ATOLL RESEARCH BULLETIN

NO. 401

CHAPTER 3

LATE QUATERNARY MORPHOLOGY OF THE COCOS (KEELING) ISLANDS

BY

D.E. SEARLE

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
FEBRUARY 1994

CHAPTER 3

LATE QUATERNARY MORPHOLOGY OF THE COCOS (KEELING) ISLANDS

BY

D.E. SEARLE *

ABSTRACT

Seismic profiles have been obtained from Cocos lagoon and correlated with radiometric-dated core data. They show that the Last Interglacial atoll had a very similar morphology to the present atoll, and lies 8 to 28 m below sea level. It is overlain by 8 to 18 m of Holocene reefal deposits. Two deeper surfaces, of similar shape to the overlying reef surfaces, are recorded beneath the lagoon. These are tentatively identified as solution unconformities formed during glacial lowstands at oxygen isotope stages 6 and 8. Blue holes in Cocos lagoon are interpreted as solution dolines modified by clastic-controlled growth during submergence and relief enhancement by facies-controlled solution weathering during emergence. The data support the antecedent model of reef development on a subsiding base. However, unlike Purdy's (1974) antecedent karst model, both constructional relief and differential erosion are emphasised. Preservation of thin reef caps indicates that the atoll surface may have been lowered by as much as 18 m during each glacial cycle by subaerial erosion and solution. This allows an improved estimate of 0.02 mm/yr for subsidence of the atoll during the late Quaternary.

INTRODUCTION

Charles Darwin visited the Cocos (Keeling) Islands in 1836 and collected field evidence in support of his subsidence theory of atoll formation. This theory recognises an evolutionary sequence by vertical reef growth from volcanic island fringing reefs, through barrier reefs, to coral atolls driven by gradual subsidence of the volcanic island core. Drilling through Pacific atolls has encountered thick, shallow-water, reef-associated limestone overlying basal basalt; these results have substantiated Darwin's theory. Isostasy and plate tectonics provide explanation for subsidence and co-existence of evolutionary reef phases along linear island chains.

Darwin's field evidence from Cocos consisted of observation of erosion of the shoreline and collapse of coconut palms by undercutting at the shoreline. He inferred subsidence from this geomorphic evidence - an interpretation that has been strongly questioned, for example by Ross (1855).

A cemented coral conglomerate platform underlies many of the Cocos Islands and is exposed along the ocean shoreline. Dating of material from this platform, which has been identified as a former reef flat, indicates that sea level was about 1 m higher than present some 3000 years ago (Woodroffe et al. 1990).

Drilling on the Cocos Islands has intersected the "Thurber" discontinuity, a solution unconformity separating Holocene from Pleistocene reef that, at one site, has been dated at about 120, 000 years B.P. This corresponds to the Last interglacial oxygen

---

* Department of Minerals and Energy, P.O. Box 194, Brisbane, Queensland, 4001.

isotope substage 5e (Woodroffe et al. 1991). The discontinuity lies at 6-16 m below sea level (revised depths, see Fig. 1 and Woodroffe et al. this volume). Woodroffe et al. (1991) interpreted the data to imply a subsidence rate of 0.1 mm/yr over the last 120, 000 years.

Thus, the Cocos (Keeling) Islands have been undergoing gradual, long term subsidence. Superimposed on this are millennia scale, glacially-induced eustatic movements in relative sea level and consequent hydro-isostatic adjustments. The most recent relative sea-level change has been a slight fall over the last few thousand years.

This paper is concerned with the structure of the Cocos (Keeling) Atoll during the Late Quaternary, and the influence of antecedent topography on the morphology of the modern atoll.

REGIONAL SETTING

The Cocos (Keeling) Islands, in the eastern Indian Ocean, consist of an atollon - North Keeling Island, and a horseshoe-shaped atoll - South Keeling Islands. The South Keeling atoll lies 40km south of North Keeling and consists of a shallow circular lagoon fringed by a series of reef islands. The islands vary in size from West Island, which is 11km long, to small islands less than a kilometre long (Fig. 1).

The lagoon of South Keeling atoll is 10 km across east to west, and 12 km from north to south. To the south and east, the lagoon connects with the open ocean through inter-island channels that are about 1 m deep. To the north and north west, deep openings occur on either side of Horsburgh Island (see Kench, this volume). Cocos lagoon is shallow to the south, with much of it being exposed at low tide. To the north the lagoon deepens to over 15 m. Much of the central south-eastern part of the lagoon is occupied by steep-sided "blue-holes", some over 15 m deep (Fig. 5). The holes average 100 m across but are generally smaller and more isolated to the south east while towards the centre of the lagoon the holes commonly coalesce. Submerged patch reefs occur in the central lagoon (see Williams, this volume).

