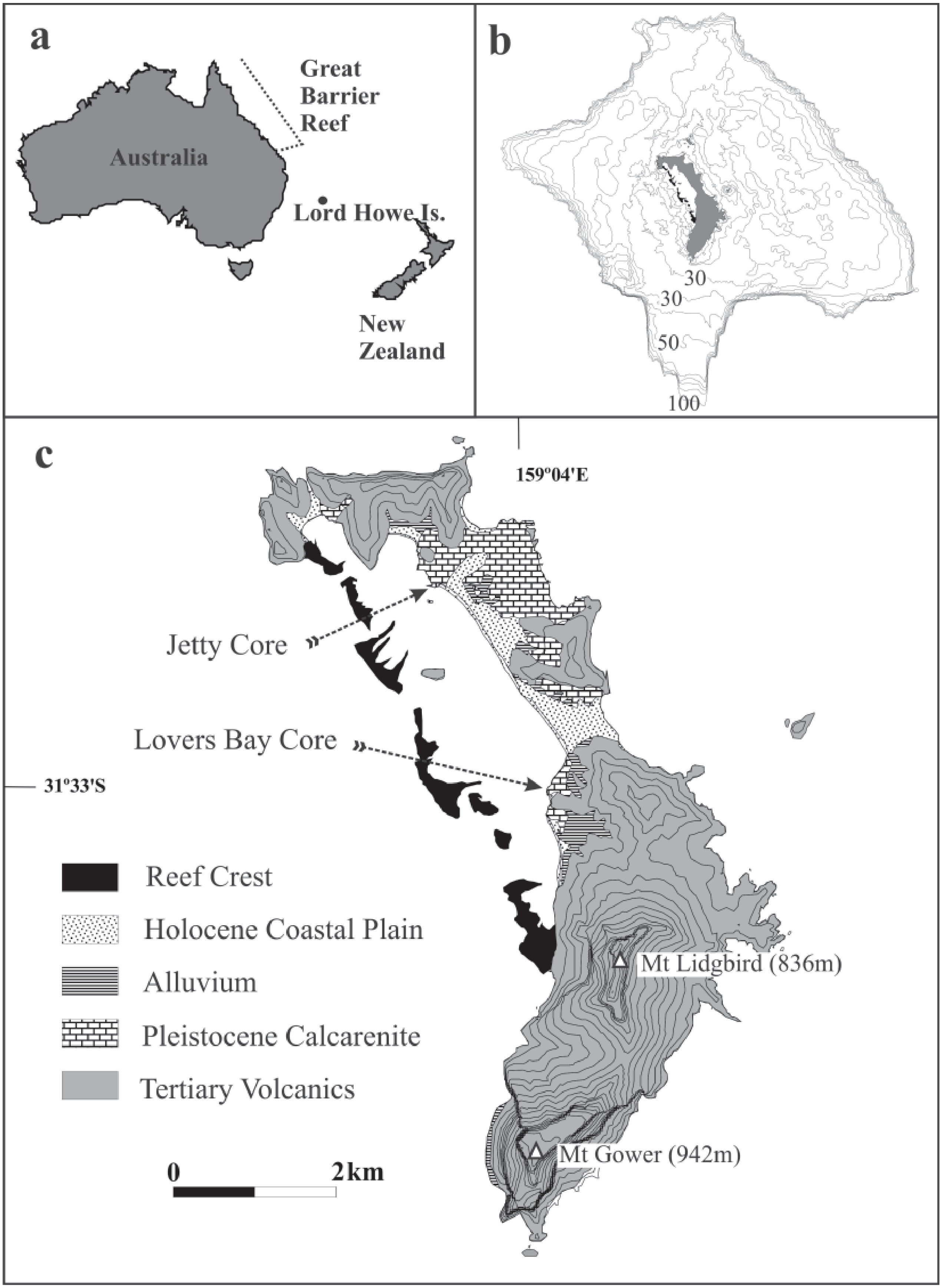


Figure 1. a) location of Lord Howe Island within the Tasman Sea south of the Great Barrier Reef; b) island shelf bathymetry in 10m intervals to 100m depth; c) geology of the island and core locations. Counters are in 10m intervals.

has not however been restricted to the Holocene. Extensive Pleistocene calcarenite dune sequences of the Searles Point and Neds Beach Formations mantle the central axis of the island and extend below the Holocene lagoonal sediments. The Searles Point formation, composed of dunes and paleosols, was deposited during MIS7 and earlier with luminescence ages of 222 +/- 28ka for the dunes units and 274 +/- 56ka for the paleosols. Calcite flowstone within the sequence ranges in age from 205 - >350ka (Brooke et al. 2003b). Beach units within the Neds Beach formation, which contain coral boulders, were deposited during MIS5e concurrently with source-bordering dune units (Woodroffe et al. 1995). Localised patchy reef growth is inferred from the occurrence of corals. A second phase of dune activity occurred at MIS5a, when the surrounding shelf would have been on average 20m deep (Brooke et al. 2003b). During this period a wide, drowned, reef structure found in the mid-shelf environments may also have been active (Woodroffe et al. 2005).

