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Drowned dolines — the blue holes of the Pompey Reefs, Great Barrier Reef

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Blue holes occur at Cockatoo and Molar Reefs, in the Pompey hard line reefs. These two holes are roughly circular in shape, between 240-295 m in diameter, and 30-40 m deep. They are completely (Cockatoo) or partially (Molar) rimmed by profuse living coral and surrounded by lagoonal depths of 5-10 m. The inner slopes of the Cockatoo blue hole are 60-70° down to a depth of 25 m, below which coalescing sediment fans markedly reduce this angle. At the Molar blue hole, slopes are mainly gentler (45°) and sediment fans and terraces occur below 16 m. Distinct biological/sedimentary associations occur in both holes. Seismic refraction studies across the rim of the blue holes show a shallow (8.5-11 m) pre-Holocene surface beneath the rims. The balance of evidence suggests that the blue holes represent collapsed dolines which may have taken more than one low sea-level period to form. The original surface structures have been modified by subaerial solution processes, and subsequent sediment infill and coral growth following the Holocene transgression.

Introduction

Like sapphires set in turquoise (front cover, this issue), the blue holes of coral reefs have long impressed mariners, naturalists and reef scientists. Examples of such circular, steep-sided holes in the Bahamas have caused comment since the end of the last century. Northrop (1890), and Agassiz (1894) firmly attributed them to terrestrial solution prior to substantial subsidence. However, at much the same time, Wharton (1898) vaguely linked the *Puits sans Fond* of Clipperton in the northern Pacific that had been described as 'a perfectly round hole in the lagoon which looks very much like an old crater' (J. Arundel *in* Wharton, 1898), with his view of the whole reef as growing on top of explosion remnants of a volcano. Volcanic rocks do project in Clipperton Rock, making Clipperton an almost-atoll (Sachet, 1962). Wharton's idea for the blue hole is somewhat far-fetched, however, and Agassiz's solution mechanism has been generally accepted for blue holes, though latterly combined with glacio-eustatism rather than with tectonic movements of reef foundations. Some recent investigators have provided powerful support for Agassiz's theory, notably Dill (1977); moreover, the origin of blue holes has become interwoven with the antecedent karst hypothesis of modern reef configuration (e.g. Purdy, 1974). Nevertheless there has been a tendency to jump to this explanation without weighing other possible modes of formation and assessing different processes subsumed within this broad standpoint.

The best Australian examples of blue holes are in the Pompey Reef Complex (Fig. 1). This is the most intricate and least known area of the Great Barrier Reef, and is composed of an inner series of linear reefs, a central series of irregular patch reefs, and an outer series of massive 'hard line' reefs. The outer reefs are up to 200 km from the mainland coast, and form a belt 140 km long and 16 km wide. Individual reefs are up to 100 km² in area.

Maxwell (1970) attributes the pattern of reefs and channels of the Pompey Complex to growth on reef-derived detritus deposited as delta sediments in a strong tidal-current regime. He is supported in his suggestion by the strong tidal currents operative in the area today (2.5-10 kt). In contrast, however, Purdy (1974) suggested that features of Big Stephens Reef, in the Pompey Complex, were analogous to karst features. Moreover, he argued that the whole barrier platform of the Central Barrier Reef had been a large limestone drainage divide in pre-Holocene times (Purdy, 1974, p. 58). Maxwell (1976) has since disagreed with these assertions and argued that 'residual morphology of the shelf has localised reef development, but there is little evidence to suggest that it has controlled shape attributes of individual reefs' (1976, p. 79). Here we report general observations made on two of the Pompey Reefs, and detailed studies of two blue holes in them made during an expedition utilising the M.V. *James Kirby*. The hard line Pompey Reefs were visited for two weeks in October 1977, when echo-profiling, scuba exploration, sediment coring, seismic refraction, grab sampling and shallow drilling were carried out. The general description of the reefs outlined below is based on these field data, with information gained from a study of vertical air photographs (1:70 000), oblique colour photographs taken by the authors from a height of 500 m, and a series of processed colour-composite images based on LANDSAT data.

Cockatoo Reef and blue hole

Cockatoo Reef (previously unnamed, location 20°45′S, 151°02′E), one of the largest reefs of the hard line Pompey Complex, is 13.6 km long in a north-westerly direction, and 8.7 km wide (Fig. 2A). It is separated from adjacent reefs by deep channels, 93 m being recorded in the southern pass. The reef is highest next to the channels, the 350 m-wide algal rim reaching a level between mean low-water springs and mean lower water neaps. Elsewhere the reef flat is slightly lower and very sandy, with small coral heads aligned parallel to the apparent direction of tidal scour over the reef top. One prominent reef-flat ridge is continuous across the entire reef. Distinctive sediment trains lead into the intricate lagoon systems, most of which appear to have a maximum depth of 10 m. It is this mesh pattern of lagoon systems and ridges which Purdy (1974) and others have considered to be analogous to the closed depressions of Pleistocene karst topography. However, the reef cap is clearly Holocene in age, a