METHODOLOGY

A high resolution continuous seismic reflection survey was carried out in the lagoon of the South Keeling Islands. The continuous seismic profiling (CSP) was conducted using a "Uniboom" sound source, triggered every half-second at an energy level of 200 Joules. A single-channel, 8-element hydrophone was used to receive the seismic signal after reflection from the seabed and subsurface. The signal was filtered to remove noise below 500 Hz and displayed as a seismic cross section on a graphic recorder. Seismic profiling was carried out at a speed of 4 knots. Position fixes were obtained every 2 minutes (about every 250 m) using a Trimble GPS unit.

In order to limit the presence of seabed multiples the sound source and hydrophone were deployed from opposite quarters of the vessel. This field technique imposes a geometrical depth scale on the records, and corrections have been applied to depths measured from the seismic records.

RESULTS

A total of 70 km of seismic profile was recorded over the northern and central part of the lagoon, Figure 1. This includes profiles across the blue holes, and profiles approaching Home and West Islands to allow correlation of seismic with drill data. Seismic profiling was not feasible in the very shallow southern part of the lagoon.

Seismic data quality was only fair owing to noise from wind waves in the lagoon generated from the persistent Trade Winds. In the shallow seagrass-covered parts of the lagoon, particularly off Home Island, no seismic signal was received by the hydrophone array. This was due to attenuation of the signal by gas bubbles adhering to the seagrass.

The seismic profiles from Cocos lagoon record subsurface data down to 45-50 milliseconds of reflection time, being limited by the system used and the nature of the sediments encountered. This converts to about 35 m in depth, assuming a conversion velocity of 1500 m/s. This value is close to the seismic velocity of sea water and reef limestone of Holocene age. Older sediments, which may be more compacted and cemented, can have higher velocities. Thickness of older units may be overestimated since a conversion velocity of 1500 m/s has to be used in the absence of measured values.

INTERPRETATION

The seismic profiles record the seabed and subsurface reflectors. The subsurface reflectors are derived from changes in physical properties at geological discontinuities. Experience in reef provinces elsewhere suggests that these discontinuities are commonly solution unconformities formed when reefs were exposed to subaerial processes during glacially-induced, sea-level lowstands (Orme et al. 1978, Searle and Harvey, 1982). Thus reflections from unconformities imply atoll emergence, while the seismic sequences bounded by these reflections are due to reef and lagoonal deposition during interglacials.

Lagoonal bathymetry is one of high relief except for the marginal areas where shallow subtidal flats commonly extend for 2 to 3 km into the lagoon. The deepest water encountered during the seismic survey was in the blue holes. One hole was 18 m deep with a rim barely deep enough to allow passage (0.5 m at high tide). Water to 16 m deep was traversed in the centre of the lagoon and close to the southern tip of Direction Island.

Three subsurface reflectors (referred to as A, B, and C in descending order) are present on the seismic records (Figs. 2 and 3). These reflectors, together with the seabed reflection, form the sequence boundaries of 4 depositional units.

The seismic sequence bounded by reflector A and the seabed varies in thickness from 8 to 18 m. It is thickest towards the southern part of the lagoon where blue holes appear to be infilled (Fig. 3). Unlike seismic data from the Great Barrier Reef Province (see Orme et al. 1978; Searle, 1983; Searle and Flood 1988) little internal structure is apparent in this sequence, and it is not possible to differentiate between reef rock and bioclastic facies.

Reflector A varies in depth from 11.5 m where it rises towards West Island, to 28 m in the centre of the lagoon. The shape of the subsurface defined by reflector A closely matches that of the lagoonal seabed. Both have high relief, except where they rise gently towards the islands; are deepest in the centre of the lagoon; and steepest dips are apparent over the blue holes and their rims. The data have been tested for velocity distortion using published refraction velocities for reefal limestone of Holocene age (Harvey and Hopley 1981). Less than 20% of the relief on reflector A can be accounted for by this effect. Similarities in the morphology of the lagoon and its subsurface as seen on the seismic records are, therefore, real and not attributable to distortion.

A thin sequence separates reflectors A and B. This sequence averages only 1 - 2 m in thickness except off the northern part of West Island where it increases to 5 m (Fig. 2).

Reflector B lies at depths of 16 to 32 m, and generally conforms with the shape of reflector A. It is deepest beneath the centre of the lagoon and shallowest off the northern part of West Island. Here it forms a terrace at -17 m overlying a -20 m terrace defined by reflector C (Figure 2). Beneath the blue holes reflector B lies at a depth of 24 to 26 m, being deeper below the holes and somewhat shallower below their rims.