METHODS

Coring was undertaken in two phases. A diamond triple barrel Jacro 210 system was used to core at the edge of the wharf in 1996 and a single barrel tungsten tipped manually operated hydraulic system was used to core in Lovers Bay in 1997 (Fig. 1). The Jacro system utilised wire-line retrieval while the single barrel system required extraction of the entire drill string to recover sample. Depth accuracy is therefore very high for the Jacro system, however it is also very good for the single barrel drill because careful field observation and frequent core extraction provided intermittent, but very reliable, calculation of depth of core sample from the diamond cutting head and catcher.

Component analysis was undertaken by point counting thin sections under a petrographic microscope using a grid of 400 points. Components were identified using keys in Milliman (1974), Adams et al. (1984) and Scoffin (1987). Photographs of each main compositional group present in the slides were used as a reference to maintain identification consistency. Mineral composition was determined on powdered samples using a Phillips X-ray diffractometer. Each sample was scanned from 20 to 40° (2 theta) at 1° min31, using Cu-K radiation at 40 kv and 30 mA.

An initial Uranium series age was obtained by Brooke et al. (2003b) using the U/Th, α-spectrometry. Additional ages were obtained as part of this study using the TIMS uranium-series dating technique at University of Queensland following the analytical procedures described in Zhao et al. (2001), except that known $^{236}U/^{233}U$ ratio in a ^{229}Th-^{233}U-^{236}U mixed spike was used for mass fractionation correction for the samples. $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ activity ratios of the samples are normalised to the corresponding ratios measured for the secular-equilibrium HU-1 standard and their ages calculated using half-lives of 75,380 years (^{230}Th) and 244,600 years (^{234}U).

RESULTS

The entire pre-Holocene carbonate reef sequence was cored in both the northern and southern parts of the lagoon with the basement basalt being encountered at 10.8m depth below the jetty **(Fig. 2)** and at 4.5m depth in Lovers Bay. At both locations reef limestone was buried beneath the calcarenite dune sequences that mantle the lower elevations of the island. Core recovery below the jetty, using the Jacro system, was good, varying between 52% for the upper 1.5m of the reef and 100% for the lower sections (Fig. 2). This core therefore forms the basis of the following descriptions supported by the results from Lovers Bay where recovery was around 10% using the single barrel system.

Below the jetty, pre-Holocene corals were encountered at 3.5m below the lagoon floor (4.89m below Indian Spring Low Water (ISLW)). The reef is buried beneath the calcarenite dunes of the Neds Beach Formation which in turn are buried by soil and mangrove mud deposits dated at 6ka (Woodroffe et al. 1995). Three units can be identified within the core based on their sedimentology, composition, and degree of calcite recrystallisation, these being an upper and a lower reef unit, and a basal beach unit overlying basalt. The depths mentioned in the following section are relative to the lagoon floor, 1.39m below ISLW.

Upper Reef Unit

3.5 – 5m depth.– The upper reef unit extends from 3.5m to approximately 6.7m depth. Well rounded coral and algal grains bound in a sandy mud matrix dominate the uppermost part of the unit from its top to 5m depth where a small coral, 250mm thick occurred **(Fig. 3a)**. Coralline algae is the dominant grain type, comprising between 42 and 51% of the sand, with coral the next major constituent (10-21%). Foraminifera account for up to 11% of the sand and are composed entirely of encrusting forms. The gravel size fraction tends to be sub-well rounded, have little carbonate encrustation and the orientation of larger coral branches (centimetres in length) is random. Sponge boring is evident although it is not major with some coral clasts being well preserved, showing individual polyps. An articulated mollusc is present halfway down this core section and it shows well preserved shell structure which indicates that little, if any, post mortem transport of this clast has occurred (Fig. 3a). Voids tend to be open within this section accounting for 6 – 15% of the rock volume, with calcite cements occupying <10% of the core. These cements tend to be equant, granular and continuous where present with forming rims composed of crystals 60-105 µm in length **(Fig. 4a)**. Almost no calcite recrystallisation of coral is observed in thin section above 5m depth within the core with XRD of the coral at 5m depth indicating an aragonite content of 99%. Uranium-series ages on this

