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Julia M. James Stegamite, Webbs Cave

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Cover: Mark Bonwick examining a "Stegamite", Webbs Cave, Nullarbor Plain.

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A GIANT LATE PLEISTOCENE HALITE SPELEOTHEM FROM WEBBS CAVE, NULLARBOR PLAIN, SOUTHEASTERN WESTERN AUSTRALIA

Albert Goede, Tim C. Atkinson and Peter J. Rowe

Abstract

A giant halite stalagmite found in a broken condition, and believed to be the tallest recorded anywhere in the world, was collected from Webbs Cave in the Mundrabilla area of the Nullarbor Plain. Reconstruction by fitting together the major fragments showed that it had been 2780 mm tall. Its collapse was due to water percolating down the side and dissolving a cylindrical hole near the base. Uranium series dating proved to be extremely difficult due to the exceedingly low uranium content ($2\ \mu g\ kg^{-1}$). Analysis of a bulk sample indicates late Pleistocene deposition between 20 and 37 ka. Previous dating of a small halite speleothem from Webbs Cave has shown a Holocene period of halite deposition dated at 2.5 ± 1.2 ka.

INTRODUCTION

Webbs Cave is located in the Mundrabilla area, a central portion of the Nullarbor Plain (Figure 1). The name "Nullarbor" is applied to an extensive area of semi-arid karst underlain by marine limestones ranging in age from Eocene to Miocene. Most of the Plain consists of an extensive plateau, the Hampton Tableland, reaching a maximum surface elevation of 240 m in the north-west and declining towards the coast where for much of its length it terminates in spectacular coastal cliffs up to 90 m high.

In the central portion of the plain, including the region south of the Mundrabilla area, the Hampton Tableland is separated from the coast by a low-lying limestone erosional surface, the Roe Plains, covered by a thin veneer of early Pleistocene marine sediments. The Roe Plains are separated from the Hampton Tableland by the Hampton Range, a relict seacliff dissected by short ephemeral stream channels with associated alluvial fans.

The area has a semi-arid climate with a mean annual precipitation of approximately 250 mm characterised by a

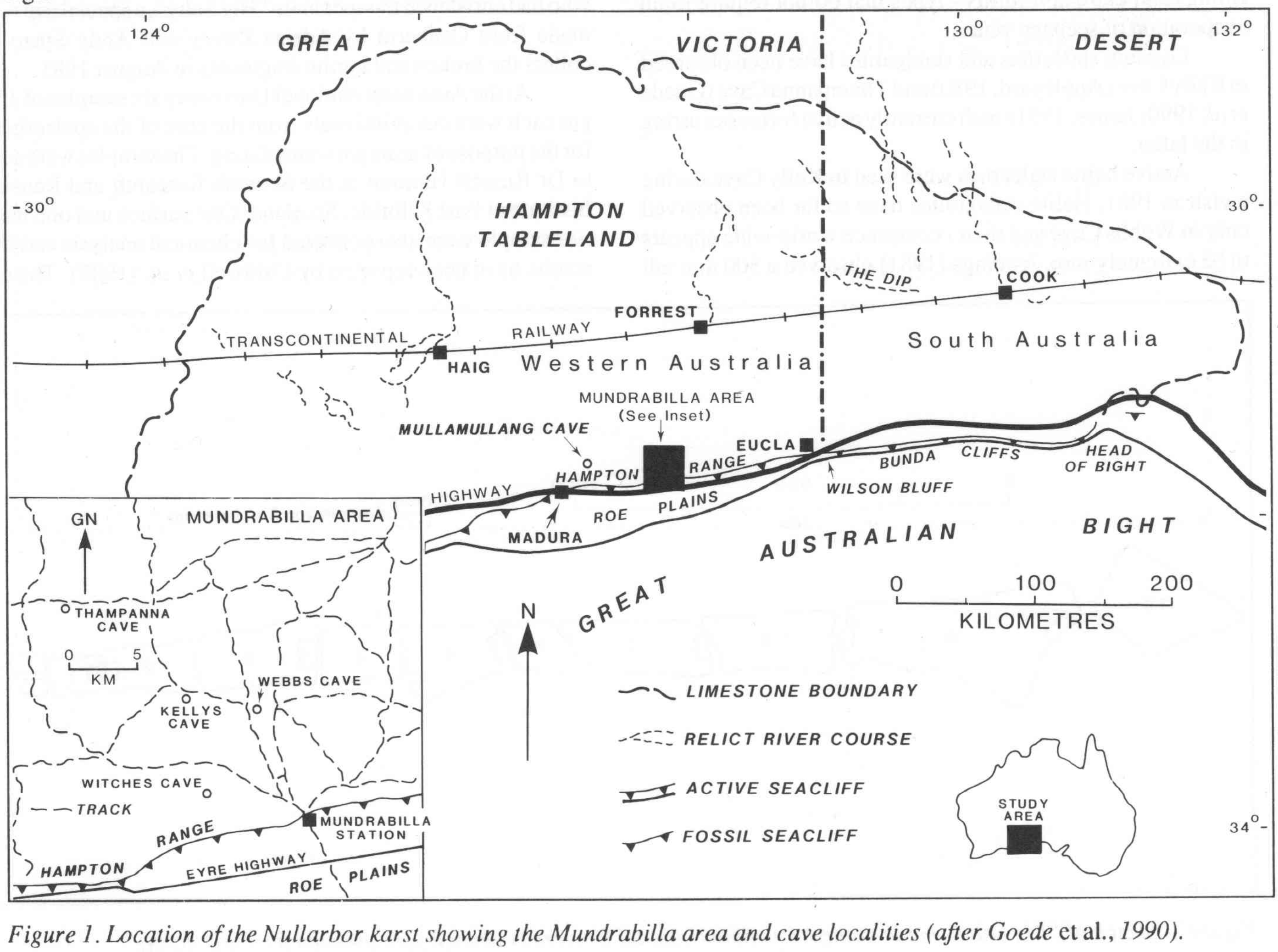

Figure 1. Location of the Nullarbor karst showing the Mundrabilla area and cave localities (after Goede et al., *1990).*

winter maximum. The mean annual temperature is 19°C and cave temperatures are usually within 1°C of this figure (James, 1991).

The Roe Plains in the Mundrabilla area are approximately 30 km wide. Webbs Cave is located on the Hampton Tableland some 9 km north of the Hampton Range. A number of other caves are known in the area and have been discussed in more detail elsewhere (Goede *et al.*, 1990; James, 1991). Webbs Cave falls within the coastal belt of woody vegetation dominated by species of eucalypts and acacias. Further inland the vegetation grades into a treeless steppe dominated by halophytic plants.

The Mundrabilla caves are relatively rich in calcium carbonate speleothems but much of the material has been severely fragmented by subsequent salt wedging. Uranium series dating has shown that the major periods of carbonate deposition predate 400 ka (Goede *et al.*, 1990) but there are minor exceptions with modern carbonate deposition taking place in the entrance chambers of a few caves, e.g. Thampanna Cave (James, 1991; Eberhard, 1991) and Jimmy's Cave (Goede *et al.*, 1990). It occurs where such chambers are located beneath large dish-shaped depressions that concentrate surface drainage.

Gypsum and halite speleothems are abundant in some of the Mundrabilla Caves. Considerable amounts of halite have also been reported from some caves elsewhere in the plain, e.g. Salt Cellars in Mullamullang (Dunkley & Wigley, 1967). Halite speleothems are usually in the form of wall crusts, fissure fillings and extrusion forms - types that do not require rapid evaporation of seepage water.