Sequence B/C, where recognised, is only 1-2 m thick (Figs. 2 and 3).

Reflector C, although commonly lost below the limit of penetration, lies at depths of 18 to 32 m. Reflector C is best developed between the northern part of West Island and the central lagoon where it forms the -20 m terrace that then dips towards the centre of the lagoon (Figure 2). Reflector C is also present at about -22 m off Direction Island, dipping towards the centre of the lagoon.

DISCUSSION

Drilling on the Cocos (Keeling) Islands (Woodroffe et al. 1991; Woodroffe et al. this volume; Falkland, this volume) intersected the "Thurber" discontinuity at depths of 6 to 16 m below mean sea level (Fig. 1). Projection of reflector A from the seismic profiles that come closest to the drillholes on West Island allow correlation with the top of the older limestone at the "Thurber" discontinuity (Figs. 2 and 4). On Cocos this older limestone has been dated as Last Interglacial in age (123 ± 7 ka B.P., Woodroffe et al. 1991). Thus reflector A is interpreted as the weathered surface of the Last Interglacial atoll modified by subaerial exposure prior to the Postglacial transgression, and upon which Holocene reef has developed. Reflector A marks the Holocene/Pleistocene boundary.

Reflectors B and C (Figs. 2 and 3) are interpreted as older solution unconformities formed by subaerial exposure on progressively older atoll surfaces. The sea-level curve of Chappell (1983) shows glacial lowstands reaching minina at 150, 000 and 260, 000 years B.P.; reflectors B and C, respectively, may represent the subaerial surfaces formed during these episodes (oxygen isotope stages 6 and 8) and upon which subsequent reef development took place.

The sequence below reflector C probably consists of reefal deposits dating from the highstand of oxygen isotope stage 9. Seismic sequences B/C and A/B represent reefal limestone deposited during highstand stages 7 and 5e, respectively.

Although reflectors B and C are imperfectly recorded by the seismic system, the shape of the ancestral atoll lagoon (after subaerial weathering) appears to have been preserved during the Late Quaternary through to the present day. Even at the relatively fine scale of blue holes, shape has been preserved, and possibly enhanced (Fig. 3). The most noticeable difference in atoll shape since the formation of surface B has been the progradation of Last Interglacial age reefal sediments over the -17 m terrace off West Island (Fig. 2).

The unconformity defined by reflector A is interpreted as the weathered surface of the Last Interglacial reef. This surface lies 6-16 m below mean sea level beneath the islands (Woodroffe et al. 1991, and this volume), and dips beneath the lagoon to a depth of 28m below mean sea level. Off West Island, where the best subsurface data is available, this Holocene/Pleistocene interface dips at 4 m/km into the lagoon (Fig. 4). Below the blue holes and the submerged patch reefs in the centre of the lagoon surface A is substantially mimiced by the modern reefal surface (Fig. 3). Thus the morphology of the modern atoll is inherited from its antecedent platform, which, in its turn appears to have been inherited from older atoll landforms. In this respect, the data from Cocos support the antecedent karst theory of Purdy (1974).

It appears that atoll landforms maintain and even amplify their antecedent relief. This may be due to either differential accretion during submergence, or to differential erosion during subaerial exposure, or a combination of both processes. Accretion by vertical reef growth during marine transgressions would be more rapid in the shallow photic zone, aided by a process of clastic control whereby coral growth can be retarded by biodetritus deposited in low areas (Goreau and Land 1974).

Subaerial erosion may also amplify relief by facies control of solution weathering (Bloom 1974). Under this process the less permeable lagoonal sand and mud facies would dissolve away faster than the more permeable reef framework and coarse rubble/conglomerate facies. On a smaller scale, facies control accounts for the development of blue holes. Once elevation differences were present in the proto-atoll lagoon the positive features would be exploited by coral colonisation and vertical growth. Then, as now, the lagoon would tend to silt up by progradation of bioclastic sand and mud behind the windward margin. The negative areas between reef patches would gradually infill as an intertidal reef flat developed in the lagoon. Upon emergence the surface would experience facies-controlled differential weathering through internal drainage and solution. This would result in the formation of residual prominences at the site of former patch reefs, and the development of solution dolines in the intervening lagoonal mud and sand facies. Subsequent glacial cycles would emphasise relief by constructional (highstand phases) and solution weathering (lowstand phases) processes forming relatively deep blue holes.

While blue holes are relatively numerous in the Caribbean, few have been reported from the Indo-Pacific region (Purdy 1974). Deep blue holes are not common in the Great Barrier Reef; they occur singly, and partly for that reason are considered as collapsed doline features (Backshall et al. 1979). The blue holes on Cocos, by contrast, dominate the southern central area of the lagoon. They are unlikely to be juxtaposed collapse features, and are considered to be multi-generational solution dolines.