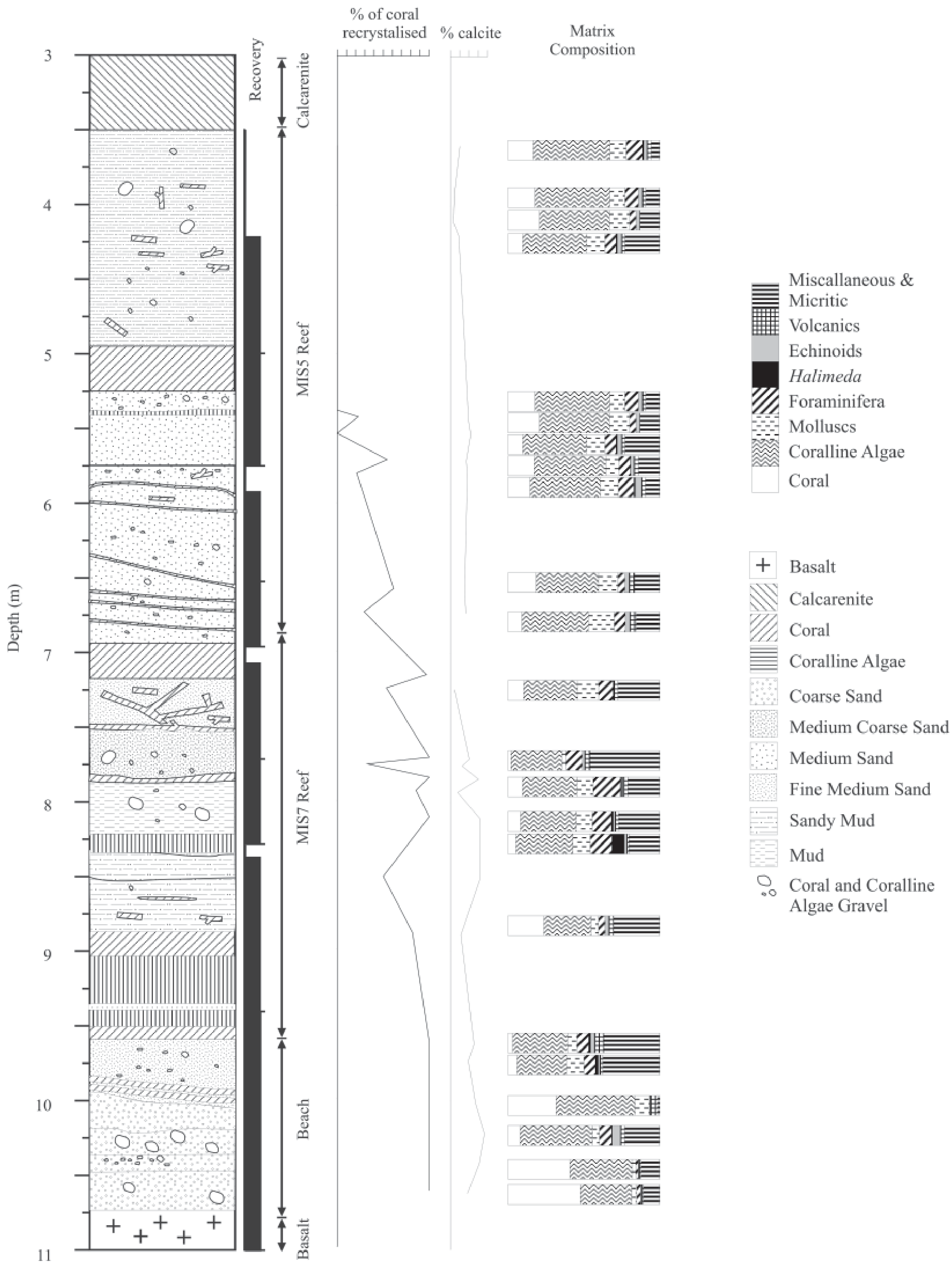


Figure 2. Graphic log of jetty core, showing the main reef units and matrix composition.