Gypsum stalactites and stalagmites have been observed in Kelly Cave (Appleyard, 1980) and Thampanna Cave (Goede *et al.* 1990; James, 1991) with currently active forms occurring in the latter.

Active halite stalactites were seen in Kelly Cave during a visit in 1981. Halite stalagmites have so far been observed only in Webbs Cave and their occurrence world-wide appears to be extremely rare. Jennings (1981) observed a 500 mm tall halite stalagmite from Central Asia on display in the Museum of Geology in Peking, China. No other references to halite stalagmites are known to the authors. The formation of halite stalactites and especially stalagmites would require extremely rapid evaporation of drip waters to ensure supersaturation. Low humidity of the cave atmosphere alone may not be able to achieve this and may have to be combined with strong air currents. Strong air movement is well known in Webbs Cave, where it has also contributed to the high level of salt wedging of both carbonate speleothems and limestone bedrock (see photograph 5 in Jennings, 1983).

The halite stalagmite discussed here was discovered in Webbs Cave in April, 1981 by one of the authors (A.G.) and A. Davey. It was reconstructed from 10 major and several minor fragments (Figure 2) found scattered around the floor of the chamber. The fragments were fitted together to form a stalagmite 2780 mm tall prior to its collapse. Collapse appeared to have been due to attack by aggressive drip water subsequent to its deposition. The water dissolved a half tube down the side of the stalagmite which passed through it at the base as a cylindrical solution tube.

The party was not equipped to collect the specimen and maintain it in a suitable condition for later analysis. However, one of us (A.G.) collected a 160 mm high halite stalagmite from Webbs Cave for experimental uranium series dating. Multiple dates were successfully obtained and the results reported (Goede *et al.*, 1990). It was found to have been deposited quite rapidly at about 4 ka BP. On the instigation of the late Dr Joe Jennings who had christened the specimen "Big Salty", a special trip was made from Canberra by Adrian Davey and Andy Spate to collect the broken stalagmite fragments in August 1981.

At the Australian National University six samples of 150 gm each were cut at intervals from the core of the speleothem for the purpose of uranium series dating. The samples were sent to Dr Russell Harmon at the Scottish Research and Reactor Institute at East Kilbride, Scotland. One surface and one interior sample were also collected for chemical analysis and the results have been reported by Caldwell *et al.* (1982). The re-

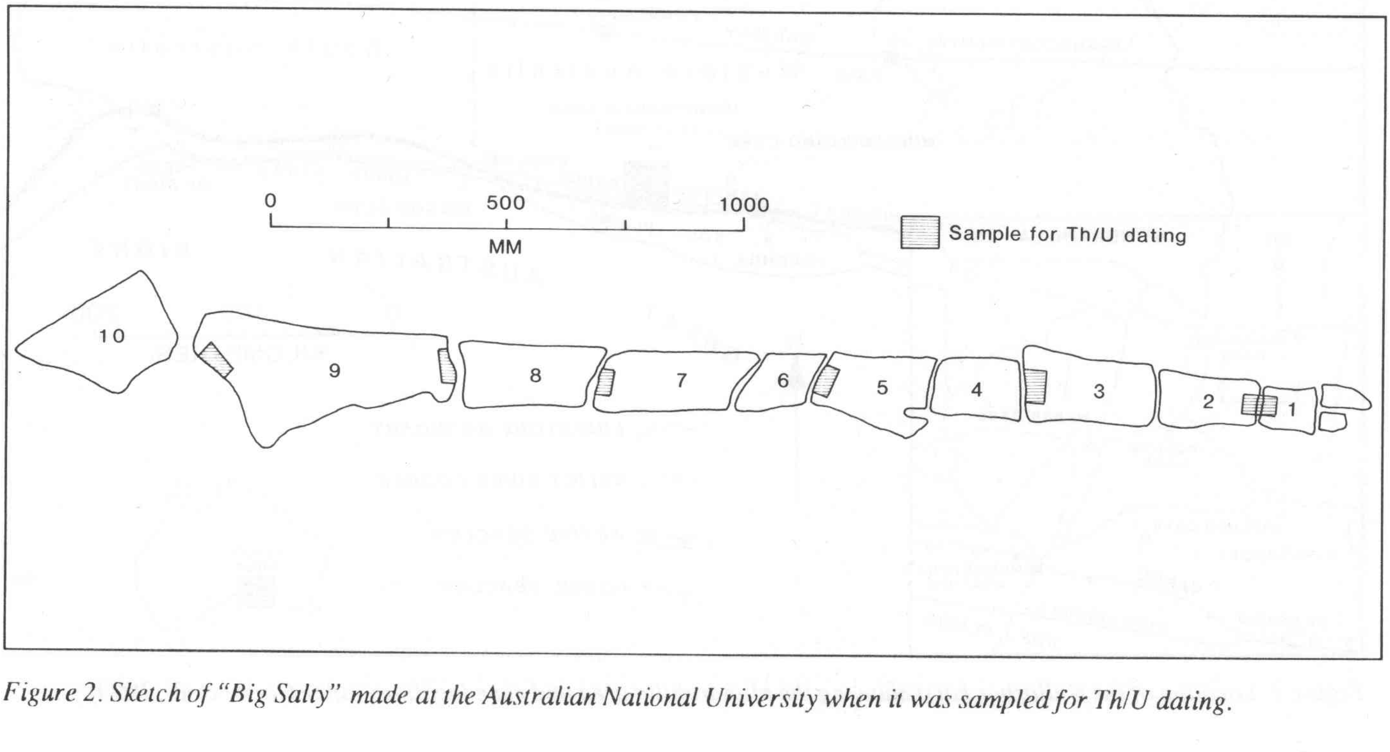

Figure 2. Sketch of "Big Salty" made at the Australian National University when it was sampled for Th/U dating.

mainder of the specimen was sent to the West Australian Museum where it was added to their collections and will eventually be placed on display.

When the samples for uranium series dating reached Scotland, Dr Russell Harmon was about to depart for the Southern Methodist University at Dallas, Texas, to take up a new appointment. He took the samples with him as he intended to set up a new laboratory. Unfortunately, because of lack of financial support, the new dating laboratory never became a reality. After some years the samples were sent to the University of East Anglia for Th/U analysis by two of us (T.C.A. & P.J.R.) and the results are reported in this paper.

CHEMICAL COMPOSITION & PHYSICAL NATURE

As already mentioned, two samples were examined by Caldwell *et al.* (1982) and the results reported. An interior sample (19) was pure white in colour and chemical analysis revealed a halite content of 95.8%. The main impurities expressed as percentages were Ca (.29), Mg (.12), K (.72), SO_4 (.06), HCO_3 (.15), Br (.20) and H_2O (2.04). The total percentage analysed was 99.4% and pigmented residues were reported to be absent.

A sample of surface skin (20) was examined and found to contain more substantial amounts of gypsum and calcite in the form of sand and silt-sized crystals than the interior of the stalagmite. The sample colour was very pale brown to light yellow brown and this was found to be due to the presence of some organic carbon and a small amount of iron (Fe 0.4%). The distinctive nature of the surface skin was interpreted as being due to re-solution and re-deposition effects. In support of this the authors reported the presence of "a half-round re-solution channel running down the side of the stalagmite, which near the base goes inside it, emerging as a cylindrical hole at the base" (Caldwell *et al.*, 1982).