The Holocene pattern of atoll development may be taken as a model for earlier cycles. The difference in thickness between the older Pleistocene reef and associated lagoonal sediments, and Holocene deposits is presumably due to subaerial erosion of the older sediments. It is interesting to speculate on the relationship between reef growth and subaerial erosion, and consider implications of sea level and subsidence for the preservation of the resulting reef cap.

The data from Cocos implies a mean accretion rate of 2 mm/yr, based on an average thickness of Holocene of 16 m deposited since the sea flooded the atoll some 8000 years ago. Reefal accretion could only occur during submergence for, say 10% of each Late Quaternary glacial cycle. This would add 20 m to the reef cap during each interglacial cycle. As sequences A/B and B/C are only 1-2 m thick, 18 m of reef cap must have been eroded during the remaining 90% of time when the atoll was emergent, hence an erosion rate of 0.2 mm/yr is implied.

Data on erosion rates is sparse and values vary greatly. For instance, Trudgill (1976) provides an average value of 0.26 mm/yr from Aldabra Atoll from a range of values that vary with lithology, mineralogy and soil cover. Purdy (1974), quoting Land *et al* (1967), provides values of 0.01-0.04 mm/yr that vary with rainfall. Data for reefal accretion appears less extreme and better established. On Cocos, Holocene accretion estimated from the seismic and core data falls within the range of estimates for other atolls, see, for example, Marshall and Jacobsen (1985).

For the reef cap to be repeatedly accommodated, highstand sea levels must rise, or the atoll must subside. Accepting the latter as the most feasible in the longer term, a subsidence rate of 0.02 mm/yr is implied from the data. This allows for a 2 m increment to the reef cap during each glacial cycle. Subsidence rates for Cocos (Woodroffe et al. 1991) can now be refined to the lower value of 0.02 mm/yr, which is closer to global average oceanic subsidence rates (Ladd et al. 1970, Menard 1986).

CONCLUSIONS

Continuous high resolution seismic data has been obtained from Cocos lagoon. Correlation with radiometric-dated core data from the Cocos islands allows reconstruction of the shape of the Last interglacial atoll.

The Last Interglacial atoll surface, both island and lagoon, has a very similar morphology to the present atoll, and lies 8 to 28 m below sea level. It is overlain by 8 to 18 m of Holocene reefal deposits.

Two deeper surfaces, of similar shape to the overlying reef surfaces, are recorded beneath the lagoon. These are tentatively identified as solution unconformities dating from subaerial exposure of earlier atolls during glacial lowstands at oxygen isotope stages 6 and 8.

A field of partially-infilled blue holes seen in the southern central part of the lagoon is underlaid by antecedent depressions. These are interpreted as solution dolines modified by clastic-controlled growth during submergence and relief enhanced by facies-controlled solution weathering during emergence.

The seismic data, correlated to core data, supports the antecedent model of reef development on a subsiding base. However, unlike Purdy's (1974) antecedent karst model, both constructional relief and differential erosion are envisaged as mechanisms for preserving atoll morphology through late Quaternary time.

The preservation of only thin former reefs indicates that the atoll surface was significantly lowered by subaerial erosion and solution during each glacial cycle. The data allow an improved estimate of 0.02 mm/yr for subsidence of Cocos Atoll during the late Quaternary.

ACKNOWLEDGMENTS

The seismic work in the Cocos (Keeling) lagoon was undertaken at the kind invitation of Colin Woodroffe, Roger McLean and Eugene Wallensky. The survey was conducted aboard John Clunies-Ross' vessel "Madaeke". Major John Mobbs (Australian Defence Force Academy, Canberra) provided full survey control for this work. Colin Woodroffe has provided useful comments on this paper. The research was funded by the Australian Research Council. This paper is published with the permission of the Chief Government Geologist, Department of Minerals and Energy, Brisbane.

REFERENCES

Backshall, D.G., Barnett, J., Davies, P.J., Duncan, D.C., Harvey, N., Hopley, D., Isdale, P., Jennings, J.N. and Moss, R., 1979. Drowned dolines-the blue holes of the Pompey Reefs, Great Barrier Reef. BMR J. Aust. Geol. Geophy. 4: 99-109.

Bloom, A.L., 1974. Geomorphology of reef complexes. In Laporth, L.F. (editor) Reefs in Time and Space. Soc. Econ. Palaeont. Mineral. Spec. Pub. 18: 1 - 8.

Chappell, J,. 1983. A revised sea level record for the last 300 000 years from Papua New Guinea. Search 14: 99 - 101.