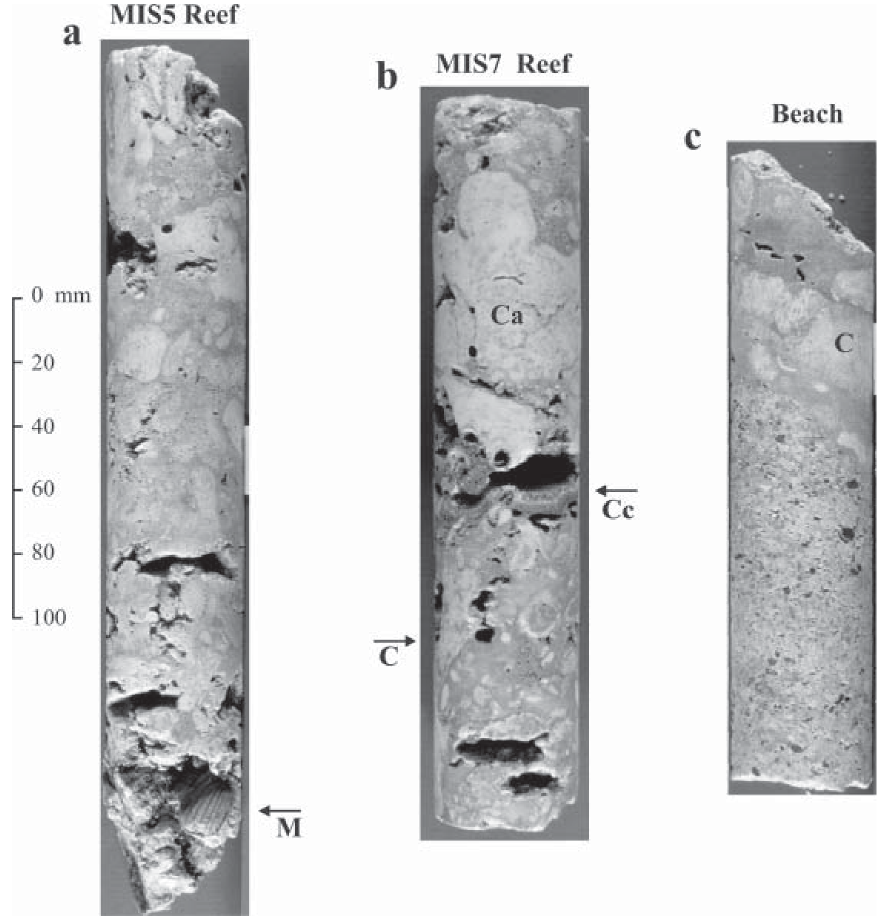


Figure 3. Jetty core photographs. a) the upper reef unit from approximately 4.0m depth. Note the well preserved mollusc (M) at the base of the section and open pore spaces; b) the lower reef unit at from 7.7 - 7.9m depth. Coral (C) and Coralline Algae (Ca) framework are present with calcite infill of voids (Cc) being apparent, c) the basal beach unit from 9.9 - 10.2m depth.

coral yielded an age of 120 +9 -8 ka (Brooke et al. 2003b) indicating growth during MIS 5e. A small cavity (10-20mm wide) formed by mollusc borings has its bottom half infilled by mud and fine sand indicating the clast has remained in its present position since initial burial.

5 – 6.7m depth.– A coarse to medium, well-sorted sand unit overlies an alternating sequence of coarsening and fining upwards beds, 50-100mm thick, bounded by encrusting coral species, extending down to the base of the upper reef unit. Coralline algae remains the dominant constituent of the sand comprising between 41 and 49% of grains, with coral the next main grain type (9-21%). Foraminifera are common (up to 10%) and tend to be a mix of free living and encrusting forms. The well-sorted sand unit (60-70% medium-coarse sand) is 0.3m thick, has 9-12% void space and 19-22% calcite cements. Sediments below the sand tend to be a bimodal mix of gravel and fine sandy mud. The gravels are well rounded and have little or no carbonate encrustation. From 6.53m depth, mud is the dominant matrix and coral framework becomes more important, however the broad composition of sand, mud and gravel sized coral is similar to the upper part of the sequence, with the exception of the presence of calcite infill of some of the void space. These cements tend to be composed of equant, granular crystals, approximately 90 μm long.

Lower Reef Unit

Below 6.7m depth there is a marked increase in the proportion of calcite cementation of void spaces as well as recrystallisation of the larger coral gravels and framework. XRD analysis of a Goniastera head coral cored between 6.87-7.15m depth indicates it is composed of 97% calcite, indicating complete recrystallisation by meteoric waters. Below this coral, calcite cements attain thicknesses of several millimetres and thin section analysis indicates over 50% recrystallisation of corals (except for one sample at 7.73m depth), with the majority (64%) being completely recrystallised (Fig. 4b, c). The increase in the calcitic content, combined with a change in sedimentology is used to define the lower reef unit in the core, which extends to 9.83m depth where it overlies a beach sequence. The lower reef sequence contrasts with the upper unit, being dominated by coral and algal framework, interbedded with fine sand and mud units. Many of the branching coral species appear