RADIOMETRIC DATING

The $^{230}Th/^{234}U$ method of uranium-series disequilibrium dating has long been applied as a reliable technique to date carbonate speleothems (Gascoyne & Schwarcz, 1982). It has also been successfully applied to evaporites found in lake sediments including halites (Peng *et al.*, 1978). Since no Th/U dating of halite speleothems had been reported, experimental dating was first attempted on a 160 mm high stalagmite also collected from Webbs Cave. This was found to contain uranium concentrations of 0.1 mg kg $^{-1}$. With only minor detrital contamination this was adequate to obtain meaningful dates. The procedure followed was similar to that used to date carbonates and details have been reported by Goede *et al.* (1990). The authors presented details of the analyses and the dates obtained.

Analyses of both the top and basal samples of the large stalagmite were initially attempted using 60 gm weight for each but this proved to be unsuccessful as the uranium concentration in both cases was found to be too low to measure. This was very unfortunate as it made it impossible to determine the $^{230}Th/^{234}U$ ratios of the individual samples to obtain a series of dates that would have provided reliable estimates of the growth rates and the time span over which the halite had been accumulating. In an attempt to obtain an approximate age for the period of halite formation all the remaining sample material was bulked and analysed as a single sample. The results of the analysis are shown in Table 1.

Table 1

Sample weight 776.8 g	Detrital weight (acid insoluble) = 0.05 g
U conc. 0.0023 ppm	
Chemical Yields: U 21.2% Th 77.2%	
$^{234}U/^{238}U = 0.636 \pm 0.023$	$^{230}Th/^{232}Th = 3.918 \pm 0.341$
$^{230}Th/^{234}U = 0.297 \pm 0.014$	
Uncorrected date = 39,700 ± 2300 years	

The very low $^{230}Th/^{232}Th$ ratio indicates detrital contamination despite the low detrital content of the bulk sample and reflects a problem associated with the very low concentration of radio-isotopes. The ratio indicates that the sample is probably younger than the uncorrected date of 39.7 ka. Correcting for detrital Th only (not U) using the method of Schwarcz (1980, p. 20 eqn. 8) yields the following range of corrected dates (Table 2) using initial $^{230}Th/^{232}Th$ ratios in the range of 0.25 to 2.00.

It is difficult to assess which of these ratios is the most appropriate in this case. We have chosen values that span the range deduced by other workers, either by comparison with independent dating techniques (Kaufman and Broecker, 1965; Kaufman et al. 1971) or from a *"common-age"* determination following multiple sample analysis (Ku et al., 1979).

Table 2

Initial ratio $^{230}Th/^{232}Th$	0.25	0.50	0.75	1.0	1.25	1.50	1.75	2.0
Corrected date (ka)	37.5	35.2	32.9	30.6	28.2	25.8	23.3	20.8

It can be concluded that the material has an apparent age in the range 21-38 ka. Since the date is based on a bulk sample of all the material that remained after the initial pair of analyses it must be considered as meaningful only in that it indicates a late Last Glacial age for the stalagmite.

DISCUSSION

On a world scale halite speleothems in caves of semi-arid and arid regions appear to be uncommon (White, 1976) and the occurrence of halite stalagmites extremely rare. To our knowledge only one other occurrence, from Central Asia, has been reported in the literature (Jennings, 1981). It has also been asserted by Jennings (1983) that the "Nullarbor caves are particularly rich in halite, ...".

The occurrence in caves of chemical deposits that are predominantly composed of carbonate, sulphate or halide deposits can be seen as a logical sequence when progressing from humid to arid environments with no chemical deposition at all under conditions of extreme aridity.

Halite may be derived from different sources. Sodium chloride may have been stored within the limestone since the time of its deposition. However, since the limestones that underlie the Nullarbor Plain have been above sea level for at least ten million years and since for a large part of this time they have probably been subjected to significantly wetter conditions than prevail today, it seems improbable that primary salt is a significant source. Halite may also be released as a result of the weathering of primary minerals but the possible content of such minerals will be very low in a pure limestone.

It is highly probable that the bulk of the sodium chloride is of oceanic origin and has been carried inland from the Great Australian Bight by SW and S winds. Such an origin is strongly favoured by the evidence from groundwater composition. Total salinity, dominated by chloride, ranges from an average of 2,500 ppm in the northern part of the plain to 35,000 ppm beneath the Roe Plains (Lowry & Jennings, 1974). This trend occurs despite a significant increase in precipitation towards the coast and strongly supports a cyclic origin for the chloride.

As long as there is sufficient precipitation to provide downward percolation in the vadose zone, significant accumulation of halides in the soil is unlikely as the primary permeability of the limestone is high. The plateau however is covered by a variety of calcareous soils including significant amounts of concretionary calcium carbonate - sufficiently massive in places to form a calcrete. Such soils can cause temporary surface and sub-surface ponding of water causing large evaporation losses especially in summer. Under sufficiently dry conditions this may lead to little or no downward percolation and a build-up of halites in the soil. A change to slightly wetter and/or cooler conditions may cause resumption of percolation, but with a very high content of soluble salts. Such a situation could lead to the deposition of halite speleothems provided that the seepage water is subject to strong evaporation on coming into contact with the cave atmosphere.

Richards (1971) has reported relative humidities ranging from 83% to 100% in the Nullarbor caves and this may be sufficient to cause the formation of halite wall crusts and extrusion speleothems common in some of the caves. The formation of stalactites and stalagmites takes place under conditions of more rapid water movement and strong air movements may be required to cause their accumulation.

Strong air currents have been observed not only in Webbs Cave where halite speleothems are found but also in nearby Kelly and Thampanna Caves where similar forms are composed of gypsum.

If the formation of halite stalactites and stalagmites is due to the flushing out of cyclic salts that have accumulated in the calcrete capping, halite deposition can be expected to cease and may give way to resolution processes when the soil store of cyclic salts is depleted. Re-solution may continue until percolation ceases with a return to drier conditions.

Goede *et al* (1990) when discussing the dating of a small halite stalagmite from Webbs Cave, pointed out that the $^{234}U/^{238}U$ ratios of 0.73 to 0.78 found in this speleothem, were much less than the value of 1.14 normally found in seawater. The ratio for the big halite stalagmite at 0.64 is even lower (Table 1). They suggested that "the source of uranium in the stalagmite is not directly from sea spray or derived from marine salts in rainfall". Such a low activity ratio indicates "that the percolating water dissolved uranium from a second source which had already been subject to extensive leaching. The second source is believed to be either the limestone above the cave and/or the calcrete capping, both exposed to extensive leaching over a long period of time. It supports the suggestion that the soluble salts, while ultimately of marine origin, were stored in the overlying soil or bedrock for a significant time period. The $^{234}U/^{238}U$ ratio of the big stalagmite may be lower than that of the small stalagmite due to a reduced marine influence at a time when sea levels were low and the coast considerably more distant.

CONCLUSIONS

The dating of "Big Salty", while imprecise, is the first evidence of Late Pleistocene halite deposition from a Nullarbor cave. Taken together with the earlier dating of the small halite stalagmite (W-1) from Webbs Cave at 2.5 ± 1.2 ka it indicates clearly that there have been at least two phases of formation of halite stalagmites.

These phases are interpreted as slight swings to a more humid environment following periods of cessation of percolation under conditions of aridity, sufficiently extreme to have caused accumulation of soluble salts in the soil/calcrete zone. Deposition is believed to be associated with downward flushing of salts from the soil zone and would have continued until the bulk of the accumulation had been flushed out. At this stage the percolation ceased to become saturated and resolution occurred until percolation ceased with a return to more arid conditions.

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THE PHOTOTROPIC PHYTOSPELEOTHEMS OF MOSS PALACE. MOLE CREEK, TASMANIA.

Michael J. Lichon

Abstract

In Moss Palace, the presence of unusual speleothems further justifies the conservation of the Dogs Head Hill karst at Mole Creek, Tasmania. A "symbiotic" carbonate deposition and growth of the moss *Distichophyllum microcarpum* results in phototropic phytospeleothems, in the form of fan-shaped erratics.