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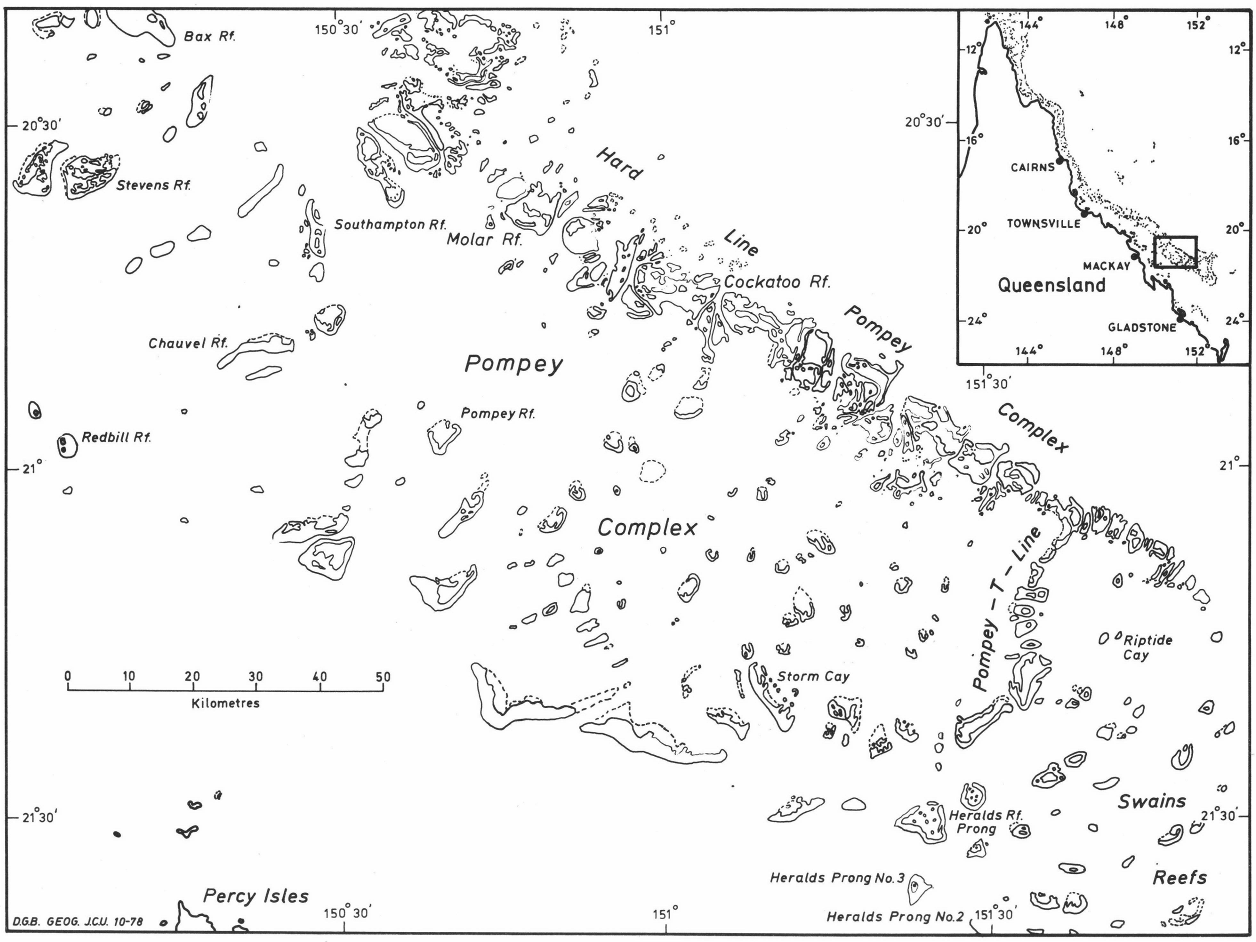


Figure 1. Location of Molar and Cockatoo Reefs in the Pompey Complex.

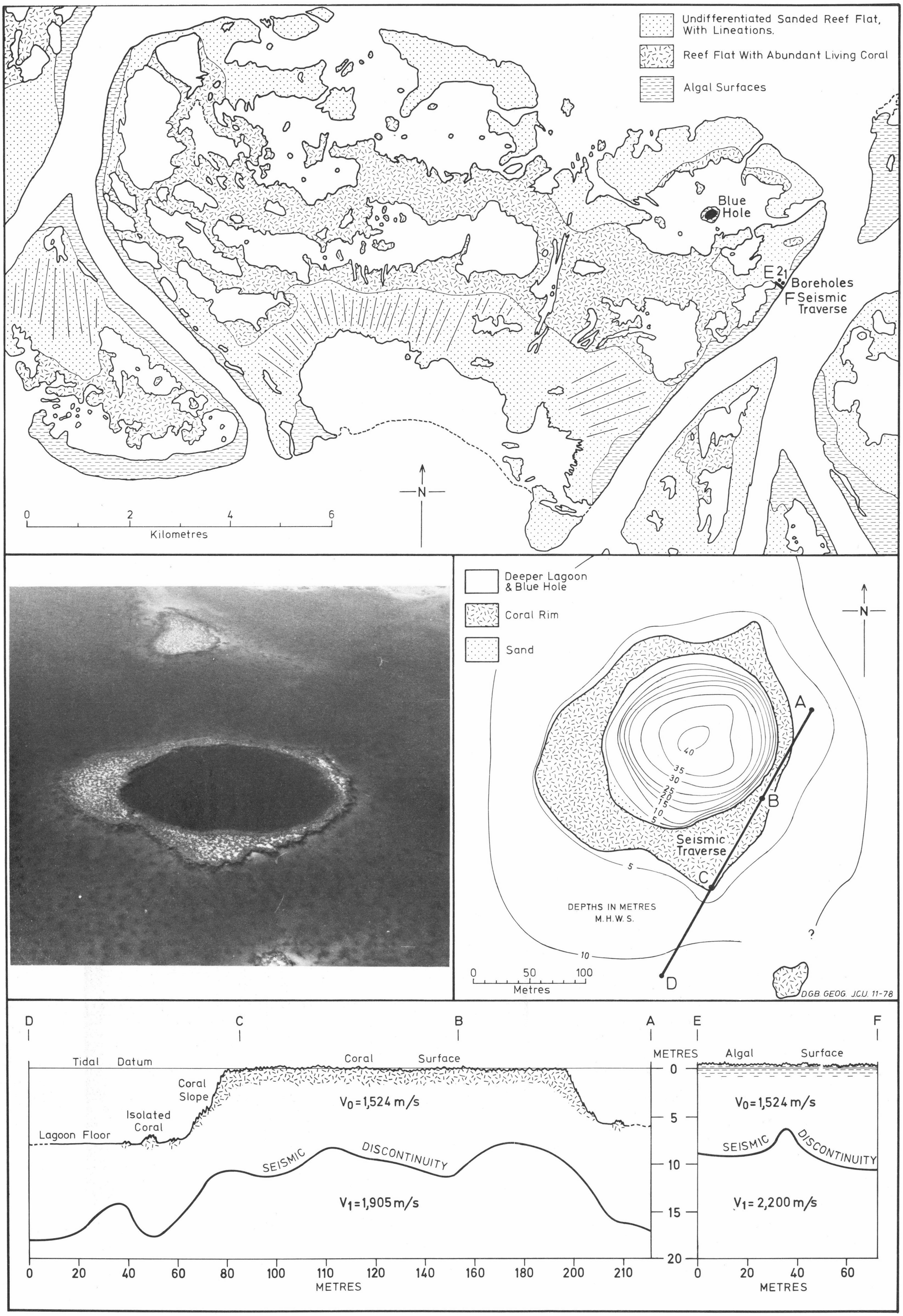
Code No.	*Location*	*Depth (cm)*	*Material*	*Aragonite (percent)*	*Radiocarbon age (years B.P.)*
GaK7270	Cockatoo Reef Algal Rim. Hole 1	15-22	*Acropora* separated from Algal Cement	98	4100 ± 100
GaK7271	Cockatoo Reef Algal Rim. Hole 1	55-70	*Acropora* separated from Algal Cement	98	3480 ± 120
GaK7269	Cockatoo Reef Algal Rim. Hole 2	12-17	*Acropora* separated from Algal Cement	98	30 ± 100
GaK7268	Molar Reef On Seismic Line C-D	65-75	*Acropora* Shingle	98	1310 ± 100
NSW259	Cockatoo Blue Hole	0-5	Coral/Algal Sediment	75	860 ± 100
NSW268	Cockatoo Blue Hole	50-60	Coral/Algal Sediment	75	1000 ± 100
NSW269	Molar Blue Hole	0-5	Coral/Algal Sediment	75	1390 ± 130

Table 1. Radiocarbon ages of rock and sediments from Cockatoo and Molar Reefs.

date of 4100 ± 100 y. BP (Table 1), being the oldest date obtained from algal-cemented *Acropora* in two drill holes into the southern algal rim.