Goreau, T.F., and Land, L.S. 1974. Fore-reef morphology and depositional processes, north Jamaica. In Laporth, L.F. (editor) Reefs in Time and Space. Soc. Econ. Palaeont. Mineral. Spec. Pub. 18: 77 - 89.

Harvey, N. and Hopley, D. 1981. The relationship between modern reef morphology and a pre-Holocene substrate in the Great Barrier Reef Province. Proc. 4th Int. Coral Symp. 1: 549-554.

Land, L.S., Mackenzie, F.T, and Gould, S.J. 1967. Pliestocene history of Bermuda. Geol. Soc. Amer. Bull. 78: 993-1006.

Marshall, J.F. and Jacobsen, G. 1985. Holocene growth of a mid-Pacific atoll: Tarawa, Kiribati. Coral Reefs. 4: 11-17.

Menard, H.W. 1986. Islands. Scientific American Library, 230pp.

Orme, G.R., Flood, P.G. and Sargent, G.E.G. 1978. Sedimentation trends in the lee of outer (ribbon) reefs, Northern Region of the Great Barrier Reef Province. Phil. Trans. R. Soc. Lond. A291: 85 - 99.

Purdy, E.G. 1974. Reef configurations: cause and effect. In Laporth, L.F. (editor) Reefs in Time and Space. Soc. Econ. Palaeont. Mineral. Spec. Pub. 18: 9 - 76.

Ross, J.C. 1855. Review of the theory of coral formations set forth by Ch. Darwin in his book entitled: Researches in Geology and Natural History. Natuurkd. Tijdschr. Ned. Indie. 8: 1-43.

Searle, D.E. 1983. Late Quaternary controls on the development of the Great Barrier Reef: Geophysical Evidence. BMR J. Aust. Geol. Geophy. 8: 3, 267-276.

Searle, D.E., and Harvey, N. 1982. Interpretation of inter-reefal seismic data: A case study from Michaelmas Reef, Australia. Marine Geol. 46: MR-MR16.

Searle, D.E., and Flood, P.G. 1988. *Halimeda* bioherms of the Swain Reefs - southern GBR. Proc. 6th Int. Coral Reef Symp. 3: 139-144.

Trudgill, S.T. 1976. The subaerial and subsoil erosion of limestones on Aldabra Atoll, Indian Ocean. Z. Geomorph., Suppl. Bd. 26: 201 - 210.

Woodroffe, C.D., McLean, R.F. Polloch, H.A. and Wallensky, E. 1990. Sea level and coral atolls: late Holocene emergence in the Indian Ocean. Geology. 18: 62-66.

Woodroffe, C.D., Veeh, H.H., Falkland, A.C., McLean, R.F. and Wallensky, E. 1991. Last interglacial reef and subsidence of th Cocos (Keeling) Islands, Indian Ocean.Marine Geol. 96: 137-143.