MOSS PALACE

Moss Palace (Figure 1) was discovered during a reconnaissance of Dogs Head Hill by Phill Gregg, Deborah Hunter and the author, 12/3/1988. This cave was untouched by human visitation, and does not correspond to any record in the inventory compiled by Kiernan (1984). The rift-guided cave has approximately 45 m of passage in two levels. The entrance leads to a narrow, high passage sloping down to a 2 m wide rift. The passage at the bottom of the rift returns underneath the upper level and pinches out a little farther. The overall length is about 25 m, total depth about 6 m. The cave walls are largely coated by white flowstone and delicate calcite speleothems, demanding extreme measures for the caver to avoid impact. The upper level is lined with smooth white flowstone, and floored with delicate gours, some of which contain oolites. The main features of the rift are the wall of fan-shaped erratics, described later, on one side and white knobbly flowstone on the other. There is also some moonmilk on this wall. The lower passage has more conventional types of speleothems, though in unusual combinations. There is evidence towards the end of the lower passage that indicates at least four stages of flowstone and dripstone deposition and vadose solution. A further expedition produced a photographic record of the cave and its speleothems. In the context of the small size of the cave and its high sensitivity to visitation, a further expedition for mapping was considered a frivolous exercise. During a subsequent brief visit in October 1990, it was noted that an unidentified bird, possibly a Tawny Frogmouth or Owlet Nightjar, had taken up a nesting site on a high shelf in the upper level, and was depositing guano and debris onto the clean flowstone wall below.

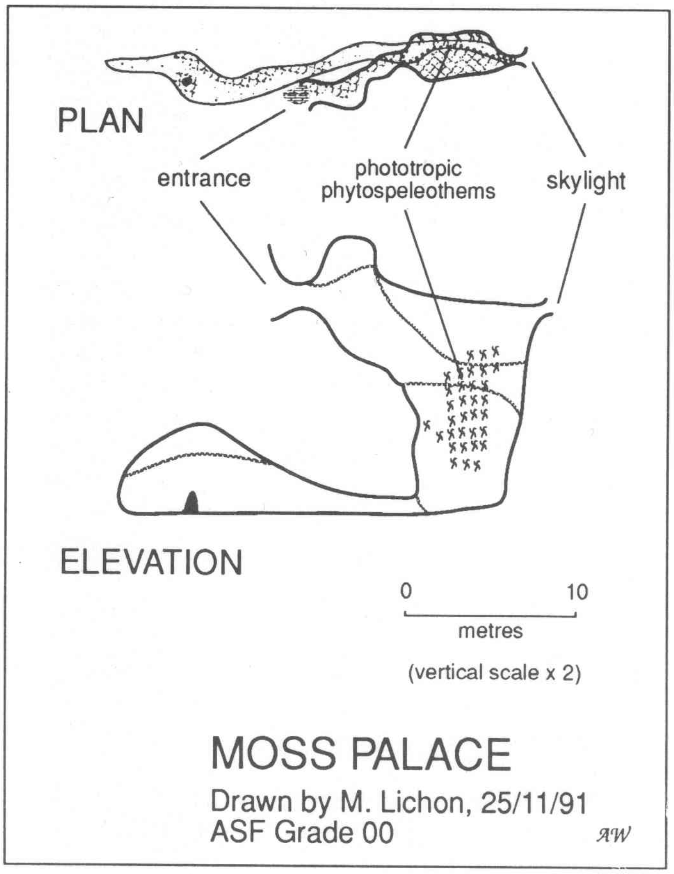

Figure 1. Moss Palace

PHOTOTROPIC PHYTOSPELEOTHEMS.

Description: The twilight zones of Moss Palace feature phototropic phytospeleothems, ranging from 2 mm to 200 mm in length, (see Figure 2, Plates 1 & 2). They are found both near the entrance and 2-6 m below a 0.5 m^2 skylight at the other end of the cave. The best developed speleothems are 5 m below the skylight. These fan- shaped erratics, (Plate 1), grow outwards

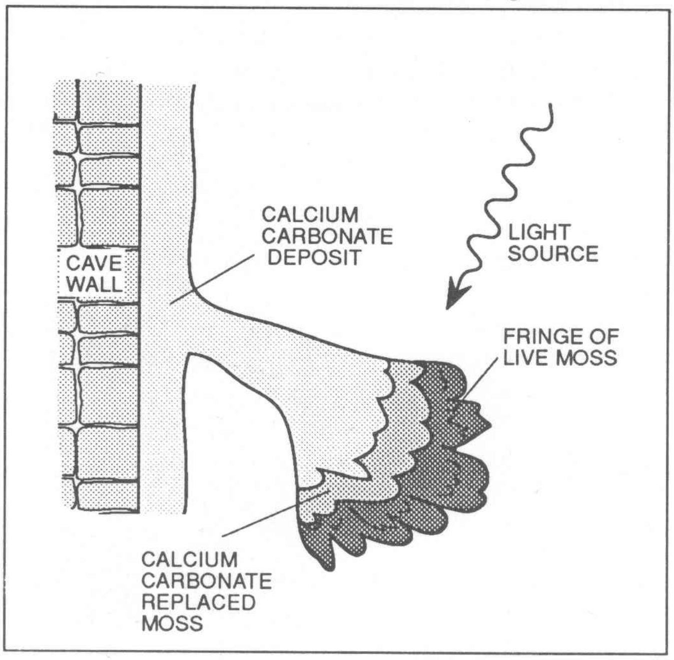

Figure 2.Simplified form of a phototropic phytoerratic.

from wall surfaces, oriented with the face of the fan perpendicular to the source of the light, (Figure 2). They mostly occur in overlapping clusters, (Plate 2), with only the outermost edges being readily visible from the direction of the light. These edges consist of a fringe of living moss, *Distichophyllum microcarpum*, (Scott, Stone & Rosser, 1976). The moss appears to be in the process of calcification, being increasingly advanced back from the edge of the growing fringe. The calcium carbonate deposit completely replaces the older, dead moss, and the speleothem becomes thickened towards the base by a coat of calcite material. During and following periods of wet weather, these speleothems are heavily dowsed by water; at other times they were observed to remain wet or moist. The cave has not been visited during extreme drought conditions.

DISCUSSION

The presence of phototropic phytospeleothems in Tasmanian caves has not previously been described. While phototropic speleothems are known in the tropics, personal consultation with several well-travelled speleologists yielded no previous encounters with this type of speleothem in temperate Australia, neither growing nor in remnant form.

Hill and Forti (1986), and Ford and Williams (1989) classify the forms of cave deposits, and put forward mechanisms to explain their formation. Growth of erratics include situations of crystal growth when evaporation rates exceed water seepage flows, thus preventing formation of water drops, and hence normal straw stalactites. The observed water flows would contraindicate this mechanism. Jennings (1985) used the term "phytokarst" to describe **solution** features on limestone caused by biological activity. This term should not be used to describe carbonate **deposit** features. Goede (1988) pointed to the possibility of biological mechanisms for the formation of moonmilk deposits. DeSaussure (1961) concluded that green algae were the cause of phototropic cave coral in Teopisca Cavern, Mexico. Cox *et al* (1989) concluded that cyanobacteria causes phototropism of "crayfish" stalagmites in Nettle Cave and Arch Cave at Jenolan, N.S.W. Dalby (1966) described carbonate accumulation on the mosses *Eucladium verticillatum* and *Barbula tophacea*, growing at inclined angles from the ceiling of disused coal mine level in the twilight zone at Dorset (U.K.) by the seaside. *D. microcarpum* has previously been observed on bare karst substrates; George Scott (pers. comm.) observed the species growing on limestone under 5 m of water at Ewens Ponds, S.A., but no carbonate growth was noted in this situation. Recently, the author observed copious growth of *D. microcarpum* at the entrance and twilight zone of Gillam Cave (MC 78). This was found to be devoid of any associated phytospeleothem growth.