The blue hole of this reef is centrally situated in the large lagoon at the northeastern end of the reef (Fig. 2A). The lagoon has a maximum depth of just over 10 m and is open to the ocean in three places. Its floor is sandy, with only a few isolated coral heads. Twenty-three sediment samples from the lagoon and rim of the blue hole were dominantly fine sand (mean size 2.03 to 2.48 ϕ), only moderately sorted (SD = 1.03 to 1.53 ϕ) in the deeper lagoon, but becoming both coarser and more poorly sorted within 25 m of the living coral rim of the blue hole (mean size 1.29 to

Figure 2. A. Plan of Cockatoo Reef showing the positions of the blue hole, seismic traverses and drill holes. B. Oblique aerial photograph of Cockatoo blue hole. C. Plan of blue hole drawn from closely spaced echo profiles. The position of seismic section A-D is marked. D. Seismic sections AD and EF.


Undifferentiated Sanded Reef Flat, With Lineations.
Reef Flat With Abundant Living Coral
Algal Surfaces
Blue Hole
E
2
1
F
Boreholes
Seismic Traverse
N
0 2 4 6
Kilometres
Deeper Lagoon & Blue Hole
Coral Rim
Sand
N
A
B
C
D
40
35
30
25
20
15
10
5
Seismic Traverse
5
10
?
DEPTHS IN METRES M.H.W.S.
0 50 100
Metres
DGB GEOG. JCU 11-78
D C B A E F
Tidal Datum
Coral Surface
Coral Slope
Isolated Coral
Lagoon Floor
V0 = 1,524 m/s
SEISMIC DISCONTINUITY
V1 = 1,905 m/s
METRES
0
5
10
15
20
0 20 40 60 80 100 110 120 140 160 180 200 210
METRES
Algal Surface
V0 = 1,524 m/s
SEISMIC DISCONTINUITY
V1 = 2,200 m/s
0 20 40 60
METRES

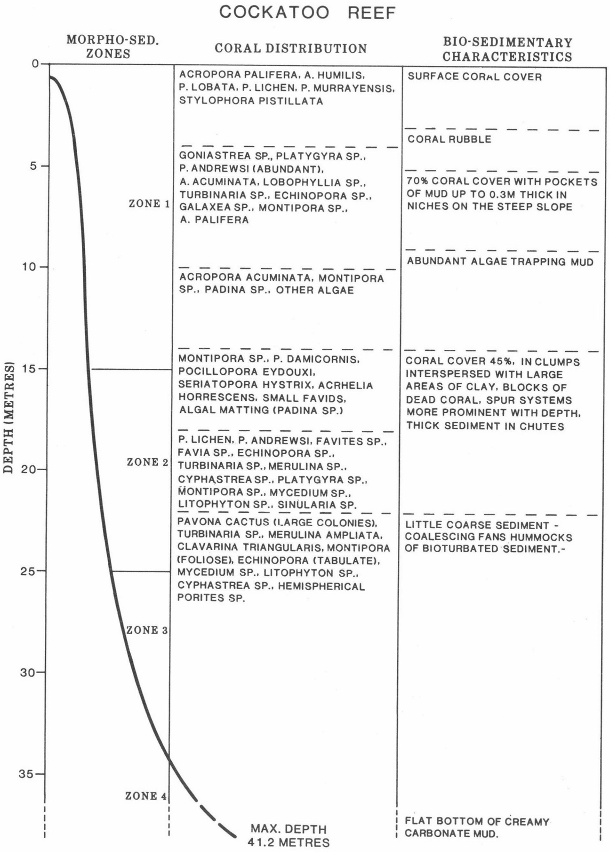


Figure 3. Bio-sedimentary characteristics of the Cockatoo blue hole. All data obtained by scuba diving.

2.21 ϕ; SD 1.39 to 1.80 ϕ). Sediments from the rim were even coarser (mean size 0.11 to 0.64 ϕ) and also poorly sorted (SD = 1.42 to 1.51 ϕ). The sediments consisted of fragments of coral, coralline algae and molluscs, with only minor amounts of foraminifera and other calcareous organisms.

The blue hole has a rim of living coral 10 to 60 m wide. The hole (Fig. 2B) is nearly circular in plan, and has a maximum length of 240 m north-south and a width of 205 m. Echo-sounding traverses across the feature show it to be bowl-shaped and slightly asymmetrical, with the steepest side to the east, where the upper slope is 60° to 70°. Elsewhere the upper slope is between 45° and 50° (Fig. 2C).

Four morpho-sedimentary zones were recognised (Fig. 3) from scuba investigations.

Zone 1

0-15 m. This is the zone of maximum coral cover (70% down to —10 m). Abundant rubble, mainly *Acropora* sticks, occurs at near —4 m (Fig. 4A). Mud-grade sediment occurs in pockets at least 0.3 m deep; such sediment contains very little sand or silt particles. Abundant worm tubes suggest much bioturbation from 12 to 15 m. Downwards there is a decrease in coral cover to 45 percent, and soft algae, particularly *Padina,* become abundant Fig. 4B). Fine carbonate is stabilised by these algae, even though the slope is 60-70°.

Zone 2

15-25 m. Still sloping at 60-70° (Fig. 4C), this zone is dominated by down-slope linear spurs of coral colonies separated by chutes 1.5 m wide at the top, but widening downwards to 7 m (Fig. 4D). The coral spurs are commonly interrupted towards their ends by irregular corridors between adjacent chutes. Fans of fine sediment spill out of the deeper ends of the chutes.

Zone 3

25-35 m. The top of this zone is delineated by a gentle break of slope; the zone is marked by the almost complete absence of corals, and the presence of a very hummocky terrain. Such hummocks, up to 0.6 m high—probably the result of burrowers—are obliterating the boundaries of adjacent coalescing sediment fans. This whole slope (30°-45°) is completely built by the coalescing fans.