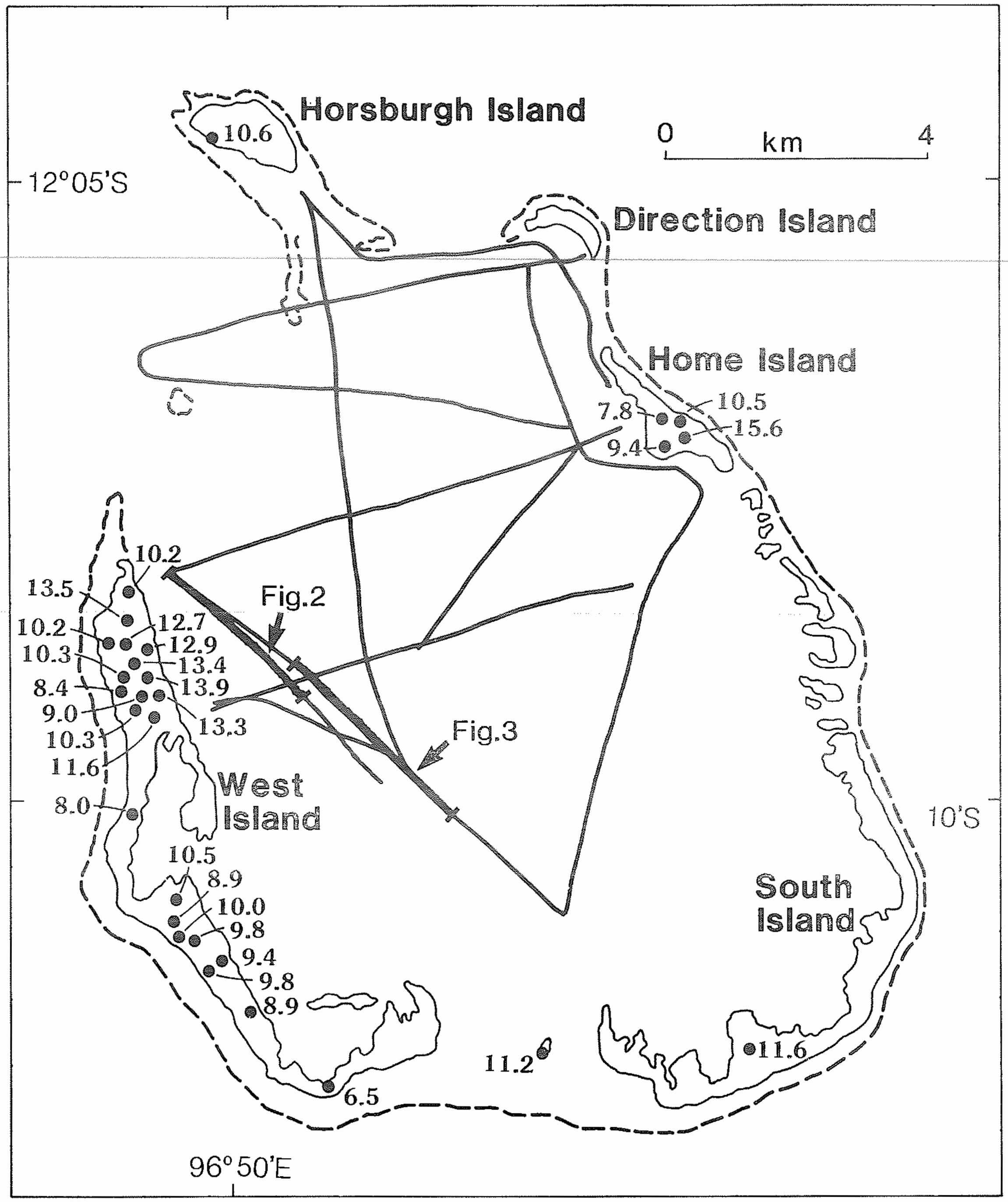

Figure 1. Cocos (Keeling) Atoll, showing the location of seismic tracks, coreholes and depths (below msl) to discontinuity.