Morphology of the Moss Palace speleothems indicates that their growth is controlled by the existence of the moss, hence the use of the term phytospeleothem. The orientation of the growth is phototropic, and erratic with respect to gravity. The specific term for the erratic speleothems would thus be "phototropic phytoerratics". The mechanism of calcium carbonate deposition may be explained by a net photosynthetic removal of CO_2 from the water supplying the moss, thus shifting the hydrogen carbonate equilibrium, resulting in carbonate deposition. There are likely to be two factors involved in this process; firstly, the photosynthesis of the moss removes CO_2 from solution to sustain the plants; secondly, the moss merely

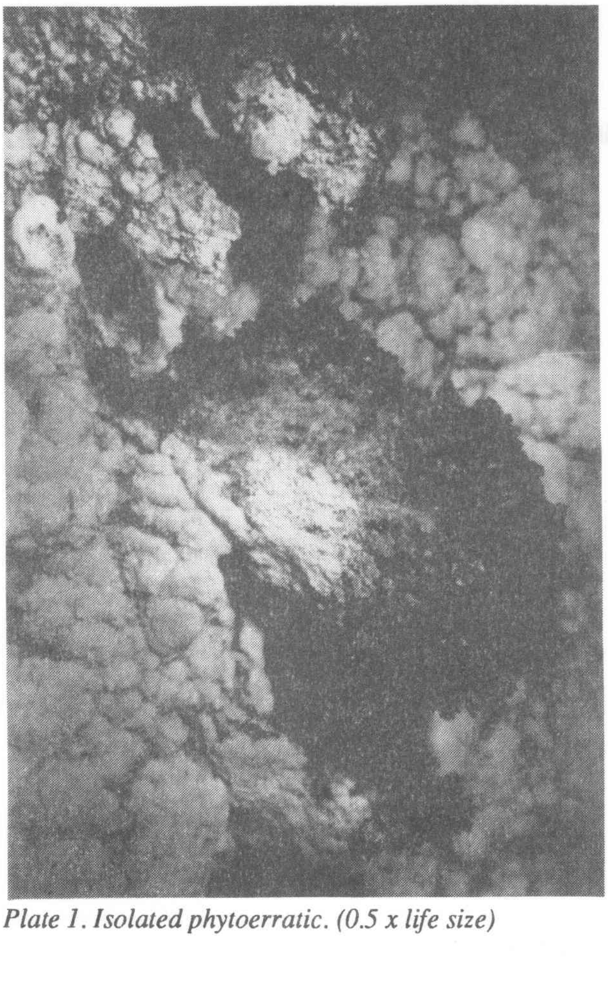

Plate 1. Isolated phytoerratic. (0.5 x life size)

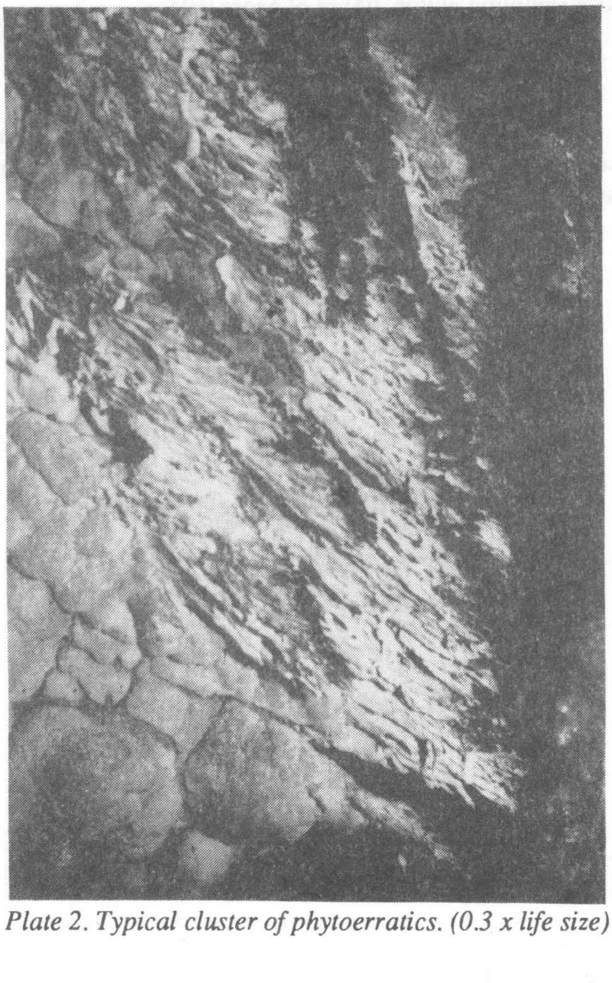

Plate 2. Typical cluster of phytoerratics. (0.3 x life size)

provides a physical substrate of large surface area for degassing of CO_2 into the cave atmosphere. It would be speculation at this stage to suggest which is the dominant factor. The subsequent thickening at the base of the speleothems is regarded as being a conventional flowstone deposit.

Subsequent to this discovery, Andrew Spate (pers. comm.) observed a number of poorly developed examples of phototropic phytospeleothems at Honeycomb I Cave, at Mole Creek.

CONSERVATION SIGNIFICANCE

The significance of the Dogs Head karst was noted by Kiernan (1984); the hill is a rare and classic hum, and there were already a number of known caves with speleological or archaeological significance. The value of the area was again highlighted by Hunter, in Cadman *et al* (1990), in the context of the discovery of Moss Palace and its phytospeleothems. There remain serious threats to the values of this National Estate area, specifically from the mining operations of the nearby limeworks; forestry, insensitive recreation and farming represent additional threats. There is temporary respite from forestry, through the recent delineation of a Recommended Area of Protection (RAP) covering the area. However this justified on the grounds of being a representative area of dry sclerophyll forest, **not** for karst values, despite the Forestry Commission employing a "Karst Officer" to address such problems. It is understood that the local mining interests regard Dogs Head Hill as a desirable deposit of high grade, readily accessible limestone in close proximity to the existing mill, and that it is looking to expand operations. There is some evidence of rock sampling within 100 m of Moss Palace.

ACKNOWLEDGMENTS

I thank Mr Paddy Dalton, Dr George Scott and Dr Heinar Streimann for their assistance with the identification of the moss.

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SOME COASTAL LANDFORMS IN AEOLIAN CALCARENITE, FLINDERS ISLAND, BASS STRAIT.

Kevin Kiernan

Abstract

Two short sections of aeolian calcarenite coastline on Flinders Island exhibit broad intertidal shore platforms with solution pans, deep intertidal notches, caves formed by emerging groundwater and by marine erosion, alveolar weathering of cliffs, and evidence of sub-calcrete mechanical rock disintegration processes. The rate of slope retreat is governed by calcrete that caps the aeolianite cliffs. Biogenic erosion processes are associated with algal penetration of the rock and abrasion by marine molluscs. The oldest erosional landforms recognisable on the aeolianite date from the Last Interglacial which implies that the rock is no younger than Middle Pleistocene. Radiometric dating of a speleothem modified by secondary solution and collected from approximately present HWM indicates that the cavity in which it formed was in existence during the late Last Glacial Stage and was invaded by the sea during the Holocene.