Zone 4

Below —35 m, the slope lessens quickly to a flat bottom composed of buff soft plastic sediment covered by algal films. There is little evidence of the burrowing activities seen in ZONE 3, but holothurians, anemones and worms are active on the bottom (Fig. 4E). The sediment has the consistency of yoghurt.

A push core was obtained in ZONE 4 sediments at a depth of —35 m, and penetrated 60 cm. The gross sedimentological features are shown in Figure 5A. No bedding is visible, the sediment being homogeneous except for the large pelecypod shell which pulled out of the core at a depth of 25 cm. Petrographic and scanning electron microscope studies of the core show the sediment to be composed of fine sand to mud, made up of degraded coral/algal fragments with abundant radiolaria, foraminifera and sponge spicules. Pellets agglutinated by organic films and algal filaments occur mainly in the lower part of the section.

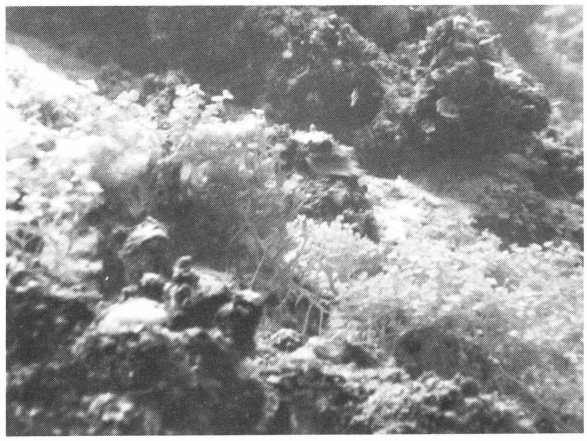
Radio-carbon dating of the cores (Fig. 5A, Table 1) show no appreciable differences in age between the top and bottom. This suggests either that abundant biologic mixing of the sediment has occurred, or such mixing occurred during deposition as a result of turbulent flow down the chutes on to the floor of the blue hole. By either method, the resultant sediments are not bedded, and rates of sedimentation could not be calculated.

Sub-surface structure was investigated by seismic refraction profiling. Two refraction transects were completed at Cockatoo Reef, one 260 m long across the rim of the blue hole, and one 77 m long across the algal rim marking the southeastern rim of the reef (Fig. 2D). Seismic section A-D (Fig. 2D) show a seismic discontinuity at depths of 16.5 and 18 m beneath the lagoon, but rising to 9 to 11 m depth beneath the coral rim ringing the blue hole. The present surface is therefore similar in gross outline to the seismic discontinuity. Profile E-F, across the southeastern algal rim, displays the seismic discontinuity sloping from —7 m to —11 m backwards towards the lagoon. Although the profile stops before reaching the lagoon, it is pertinent that the shallowest part of the disconformity underlies the algal ridge.

Molar Reef and blue hole

Molar Reef (previously unnamed, location 20°38′S, 150°48′E) is one of the northernmost of the hard line Pompey Complex reefs (Fig. 6A). It is 7.75 km long in a northeast direction, and 7.4 km wide. Like Cockatoo and other reefs of the area it is bordered by deep channels. Algal rims are prominently developed along the margins of the channel on the southeastern side of the reef and to a lesser extent on the southwestern

Figure 4. A. *Acropora* and rubble in the top 4 m of Cockatoo blue hole.

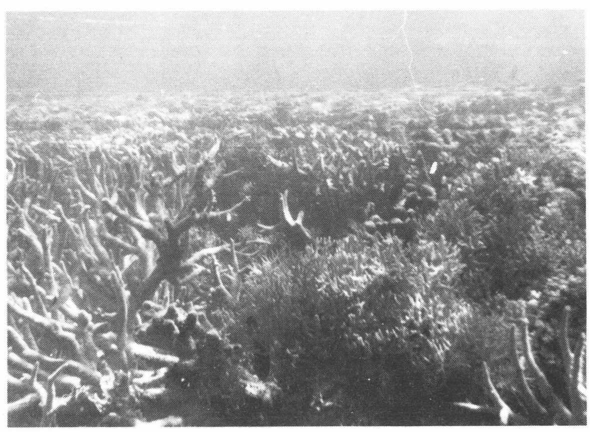


B. *Padina* on the upper slope of Cockatoo blue hole.

C. Steep slope with abundant coral in the depth range 15-25 m. Cockatoo blue hole.

D. Base of sediment chute bordering a coral spar, at 20 m.

E. Holothurian bioturbating sediment at a depth of 35 m; Cockatoo blue hole.



F. *Acropora* and *Seriatopora* mark inner edge of rim of Molar blue hole.

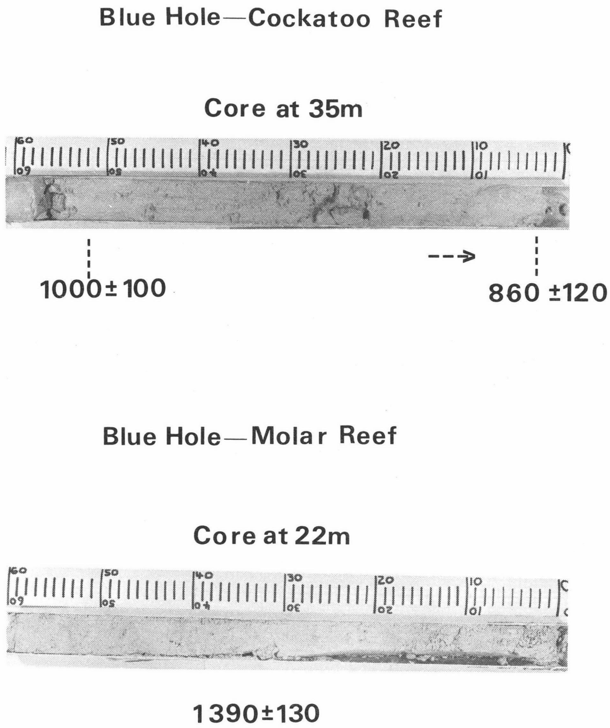


Figure 5. Push-cores, depths as shown.

and northwestern margins. A prominent feature of the reef is a central ridge separating complex lagoonal systems. The ridge rises to a level slightly above mean low water springs and has a dense cover of living corals, consisting mainly of *Pocillopora* sp., *Seriatopora* sp. and *Acropora humilis*. A shallow core 1 m into this ridge showed its upper surface to consist of similar branching corals in growth position, and probably comminuted shingle and coarse sand. Cemented shingle from a depth of 0.65 to 0.75 m produced a radiocarbon age of 1310 years ± 100 BP (Table 1). The lagoons of the reef are sand-floored and have maximum depths of 7 m. To the southwest of the central ridge much of the reef flat consists of living corals with a strong southwesterly lineation. On the northern end of the reef is a small, deep channel branching from the main channel to the north but blocked at its eastern end. Such blind channels are common features of the hard line reefs of the Pompey Complex.