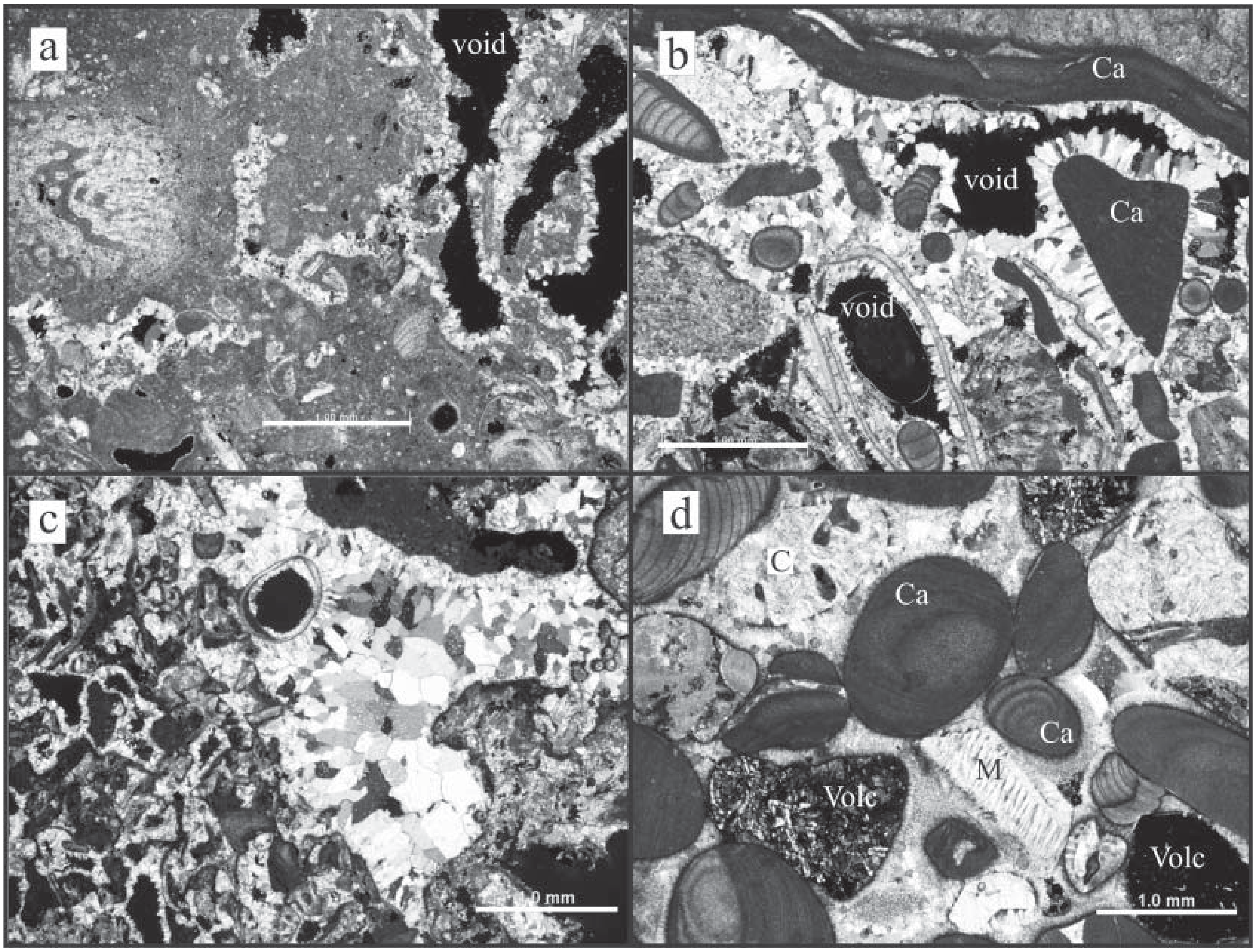


Figure 4. Thin section photographs of the Jetty Core matrix: a) the upper reef unit at 4.1m depth. The matrix is fine grained and mictric with thin blocky calcite cements being apparent; b) the lower reef unit at 6.7m depth. The calcite cements are thicker than the upper unit characterised by columnar crystals 180μm long; c) the lower reef unit at 8.1m depth. Columnar calcite cements are apparent along grain boundaries with the central parts of pores infilled with blocky cements; d) the basal beach unit at 10.0m depth. Two phases of calcite cementation are apparent, an initial acicular (fibrous) cement along the sand grains, with coarser blocky cements infilling the larger pore spaces. Ca-Coralline Algae, C-Coral, Volc-basaltic grains, M-Molluscs. Scale Bar is 1 mm.

to be in growth position and several phases of encrustation by both foraminifera and coralline algae are apparent.

An *in situ* branching framework dominates the upper part of the lower reef unit from approximately 7.15 – 7.55m depth (Fig. 3b). Preservation of the coral branches is high with individual polyps preserved on some parts of the framework. Boring and encrustation by coralline algae or foraminifera are rare. Matrix between the corals is an alternating mix of coarse sand and mud, with gravel clasts tending to be sub-rounded, and up to tens of millimetres in length. Void space is variable within the sand and mud units varying between 4 and 14%, with calcite cements accounting for <5 – 21% of the volume. As in the upper reef unit, coralline algae is the dominant component accounting for approximately 35% of the sand fraction, although in this section of the core mollusc (3-14%) and foraminifera (10-11%) grains are in greater proportion than coral (2-10%). The highest proportion of miscellaneous grains (43%) were also found within this section of the core, due to extensive recrystallisation which has occurred within both the framework and matrix materials.