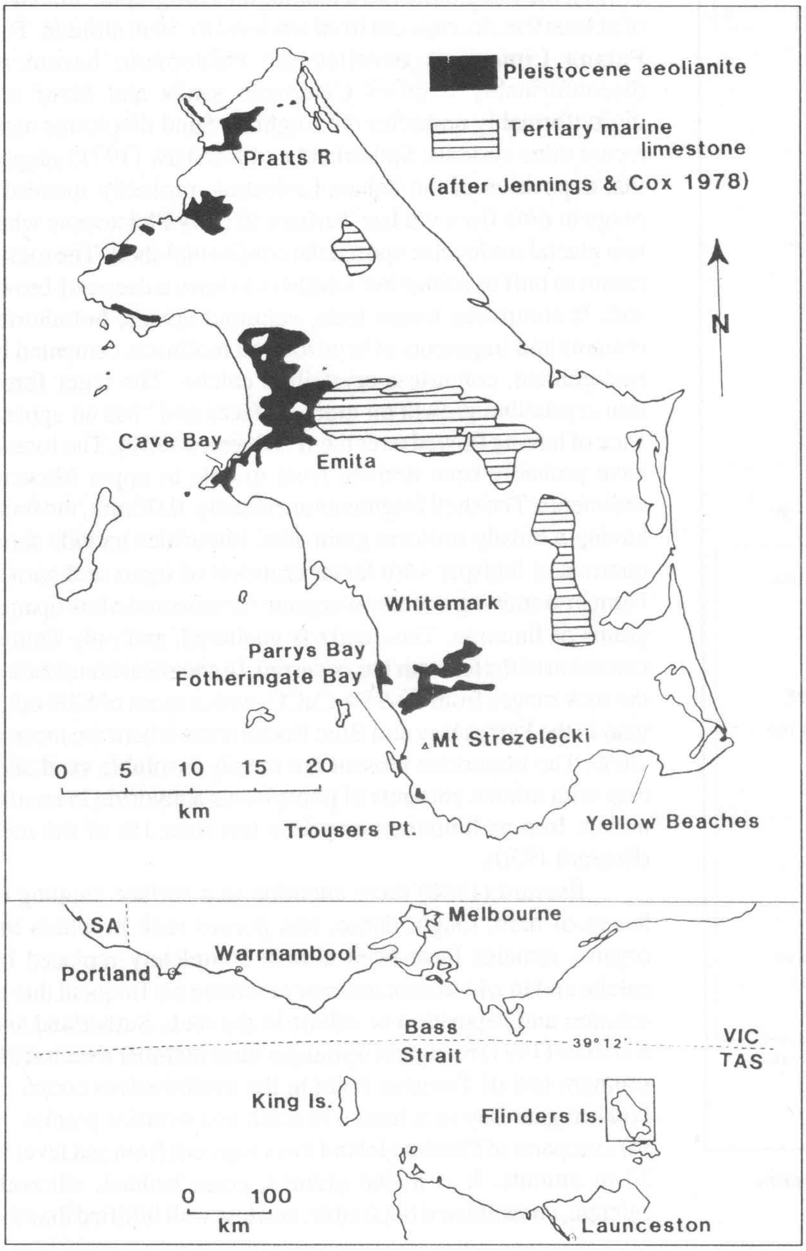

Figure 1. Location of the study area.

INTRODUCTION

The development of solutional landforms in relatively unconsolidated aeolian calcarenites of Pleistocene age involves processes distinctly different from those entailed in the development of landforms of solutional origin in harder, purer, more compact and better jointed limestones (Jennings 1968; White 1989). Examples of solutional landforms and landscapes in aeolianite have been described from a number of areas around the Australian coastline (Jennings 1968; Gill 1972; Bird 1976; White 1989). However, details of such features on the Bass Strait islands have hitherto gone largely unreported. This paper describes coastal landforms in aeolian calcarenite from two localities on the western coastline of Flinders Island.

Flinders Island has an area of ≈1, 333 km², being 65 km north-south and 40 km east-west, and rises to an altitude of 756 m at Mt Strzelecki in the south. It comprises a ridge of Palaeozoic basement rocks, notably folded quartzites, argillites, granitic rocks and later dolerite, surrounded by coastal plains of more recent age. Carbonate rocks of Tertiary and Pleistocene age crop out at various localities around Flinders Island (Jennings and Cox 1978) (Figure 1). Everard (1950) recognised three types of limestone on the island: well consolidated limestone in thin beds, as at Ranga; lightly consolidated porous limestone, comprising most of the western deposits and often possessing a surface capping; and an unconsolidated uppermost unit. The most prominent of these formations are Pleistocene calcarenites, initially regarded as marine (Everard 1950; Hughes 1957) but later recognised to be of aeolian origin (Dimmock 1957). During the late Cainozoic calcareous dunes were formed along the western coastline, with siliceous dunes forming in the east. The calcareous dunes were subsequently subject to consolidation and secondary cementation with the formation of calcareous B horizons. Leaching of the top part of the dunes has provided siliceous residues that are the basis of more recent dune fields. Consolidated dunes with a lower calcium content developed during the late Pleistocene. The orientation of contemporary parabolic dunes systems reflects the predominance of westerly winds (Sutherland and Kershaw 1971).

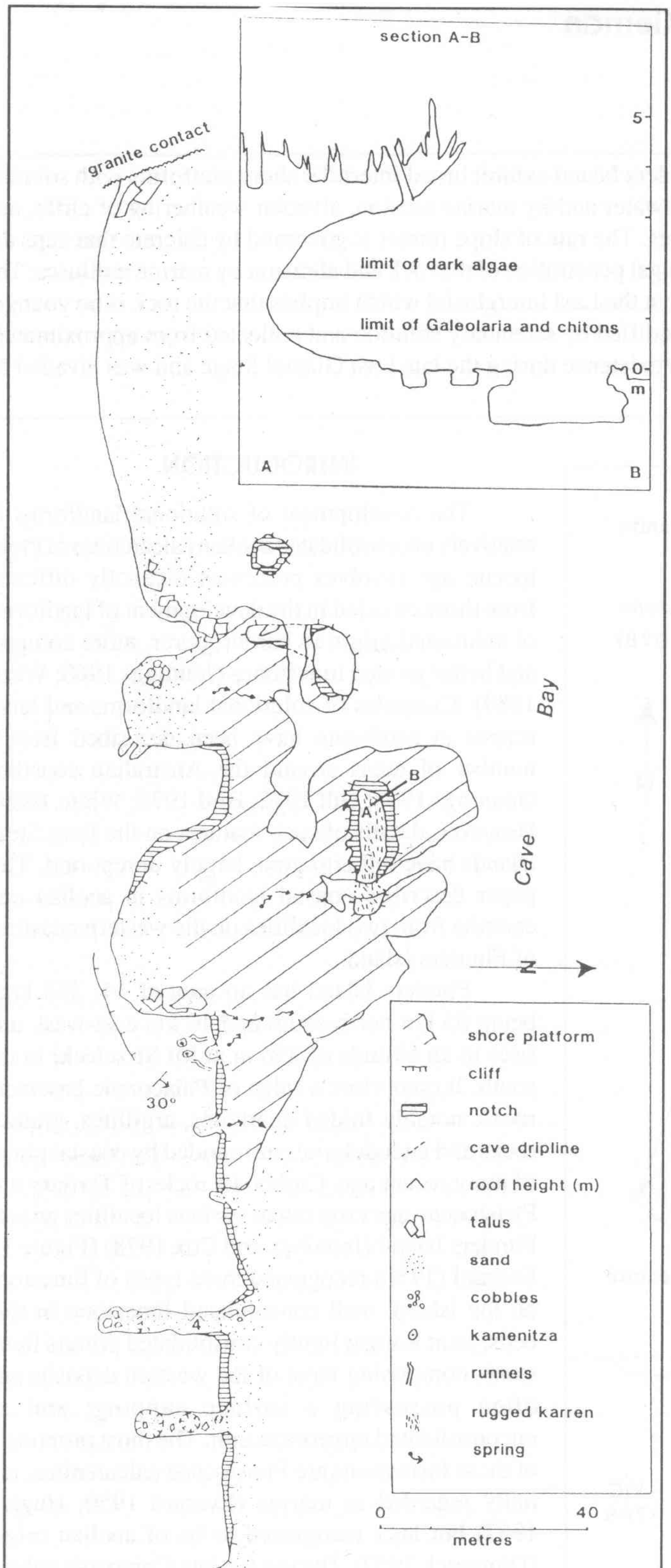

Figure 2. Sketch map of landforms along the calcarenite shoreline at Cave Bay, Flinders Island.