The blue hole of Molar Reef is near the centre of the reef southwest of the central ridge, and at the southern end of a small lagoon (Fig 6A). It has a living coral rim on the southern and eastern sides but a lip of shallow (5 m) lagoon to the north and west (Fig. 6B). The rim therefore is not completely associated with the blue hole. It is larger than the blue hole on Cockatoo Reef, having an east-west length of 295 m and a width of 260 m. It is slightly asymmetric with the steeper side to the east, but has a bowl shape very similar to that of Cockatoo Reef. The shallow concave floor commences at a depth of about 25 m, with a maximum depth of 29.25 m being recorded by echo sounder, and 32.5 m by lead line (Fig. 6C).

Detailed scuba study of this hole was hampered by poor visibility below a depth of 15 m. However, five morpho-sedimentary zones were recognised (Fig. 7).

Zone 1

Surface zone of low, stunted colonies of *Acropora palifera* and *Seriatopora hystrix* forming gullies and courses floored with coral/foraminiferal sand and gravel (Fig. 4F).

Zone 2

From the surface to a depth of 3 m, a steep slope (60-70°) marks the inner edge of the rim near the blue hole. This steep slope is formed by the vertically growing surfaces of *Acropora* and *Seriatopora* (Fig. 4F).

Zone 3

From −3 to −7 m this slope is much gentler (10°-15°) and composed almost entirely of rubble mounds of *Acropora* and *Seriatopora* (Fig. 8A). There is little evidence of bioturbation, but abundant evidence of organic degradation of coral detritus by mollusc, sponge and algal borings. A coral cover of 10 per-cent is made up mainly by *Stylophora pistillata, Pocillopora damicornis,* with some *Acropora palifera.* At the base of this zone, trapping of sediment by the alga *Padina* occurs.

Zone 4

From −7 to −16 m a change in gradient to 45° occurs. The sediment is composed mainly of coral gravel decreasing downwards where sand predominates (Fig. 8B). The 45° slope is mostly bare, but scattered colonies of *Acropora palifera,* massive *Porites, Platygyra* and *Montastrea* break up the slope (Fig. 8C, D). The lowest level at which *Seriatopora* is found is at −13 m.

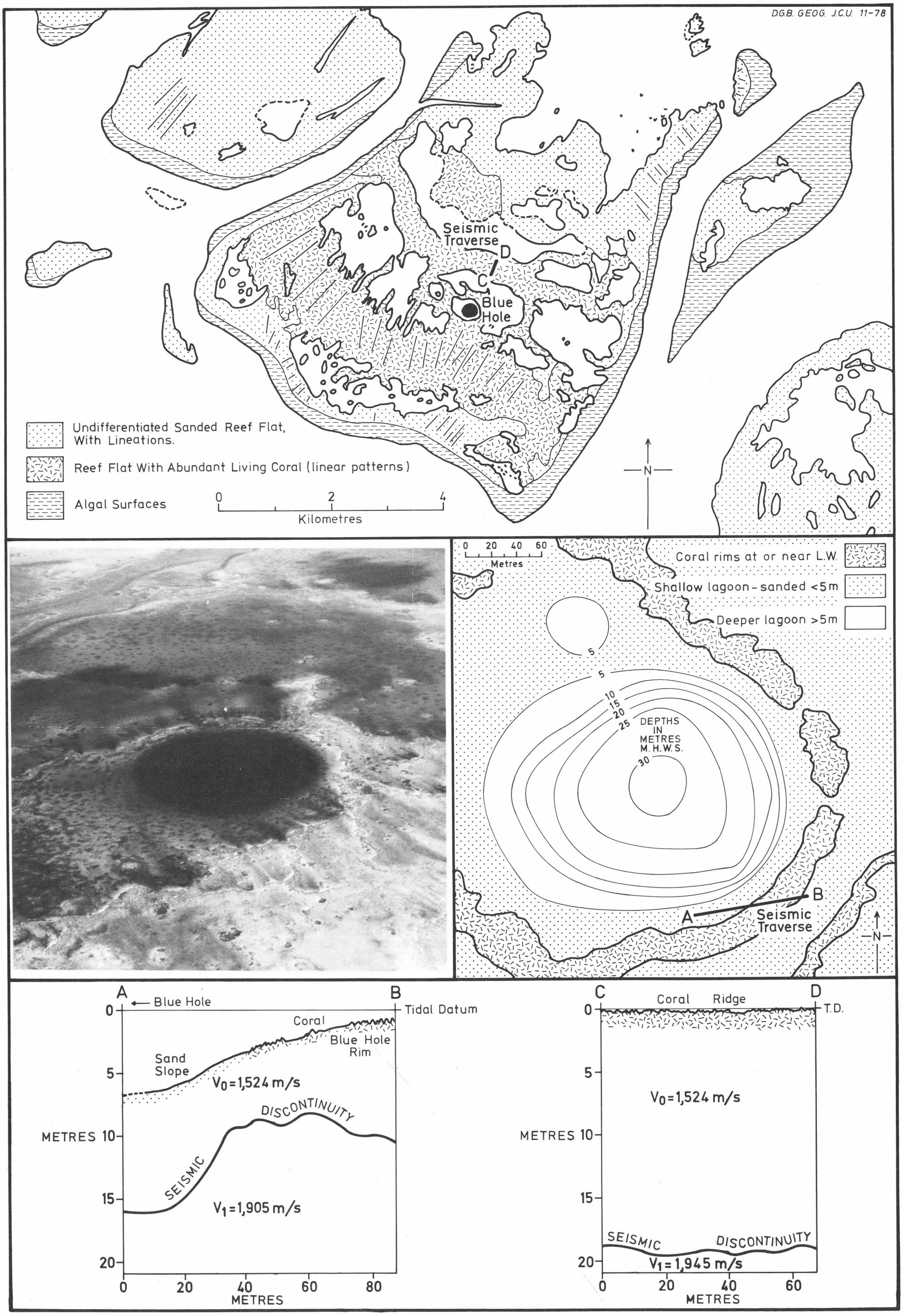
Zone 5

A marked decrease in slope below 16 m terminates in a flat plain composed of mud and admixed sand (Fig. 8E). Visibility at this depth was less than 1 m, but exploration showed the flat plain to be extensive. In fact, the divers concluded that it must represent the bottom of the blue hole. Coral cover in this zone is about 5% (Fig. 8F).