From 7.73 to 10.03m depth, coralline algae and encrusting corals dominate the framework with smaller mud dominated units interspersed between them. Minor subrounded coral gravels occur within the matrix, however such clasts are much less common than within the upper reef unit. Branching coral clasts are uncommon with coralline algal encrustations up to 0.20m thick occurring. This unit continues to 9.83m depth where the lower reef unit overlies beach deposits. Within the sedimentary units between the coralline algae and coral framework, calcite cements accounted for between 11 and 32% of the core and void space 2-12%. Larger voids up to 15mm wide contained calcite rims up to 5mm thick (Fig. 4c). Coralline algae is again the dominant sand sized grain, accounting for up to 47% of material. Foraminifera are especially common reaching their maximum abundance in the lower section of this reef unit at a depth of 7.80 m (18%) and 8.15m (13-14%). Interestingly while planktonic foraminifera dominate the species found, *Baculogypsina sphaerulata,* the most common form found on the modern reef is absent. The distinctly tropical green algae *Halimeda* which is present as a very minor component throughout the core is relatively abundant at 8.15m accounting for 8% of the sand. Recrystallisation of this section of the core was especially high, with blocky cements being common.

Beach Unit

Coarse sand and gravel units occur at the base of the core from 10.03m depth to 10.70m where they directly overlie basalt (Fig. 3c). These are grain supported units, containing well rounded coral clasts up to 100mm in diameter, and are bedded with alternating medium to coarse sand units. They are interpreted as beach units. Sand matrix dominates (42 – 63%), and although it generally is moderately to well sorted, void space is virtually absent (<0.5%) due to calcite infill (19-37%). All the coral material within this section of the core is recrystallised along with a significant proportion of the other grain types. Calcite infill tends to be composed of equigranular blocky crystals up to 0.4mm in size. In the well sorted coarse sand bed at the top of the unit, pore spaces are infilled by two types of cement (Fig. 4d). Fibrous crystals form uniform rims around well rounded grains up to 120 µm, with the remaining pore spaces occupied by equant granular crystals, indicating that at least two phases of cementation precipitation occurred within this section of the core.

Coralline algae dominates the sand fraction in the upper part of the beach section, comprising between 34 and 52% of the core. Towards the base, however, coral becomes more dominant, reaching its highest composition within the entire core in the basal beach unit; it reaches 48%, dominating the sediment directly above the basalt.

DISCUSSION

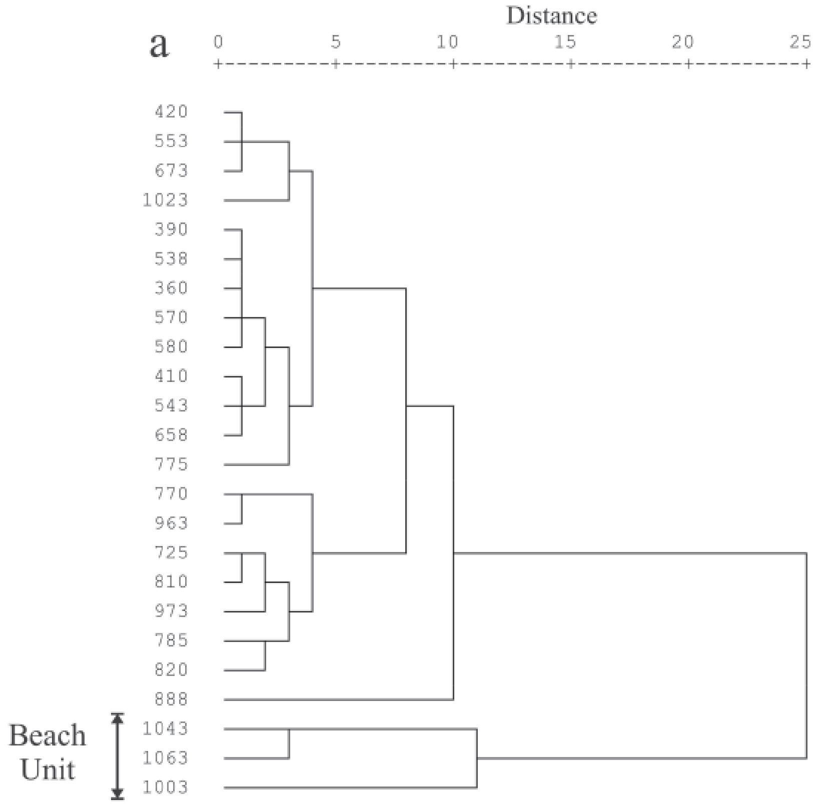
Sea surface temperatures during the Last Interglacial have been shown to be warmer than present with eustatic sea level being elevated by 3-5m above modern level (Overpeck et al. 2006), while during the penultimate interglacial period the sea surface environment was similar to today (Hearty and Kindler 1995). During the warmer sea surface periods coral reef distribution globally extended further towards the poles than at present. Along the West Australian margins coral reefs were found on Rottnest Island (32ºS) (Szabo 1979), further south than the current limit of reef growth. Presently the southern limit of reef development on the East Australian coast, and within the Pacific, occurs at Lord Howe Island. Unlike the reefs further north of the island, on Elizabeth and Middleton Reefs (Woodroffe et al. 2004) and the Great Barrier Reef (Hopley et al. 2006), older interglacial reef limestone do not form the substrate for Holocene reefs. Reef development during the previous two interglacial cycles on Lord Howe Island appears to have occurred as a shore-attached fringing reef at the base of basalt hills in the central portion of the island.