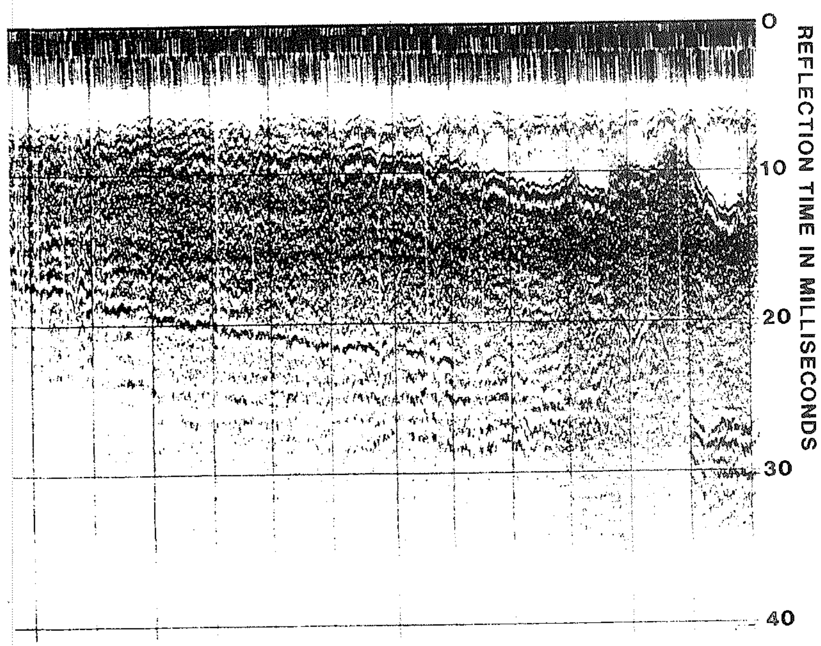

FIGURE 2a

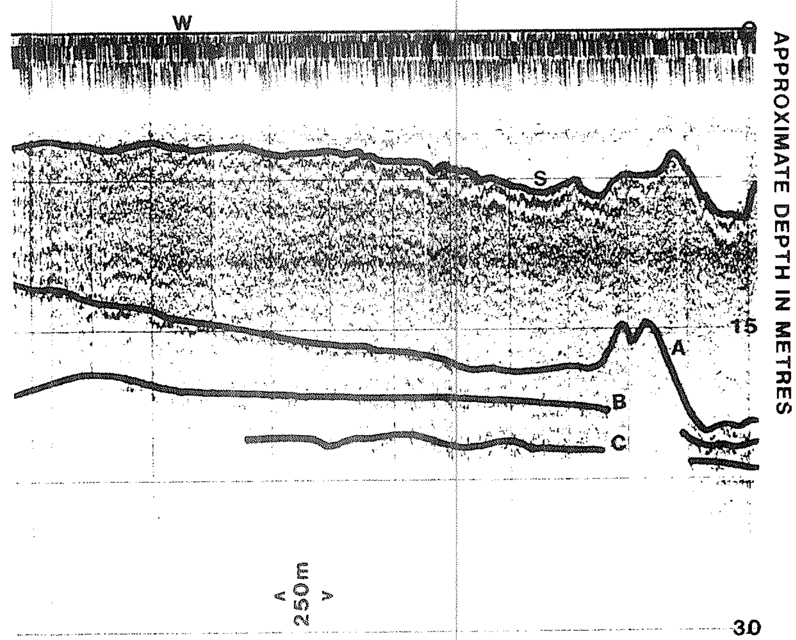

FIGURE 2b

Figure 2. a) CSP record off northern part of West Island. b) Interpreted record. W - water surface, S - seabed, A,B,C - subsurface reflectors. Note Holocene sequence, approximately 10 m thick, overlying the Last Interglacial reef surface (A).

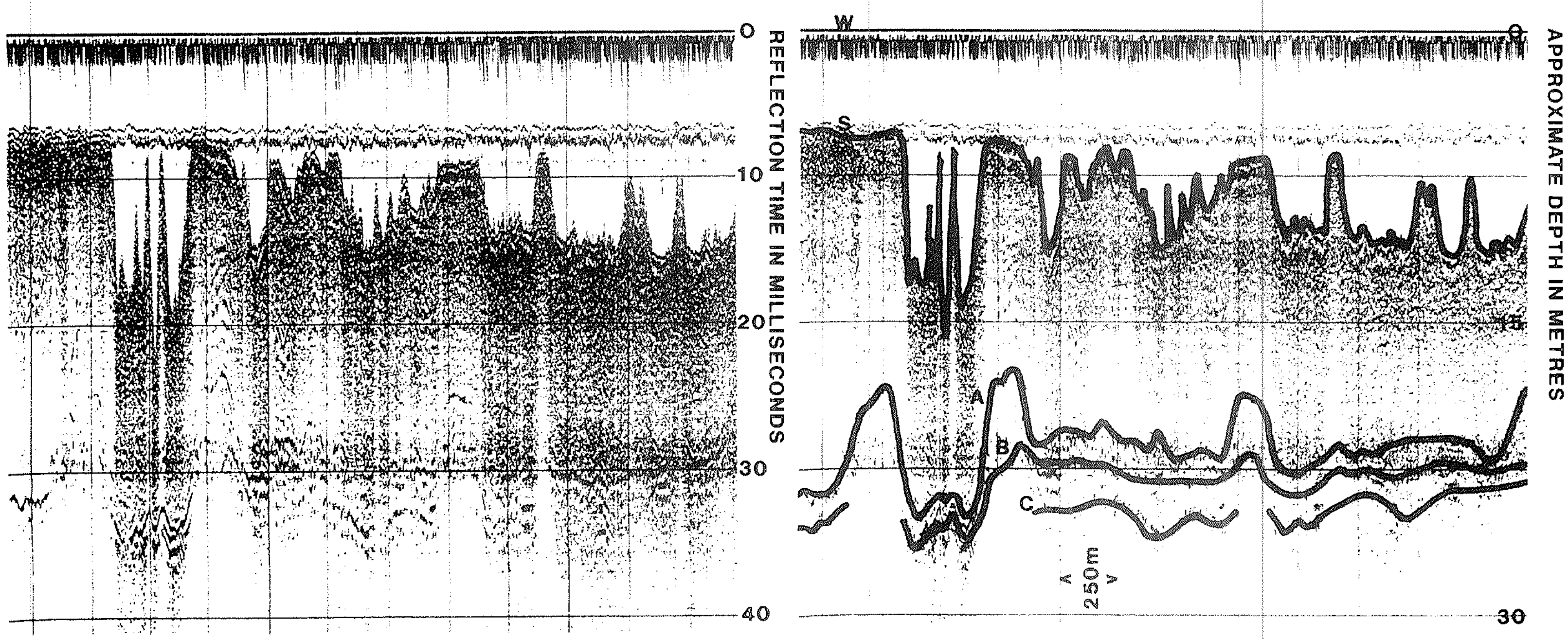

FIGURE 3a

FIGURE 3b

Figure 3. a) CSP record from southern central lagoon, traversing infilled blue hole (LHS), deep blue holes, and patch reefs (RHS). b) Interpreted record. Note general similarity in shape between modern lagoonal surface and antecedent surfaces, and enhanced relief through time.