It proved impossible to take a vertical push core because gravel-sized fragments prevented penetration. A horizontal core is shown in Figure 5B. Much of the sediment is held together by organic coatings and mucus. The radiocarbon date of 1390 ± 13 y. B.P. does not mean that sedimentation then ceased. The radiocarbon age dates the mineral components, and not the time of sedimentation.

Two refraction transects (Fig. 6D) were completed across the rim of the blue hole, and coral ridge at Molar Reef. Across the rim of the blue hole, the seismic disconformity is highest beneath the irregular coral rim (−8.5 m) and deepest (−16 m) beneath the sand slope bordering the inner margin. The section CD across the coral ridge shows the disconformity at a constant depth of about −20 m.

Figure 6. A. Plan of Molar Reef showing the position of the blue hole, and the position of seismic sections.
B. Oblique aerial photograph of Molar blue hole.
C. Plan of blue hole drawn from closely spaced echo profiles. The position of seismic section A-B is marked.
D. Seismic sections A-B and C-D.


DGB. GEOG. JCU. 11-78
Seismic Traverse
D
C
Blue Hole
Undifferentiated Sanded Reef Flat, With Lineations.
Reef Flat With Abundant Living Coral (linear patterns)
Algal Surfaces
0 2 4
Kilometres
N
0 20 40 60
Metres
Coral rims at or near L.W.
Shallow lagoon - sanded <5m
Deeper lagoon >5m
5
10
15
20
25
30
DEPTHS IN METRES M.H.W.S.
A
B
Seismic Traverse
N
A ← Blue Hole
B
Tidal Datum
Coral
Blue Hole Rim
Sand Slope
V0=1,524 m/s
SEISMIC DISCONTINUITY
V1=1,905 m/s
METRES
0 20 40 60 80
METRES
C Coral Ridge D
T.D.
V0=1,524 m/s
SEISMIC DISCONTINUITY
V1=1,945 m/s
METRES
0 20 40 60
METRES

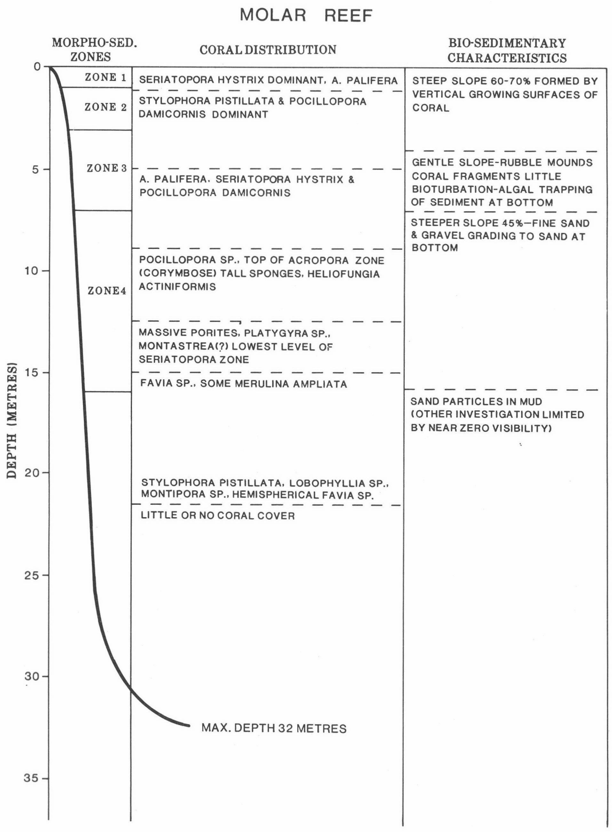


Figure 7. Bio-sedimentary characteristics of the Molar blue hole. All data obtained by scuba diving.

Discussion—origin of blue holes

Holocene coral growth and sedimentation has so obscured the nature of the pre-Holocene surface that it is necessary to consider all possible hypotheses for the formation of the blue holes. Round, closed depressions are known elsewhere to have resulted from glacial and ground ice melt processes, pseudokarst processes in basalts and laterites, volcanicity, meteorite impact, or from true karst processes. The first two groups of processes may be dismissed because of the unlikelihood of severe Pleistocene cold periods here and the absence of basalts and laterites at shallow depth beneath the reefs. Similarly a relation to constructional or destructional volcanic activity is unlikely because volcanics occur at only one locality, in the Murray Islands at the extreme northern end of the reefal province. However, a meteorite impact origin or processes of limestone karstification must be given more serious consideration.

Meteorite impact

An origin by meteorite impact cannot be ruled out on the basis of regional evidence. The dimensions of the blue holes are, for example, closely comparable to those of the Henbury craters in the Northern Territory. The fact that the blue holes' rims are capped by Holocene reef growth does not exclude an impact origin for the holes. Indeed, the rim shown by the seismic discontinuity for the Cockatoo Reef hole is typical in form for a meteorite crater. In addition, the dubious association of modern rim and blue hole at Molar Reef also does not eliminate the meteorite mechanism because rims are not necessarily formed with meteorite craters; however, it does cast some slight doubt on this interpretation. Nor is the test of presence or absence of meteoritic material critical and this cannot even be applied because of the obscuring effect of subsequent sediment. Recourse has to be made to the less satisfactory procedure of arguing from the similarity of the cases in question to those in other areas where this mode of origin can be eliminated. Suffice it to point to the long, gently sinuous line of blue holes along the east coast of Andros Island in the Bahamas, parallel and close to the steep slope dropping to the depths of the Tongue of Ocean (Jordan, 1954; Benjamin, 1970). A meteorite shower is unlikely to produce a single chain aligned along a pre-existing topographic feature over a distance of 40 km in this way. It must be admitted, however, that blue holes need not necessarily be of the same origin everywhere; the probabilities, nevertheless, are against the Queensland blue holes being modified astroblemes.

Karst erosion

Karst remains the most likely process to have formed the Pompey blue holes. However, consideration must be given to both submarine and subaerial conditions as the necessary prerequisites for their formation.