Reef development is not however established directly above the basalt basement but on a mixed sand and gravel carbonate beach. Extensive recrystallisation within the beach meant its age could not be directly determined. Calcite crystallisation within the pore spaces of the generally well sorted sediments indicated that it underwent several phases of subaerial exposure. Acicular (fibrous) cements occur only within this unit indicating marine phreatic cementation with subsequent meteoric phreatic diagenesis, the latter represented by equant granular calcite crystals (Scoffin 1987). Such diagenetic features are not found shallower within the core and combined with the complete recrystallisation of all the coral within the unit suggests that it is older than the two shallower reef units. The contact between the beach unit and basalt is sharp, with this unit representing one of the earliest stages of carbonate sedimentation found on the island.

This extensive recrystallisation of the core also means the age of the second reef unit is difficult to determine directly. Uranium (U)-series disequilibrium dating yielded a wide range of ages from 130 – 600ka **(Table 1)**. These ages cannot however be assumed to be realistic due to open-system behaviour of the U-series isotopic systematics. For instance, U leaching has taken place within two of the three dated corals with U contents lower than expected (LH11-503B and LH/653-773 with U ~1.59 and 0.87 ppm, respectively; whereas U ca. 2-3 ppm in pristine corals). U leaching is known to result in an apparent ^{230}Th date that is too old relative to the true age, as is the case with LH11-503B and LH/653-773. U leaching may not have occurred in the stratigraphically youngest sample LH-11-350C with U ~3.23 ppm. However, its elevated $\delta^{234}U(T)$ does imply the effect of open-system behaviour such as coupled

Table 1. Uranium-series disequilibrium dating results for the Jetty core.

Sample Name	Depth in core (m)	Material	U (ppm) ± 2s	^{232}Th (ppb)	^{230}Th/ ^{232}Th	^{230}Th/^{238}U ± 2s	^{234}U/ ^{238}U ± 2s	uncorr. ^{230}Th Age (ka) ± 2s	corr. ^{230}Th Age (ka) ± 2s
LH-11-350C	4	Coral	3.233 ± 0.002	0.947	8220.685	0.793 ± 0.001	1.117 ± 0.001	130.17 ± 0.52	130.17 ± 0.52
LH-11-503B	5.4	Coral	1.588 ± 0.002	0.322	21203.645	1.418 ± 0.003	1.106 ± 0.002	>500	>500
LH/653-773	7	Coral	0.873 ± 0.00	2.338	1287.266	1.137 ± 0.003	1.100 ± 0.002	598.61 ± 61.09	598.56 ± 61.10
LH-11-773A	7.8	Coralline Algae	0.713 ± 0.00	1.122	1574.645	0.817 ± 0.002	1.147 ± 0.002	129.89 ± 0.67	129.86 ± 0.67