Everard (1950) observed that the microtopography of the limestone areas differed significantly from that of most other terrains on the island and suggested that this was due to the porous limestone being particularly susceptible to erosion with this process having reached an advanced stage. Limestones fringe the foothills of the Strzelecki Range, and are prominent at 15-105 m altitude between the Strzelecki Range and the Darling Range. A small cave in this vicinity at Ranga has revealed subfossil bone remains of predominantly terrestrial species that date from 8.2 ka BP (Hope 1969). The limestone attains a maximum topographic relief of 150 m between Pratts River and The Quoin at the northern end of the island, where innumerable small depressions and domes are present. The largest single limestone area is north of Emita where limestone crops out from 15-100 m altitude and small dry valleys are known to occur. In another area at Emita there are numerous small sinkholes, the water rising from springs where the underlying granite crops out. At least one inland cave is rumoured to exist in this area. Sinkholes also occur in the Whitemark area.

Termed the Palana Limestone by Sutherland and Kershaw (1971), the calcarenite has a maximum stratigraphic thickness of at least 9 m. It crops out from sea level to 50 m altitude. The Palana Limestone overlies the Palaeozoic basement, disconformably overlies Cainozoic sands and lavas and disconformably underlies the Lughrata Sand that forms more recent dune systems. Sutherland and Kershaw (1971) suggest that deposition of the Palana Limestone probably spanned a range in time from the late Tertiary to early Pleistocene when low glacial sea levels exposed the continental shelf. The rock is cream to buff in colour but weathers to form a deep red-brown soil. It comprises foram tests, echinoid spines, holothurian remains and fragments of bryozoa and mollusca, cemented by fine-grained, colourless crystalline calcite. The latter forms thin crystalline growth on grain surfaces and "has an appearance of having flowed over them" (Everard 1950). The forams have probably been derived from middle to upper Miocene sediments. The shell fragments are usually 0.02 mm, the rock having a mostly uniform grain size. Impurities include some quartz and feldspar with lesser amounts of topaz and garnet. Faint iron staining occurs on organic remains and a few opaque grains of limonite. The quartz is unaltered, and only limited corrosion of the feldspar has occurred. In chemical composition the rock ranges from 60-95% $CaCO_3$ with a mean of 83% other than in the Parrys Bay and Blue Rocks areas where the mean is 70%. The impurities present are mostly insoluble sand and clay with minute amounts of phosphorus anhydride in combination. Iron as limonite comprises less than 1% of the rock (Everard 1950).

Everard (1950) drew attention to a surface capping or lenses of hard, tough, dense, less porous rock in which the organic remains have been almost completely replaced by calcite and in which concretionary laminae are frequent due to solution and deposition of calcite in the rock. Sutherland and Kershaw (1971) recognise a younger dune member which at the southern end of Trousers Point in the southwestern corner of Fotheringate Bay is at least 3 m thick and overlies granite. In various parts of Flinders Island this crops out from sea level to 30 m altitude. It is a fine grained, cross bedded, siliceous calcrete, consolidated but friable, and less well lithified than the rest of the Palana Limestone. It contains angular to rounded quartz grit with some feldspar and rare biotite. Sutherland and Kershaw suggest that detailed geological mapping might reveal it to be a separate formation from the Palana Limestone.

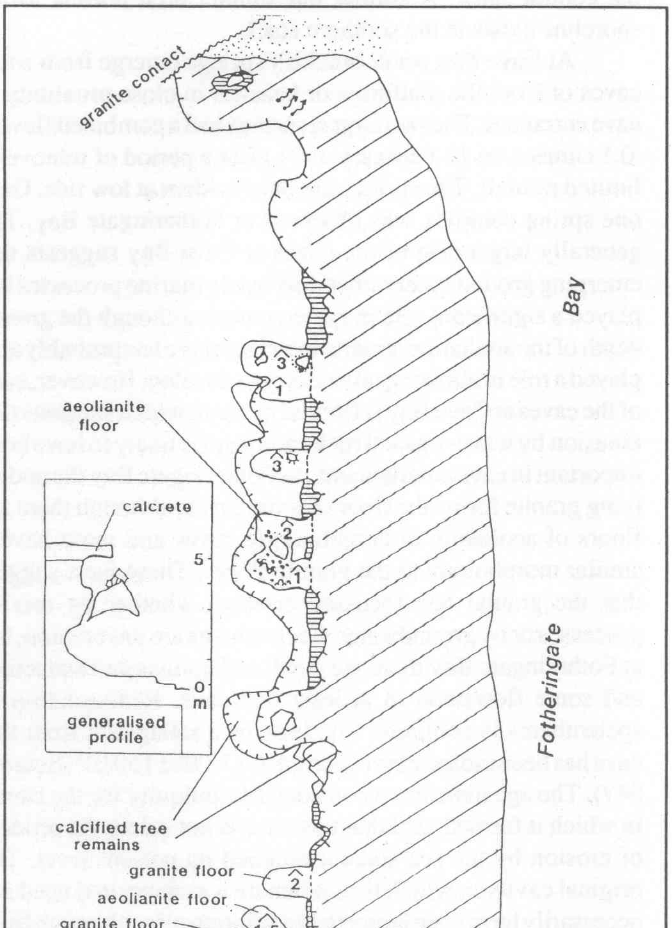

Figure 3. Sketch map of landforms along the calcarenite shoreline at Fotheringate Bay, Flinders Island.

AEOLIANITE COASTS OF FLINDERS ISLAND

This paper focuses on two coastal aeolianite outcrops on Flinders Island, at Cave Beach near Emita, and at Fotheringate Bay west of Mt Strzelecki. At Cave Beach the aeolianite crops out along 270 m of coastline (Figure 2), while at Fotheringate Bay the outcrop extends along 310 m of the coast (Figure 3). In both cases a sandy beach forms the southern boundary while outcrops of the underlying granitic rocks occur at the northern end. Stripping back of the aeolianite is exposing granite that had been smoothed by marine erosion prior to deposition of the carbonate rock. The maximum topographic relief of aeolianite exposed at the coast is 6 m, the rock being overlain by more recent uncemented sands at the top of the cliffs. The aeolianite is strongly cross-bedded in both localities but the dip is frequently towards or close to the seaward quadrant. At Fotheringate Bay calcified tree remains are very prominent, some extending for lengths of more than 3 m.

Examination of a specimen from this site reveals it to comprise bio-calcarenite that is mostly shell fragments and tests of micro-organisms of variable sphericity. Non-calcareous, angular, sub-spherical grains, mostly quartz, make up 5% of the rock. The cement is sparite but much is weathered to irregular pore-space that occupies 50% of the rock (S. Stephens, pers. comm.).