Submarine springs are well known from many coastal karst regions, for example the Anavalos spring off the Kynourian coast of the Peloponnesus in Greece, which vents onto the sea floor at a depth of −36 m (Mistardis, 1968). However, this and others like it are generally thought to have formed during a Pleistocene low sea-level period. Moreover, such springs occur in close proximity to high subaerial relief—a condition which does not occur in the Great Barrier Reef, where the blue holes are 200 km from the nearest high relief masses. A submarine vauclusian spring is therefore unlikely to have brought about the formation of our blue holes. Also it is unlikely that springs have arisen as a result of leakage from a deep basement aquifer forming part of any potential offshore extension of onshore basins. We suspect that leakage from any potential basement aquifer through the thick post-basement sequence (+2000 m) would be manifested in regional features, rather than in isolated spots forming blue holes. Submarine collapse of a cave formed subaerially during periods of low sea level seems also unlikely, because submarine flooding would provide fresh support for the roof by filling the chamber with water. We conclude therefore that formation below sea level is unlikely, and are faced with the generally accepted standpoint of Agassiz for subaerial karsting as a mechanism for blue-hole formation, a conclusion supported generally by morphological comparisons between Pacific (Emery & others, 1954; Stoddart, 1969) and Atlantic (Purdy, 1974) reef features, and sinkhole plains such as those in Kentucky (Miotke, 1973); and more specifically by the distinct resemblance of the meshwork reef structure of the Molar and Cockatoo Reefs to the solution-developed ridge and corridor morphology of the Nullarbor Plain (Jennings, 1967).

Closed depressions in karst, even of the simple form comprised under the term doline, are of many types, with several processes at play (Jennings, 1971; Quinlan, 1974). We are therefore still left with several options for the formation of blue holes. Some can be set aside summarily. General knowledge of the geology of the reefs permits rejection of the origin of the blue holes as subjacent karst dolines. An origin as dolines of the rising spring basin type (Maksimovich & Goloubeva, 1952) can be rejected because the blue holes are very much larger than known hollows of this kind, e.g. at the Blue Waterholes, Cooleman Plain, NSW

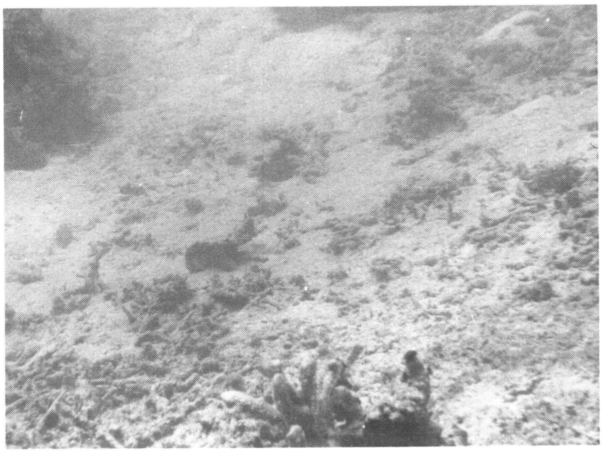
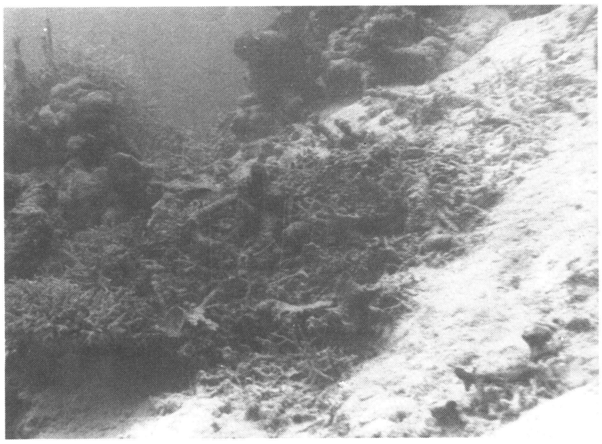
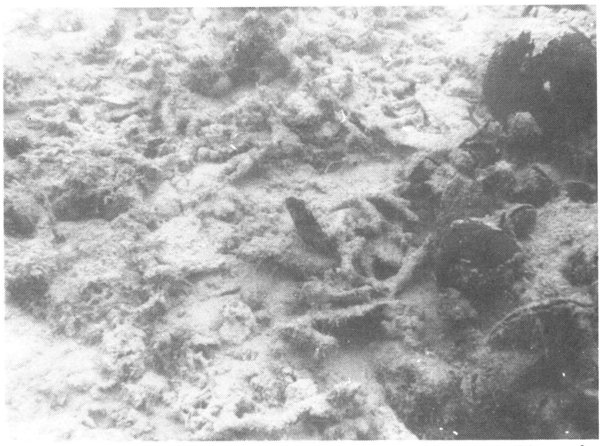


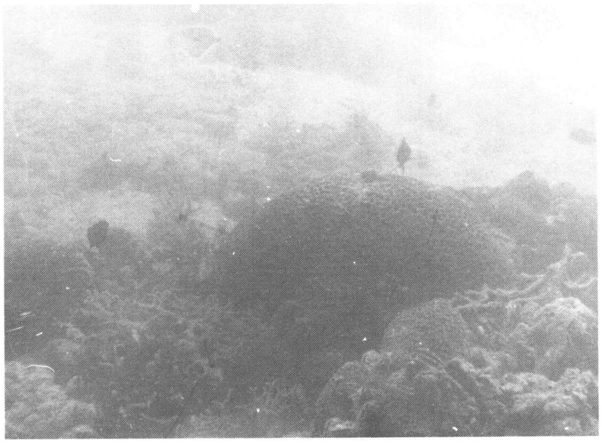
Figure 8. A. ***Acropora*** **and** ***Seriatopora*** **rubble at depths down to 7 m in Molar blue hole.**

B. Rubble with greater amounts of sand at around 12 m.





C, D. A 45° slope; ***Acropora,*** **and massive** ***Porites*** **scattered over a rubbly/sandy bottom. About —13 m in Molar blue hole.**



E. Sand/mud bottom at —20 m, with crab hole Molar blue hole.

F. Scattered interspersed corals at —20 m. Molar blue holes.

(Jennings, 1972). Subsidence dolines, i.e. the progressive removal from below of unconsolidated covering sediments down solution pipes in the reef limestone, calls for the presence of such covers elsewhere in the reefs, at least as remnants, and of this there is no evidence. The same kind of argument applies also to alluvial plain dolines. There persists the choice therefore between solution dolines and collapse dolines.