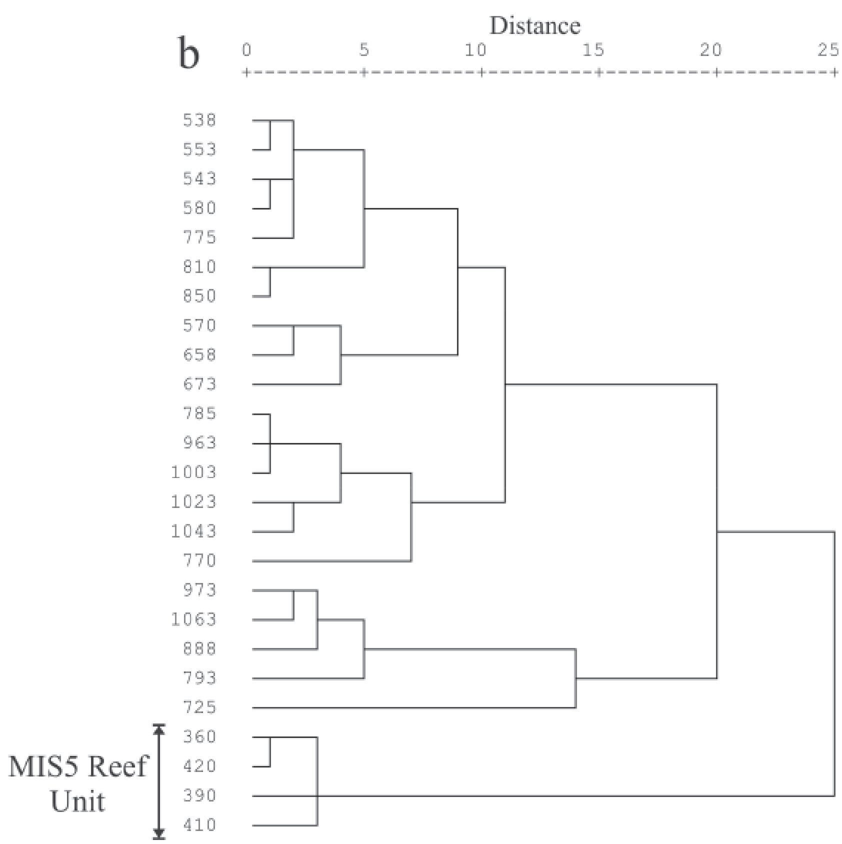


Figure 5. Hierarchical cluster analysis of jetty core matrix by depth sampled. a) Clusters based on typical chlorozoan assemblages: coral, red coralline algae, Halimeda, molluscs and foraminifera. The basal beach unit is the most significant cluster identified. b) Clusters based on percentage of void space, framework coral, calcite cements, and proportion of calcitic coral. The uppermost part of the reef sequence produces the most distinct cluster.

^{234}U and ^{230}Th addition through α-recoil (Thompson and Goldstein 2005). Application of an open-system correction (Thompson and Goldstein 2005) on this sample yields an open-system ^{230}Th age of ~120 ka. Unlike Last Interglacial corals from marine isotope stages 5 and 7 in the Bahamas (Kindler et al. 2006), Belize (Gischler 2006) and New Caledonia (Frank et al. 2006) where enough U/Th is present to calculate open-series ages, this correction cannot be applied to the other two corals from the core which have suffered serious U-leaching. The occurrence of serious U-leaching in these samples (as compared to LH-11-350C) suggests that these stratigraphically lower corals may have undergone several cycles of both marine and subaerial diagenesis, with conversion of aragonite to calcite. Thus, it is reasonable to infer that the lower reef is likely to represent sedimentation during MIS7. This would correspond to the earliest deposition of aeolianites on the island preserved as the Searles Point Formation (Brooke et al. 2003b). The MIS5 reef corresponds to a global window of LIG reef development (Stirling et al. 1995) and a period of dune activity on the island; however, it is buried by the extensive Neds Beach formation dune field (Brooke et al. 2003b).

Subtropical to tropical sediments dominate the entire sequence. While the main units can be distinguished through hierarchical cluster analysis, such groups are based more on the sedimentological character rather than the composition **(Fig. 5)**. Based on the degree of recrystallisation, a proxy for age as calcite occurrence increases significantly down core, the upper, Last Interglacial, reef is the most distinct cluster. When comparing typical chlorozoan assemblages downcore, namely coral, coralline algae, *Halimeda*, molluscs and foraminifers, the basal beach unit appears to be the most distinct with the composition of both reef units clustering together. It would therefore appear that environmental conditions conducive to tropical sedimentation have remained relatively constant through the reef development history of the island. This continues to the present day with the contemporary lagoonal sediments having a very similar composition (Kennedy and Woodroffe 2000; Kennedy 2003). This however is not surprising given that northward lithospheric plate motion over the past 200ka would place the island only a further 20km south. The preservation of the core sequence does however indicate that the island has only relatively recently crossed the Darwin Point (Grigg 1982) and moved into reef building seas.

This has meant each successive interglacial period of reef growth and associated carbonate dune activity has become more extensive, as Lord Howe Island moves further out of its marginal sea environment. It has not however reached a latitude where sustained chlorozoan sediment assemblages can be maintained through an entire interglacial phase. A large reef-like structure on the shelf hints at more extensive reef growth during the Late Pleistocene, however it like the Holocene give-up growth on its surface has not been able to maintain growth to present sea elevations (Woodroffe et al. 2005).

CONCLUSIONS

The reef system encountered on Lord Howe Island represents the southernmost dated Last and Penultimate Interglacial reefs within the Pacific. It indicates that at the limits to coral distribution, reef growth has been maintained during the past two interglacial periods. It would appear that once the environmental conditions are suitable for reef growth, the sediment character remains very similar, and it is not possible to discern how marginal an environment is from the reef sediments alone. The Lord Howe Island carbonate system also indicates that as the island has drifted into more tropical seas the volume of carbonate sediment deposition has increased significantly both in the form of terrestrial aeolianites and as shallow reef accumulations. Under present oceanographic conditions, however, Lord Howe Island is still marginal for tropical sedimentation, as it has been during past interglacial phases.

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