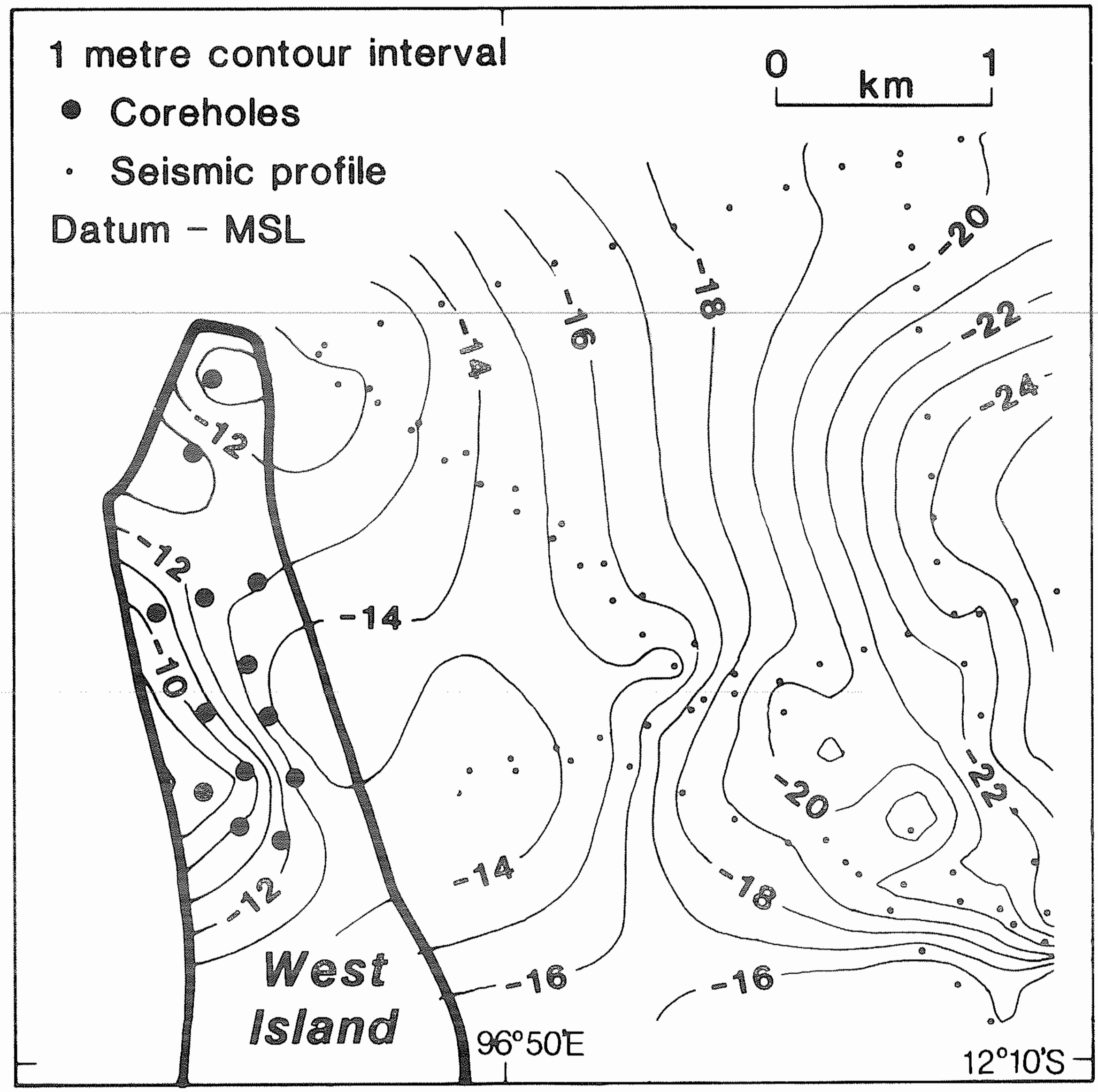

Figure 4. Contour plot of Last Interglacial atoll surface beneath western part of Cocos lagoon, based on seismic and drillhole data.

Figure 5. Oblique aerial photograph, looking east, of southen part of Cocos lagoon showing field of blue holes and atoll rim (between Home and South Islands). The holes are infilled to the south, coalesce in the midfield and pass into submerged patch reefs to the north. The seismic profile shown in Figure 3 passed close to the foreground in this photograph. Foreground width = 1500m.