Solution and collapse dolines

The distinction between solution and collapse dolines has not been made explicitly in previous studies of reef morphology; most workers have referred to terrestrial solution in a general way and broadly to sinkholes or sinks as a single category, e.g. Emery & others (1954), Newell & Rigby (1957). The major morphological features and genetic requirements of solution

	Solution doline	Collapse doline
	INITIAL STAGE	
Cause	Solution at rock surface	Collapse of cave roof, i.e. associated solution is subsurface
Shape	Funnel (conical)	Box-shaped, cylindrical
Sides	Soil covered or partly bedrock. Tending to 20-30° uniform slopes. Sometimes steeper antidip sides	Fractured rock walls, very steep (60°) to overhanging
Floor	Little or no floor, soil covered	Rockfall. Central rock pile or talus slopes below walls (dependent on shape of former cave chamber). If cave chamber partly water-filled, a cenote may result
Plan	Circular or oval	Angular where rock strong; rounded where rock weak
Relation to Caves	Frequently only embryonic cave tubes below; possibly fissure or shaft to cave passage through undisturbed bedrock	Flanking cave remnants usually survive below; sometimes entrance through rockfall
Occurrence	Commonly in fields and associated in complex depressions. May occur singly or in chains	Isolated or several in a chain. Not in fields
	LATER STAGE	
	(1) *Removal of insolubles matching enlargement* Retains funnel shape. Connection with cave below more likely and more open; minor rockfall possible (2) *Removal of insolubles failing to match enlargement* Becomes basin or dish-shaped. Parallel slope retreat accompanied by floor enlargement through soil and debris accumulation. Swamp or pond may develop. No cave connection Additional neighbouring dolines may develop; increasing likelihood of intersection of enlarging depressions	Become basin or dish-shaped. Slopes weather back to 20-30° and become partly or wholly soil-covered. Soil and fine debris conceal and flatten rockfall floor. Plan loses any initial angularity. Connection with cave remnants lost. No change to occurrence

Table 2. Summary of characters of solution and collapse dolines.

and collapse dolines are shown in Table 2. By applying the criteria in this table to the published accounts of modern reef morphology from many areas, solution dolines seem unquestionably the originator of modern morphology in the Bikini and Enewetak lagoons (Emery & others, 1954), on parts of the lagoon of Maroro reef of New Georgia (Stoddart, 1969) and both onshore and offshore in the Yucatan Peninsula (Purdy, 1974); however, collapse dolines seem just as surely to represent the original mechanism for the formation of Jordan's Florida Blue Holes (1954), and Stoddart's Lighthouse Reef Blue Hole off Belize (Stoddart, 1962), a conclusion supported by more recent studies (Dill, 1977). From the length, width and depth of seventeen blue holes in the Bight of Acklins in the southeast Bahamas (published *in* Doran, 1955), it is evident that some are collapse dolines, though others may be solution dolines.

Though the Queensland blue holes are partially infilled with recent sediments, their origin by collapse processes seems likely for the following reasons:

1. The isolation of the blue holes within the large (140 km x 85 km) Pompey Complex. Collapse dolines arise from large chambers and there are generally few in extensive systems of cave passages.
2. The slopes of the Cockatoo blue hole, generally 45-70° at the present time, are more likely to be due to collapse than to surface solution. The lesser slopes (30°-60°) of the Molar blue hole cannot be categorically attributed in this way. However, such a conclusion is strengthened when it is appreciated that the constructional modern slopes have decreased the original slope angles.
3. While the roundness in plan of the Queensland blue holes fits a solution doline mode of formation more easily, circular structures of undoubted collapse origin occur frequently, e.g. in the Gambier Limestone of South Australia, and on the Anatolian Plateau near Konya. These examples and others like them, occur in mechanically weak, often Tertiary limestones. Moreover, initial irregularities in outline would have tended to be smoothed by Holocene sediment and reef growth in the Queensland holes.

In spite of these arguments, it should be appreciated that there is a significant difference in the relation of the two holes to their nearby rims. The Molar Reef hole lies to one side of the reef mesh defined by the rim pattern; the two features appear only accidentally associated. This suggests that the rim is based on a divide around a solution doline, within part of which a smaller collapse doline has opened up. On the other hand, the rim around the Cockatoo Reef hole is related closely to the hole and bears no relation to the large reef mesh in which both are situated. Instead this rim is suggestive of an annular solution rampart around a collapse doline such as has been described from the emerged reefs of Okinawa (Flint & others, 1963). Solution ramparts develop where scarps or cliffs promote the formation of calcrete; differential lowering occurs away from them. The rise in the seismic discontinuity over the Cockatoo Reef blue hole rim fits in with this interpretation, that such a solution rampart was produced during past sea-level lows.

The processes of subterranean solution to form a large cavern, followed by collapse, and subsequent subaerial solution and modification, are unlikely to have occurred over the short period of the last glacial low sea level, i.e. 100 000 y. The formation of a large cave, and ultimately a blue hole, probably occurred over several low sea-level periods, collapse occurring in the final period of karst exposure in the last glacial.

Finally, in advocating a collapse doline mode of formation for the Queensland blue holes, we are aware that two questions arise: are young Quaternary Reef limestones strong enough to support the wide roofs required to form large dolines, and where did the water come from to form large caves? Evidence from Western Australian caves shows that Pleistocene aeolian calcarenites have sufficient strength to support wide roofs because of case hardening, and we suggest that calcretisation, almost certain to have occurred during periods of low sea levels (Harrison, 1977; Harrison & Steinen, 1978), will have added to the strength of reef limestones. Also, Maxwell's (1968, fig. 22A) map of pre-Holocene drainage on the shelf suggests that the area of the Pompey Reefs was bypassed by major streams. We are, however, uncertain how far back in the Pleistocene such a drainage pattern originated, and in any case the reef area itself is quite substantial as a catchment (12 000 km^2). On balance neither the age seriously damages our advocating collapse processes seriously damages our advocating collapse processes for the formation of the blue holes.

Conclusion

Despite the interest that blue holes excite, adequate accounts of them are rare. The most notable exception is the Lighthouse Reef blue hole off Belize which has been shown to be an undoubted collapse doline, only slightly modified after submergence (Dill, 1977). The detail of the present investigation delineates two cases where sedimentation since drowning has greatly obscured their original character, thus placing them at the opposite end of the scale from the Lighthouse blue hole where the preservation of original features makes a collapse origin absolutely certain. However, we feel that the balance of evidence indicates that the Queensland blue holes have also formed by this mechanism.

The extensive blanket of sediment probably conceals, at least in the case of the Molar Reef hole, the effects of significant surface weathering of collapse doline form prior to submergence. Both Molar and Cockatoo seem likely to be older than both the Lighthouse Reef hole and certain of the Bahamas holes for which some detail is available. The likelihood that the Cockatoo Reef rim has grown on a solution rampart reinforces this inference.

A distinction has been drawn here between the blue holes and the patterns of ridge and large shallow depressions, which constitute most parts of the reefs in which they are situated. The patterns are thought to represent fields of solution dolines, but it was not our objective to muster evidence to establish this. This interpretation, however, can be said to be consistent with the antecedent karst hypothesis, whereas we believe that the blue holes provide firm evidence of substrate control of Holocene Reef growth—that substrate being formed by karst processes.

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