The most elevated horizontal element in the landscape at Fotheringate Bay is a broad bench at 5-6 m altitude that forms the upper surface of the aeolianite. This is interpreted as the product of marine erosion. This surface is irregular with a few shallow swales 1-2 m deep, generally elongated normal to the coastline. In a few cases there are small fully enclosed depressions of similar depth but whether these are of solutional origin or are deflation hollows in the younger sands is not always clear. At Cave Bay collapse depressions occur towards the edge of the cliffs. The largest are up to 4 m in diameter and form vertical entrances 4-5 m deep to spacious caves that can also be entered via horizontal entrances from sea level. Where the collapses occur at the extremity of negotiable cave passage the inland side of the collapse is commonly degraded and formed of rubble, but all sides of collapses further seaward tend to be sharp and fresh in form.

Intertidal shore platforms are also prominent horizontal landscape features in both localities. These platforms have developed as the cliffs have receded and they are up to 50 m broad with small stacks rising from them. Large areas of the platforms are cloaked by thick mats of seaweeds, predominantly *Hormosira* spp. Enclosed depressions at a variety of scales have formed in the platforms. The smallest are irregular pans 50 cm in diameter and 40 cm deep, often with overhanging sides. Larger basins 2-3 m long with a depth of 1 m also occur, generally closer to the outer margin of the shore platforms than are the smaller pans. The larger basins often exhibit conspicuous subsurface connections to other depressions or directly to the sea. Raised rims are common, as described from limestone coasts elsewhere and commonly ascribed to encrustation by algae, notably *Lithothamnion* spp. (Bird 1976). On the raised margins of some pans on the shore platforms at Flinders Island, algal discolouration is evident to depths of a few centimetres. Part of the rim elevation is due to colonisation by seaweeds and some small molluscs, notably *Siphonaria diemenensis*, that are not present or are present only in much smaller numbers elsewhere on the platforms. There is some evidence of very minor notching just below LWM as described from steep limestone coasts elsewhere by Ford and Williams (1989).

Prominent intertidal notches have developed at the foot of the aeolianite cliffs. Maximum notch development appears to occur slightly above mean HWM if it is assumed that this is defined by the upper limit of *Galeolaria* tubes. In a few cases the focus of erosion is more elevated as a result of erosion of the aeolianite having been constrained by the altitude of the granite-aeolianite interface. In these cases erosion of the notch has resulted from abrasion by lithic tools entrained by waves, as indicated by the presence in some caves of sands and sometimes small calibre gravels, or as a result of groundwater flow having been focused at the interface. Near the northern end of the Fotheringate Bay site the notch ascends 2 m over a horizontal distance of 4-5 m due to the ascent of the underlying granite outcrop. Where best developed the notch is 3-4 m deep with a visor up to 3 m high and hosts a considerable intertidal fauna. Relatively fragile residual rock flakes and lacework within the upper part of these deep notches suggests only limited abrasion is occurring. Impressive mushroom-shaped stacks have developed at both Cave Bay and Fotheringate Bay as a result of notch formation around the perimeter of the stack, including the sides relatively protected from wave action. A plinth similar to that described by Hills (1971) from an aeolianite coast in Victoria is commonly present forming a floor to the notch 30-40 cm above the level of the intertidal platform.

Some contribution to rock breakdown by the intertidal fauna is suggested by the location of chitons *(?Chiton glaucus)* at the base of pits up to 1-2 cm deep that are larger than most of those produced by alveolar weathering but which are barely of sufficient lateral dimensions to accommodate their chiton inhabitants. Abrasion of the soft rock by the chiton shell seems likely to have been responsible for development of these pits. *Galeolaria* worm tubes are present below HWM and appear to armour the aeolianite rather than contribute to its breakdown. However, the presence of the tube network may have encouraged algal colonisation of the interstices and thereby encouraged at least some degree of rock breakdown. Unidentified barnacle species are also present. Barnacles have free swimming larvae that cement themselves to rocks and barnacles almost certainly have an armouring affect. At least two species of mussels are present, the larger being *Brachiodontes erosa*. Mussels are filter feeders that anchor themselves to the rocks with threads. Like the barnacles they probably armour the carbonate rock although their threads may penetrate voids and be the foci of some mechanical stress due to their growth or when the water is turbulent. *Kellia australis* and *Austrocochlea constricta* are also present in this zone. These two molluscs browse on algae.

Linear focusing of erosion into the aeolianite has led to the development of sea caves in both localities. The longest caves extend for 10-15 m. At Fotheringate Bay the caves are generally low-roofed with smooth, water-worn profiles and are located 2-3 m below the main calcrete layer. Calcified tree remains extend through the roofs of some caves and appear to be associated with solution pipes. At Cave Bay the caves are up to 4 m high and internal angular breakdown is more evident, including collapse sinkholes that have formed through the roofs and talus accumulations on the floor at the inner end of some caves. The most conspicuous cave at Cave Bay is an archway 5 m through, 6 m wide and 4 m high formed parallel to the shoreline by the intersection of notches formed on either side of the central stack. A similar but smaller arch normal to the shoreline exists in the southern stack.

At Cave Bay small brackish springs emerge from some caves or from the platforms or beaches in close proximity to cave entrances. The two largest springs had a combined flow of 0.1 cumecs on 12 February 1991 after a period of relatively limited rainfall. The springs are only evident at low tide. Only one spring complex was observed at Fotheringate Bay. The generally larger size of the caves at Cave Bay suggests that emerging groundwater rather than solely marine processes has played a significant role in speleogenesis although the greater depth of the aeolianite-granite interface there has probably also played a role in allowing taller caves to develop. However, each of the caves at Cave Bay is floored by sand, which suggests that abrasion by wave-washed rocks and sand is likely to have been important in cave enlargement. At Fotheringate Bay the underlying granite forms the floor of most caves, although there are floors of aeolianite in neighbouring caves and these have a similar morphology to the granite floors. These facts suggest that the granite has focussed erosion, whether by marine processes or by groundwater. Speleothems are uncommon, but at Fotheringate Bay there are small stalagmites and stalactites and some flowstone in at least one cave. Redissolution of speleothems is common. The base of a stalagmite from this cave has been radiocarbon assayed to 17,090±150 BP (Beta 43, 947). The age indicates a considerable antiquity for the cavity in which it formed, and that this cave is not solely the product of erosion by the sea since it attained its present level. The original cavity in which the carbonate was deposited need not necessarily have been larger than a solution pipe, although from the presence of other speleothems in the same cave a larger cavity seems likely.

The visor and cliff that rise above the notches have been honeycombed spectacularly by alveolar weathering. In the spray zone algal penetration of the alveoli that have formed in the aeolianite has occurred to depths of at least 1-2 mm. The alveoli in the spray zone have been colonised by *Littorina unifasciata*, a species that browses on algae. The *Littorina* may contribute some corrasion effect on this soft rock but in view of their generally low population density, their very small size relative to the alveoli, and the lack of any apparent size difference between occupied and unoccupied alveoli, any abrasion by this species may not represent a particularly great contribution to overall rock breakdown Sparsely distributed lichens are also present.

Spectacular rugged karren is a feature of these coasts, and is particularly well developed on stacks. The southern-most stack at Cave Bay presents a horrendously rugged surface to traverse, with a dense network of very sharp and very narrow spires of honeycombed aeolianite 1-1.5 m high, sometimes surrounding flat-floored pans up to 50 cm in diameter. Solution pipes that penetrate the visor of this stack appear to have evolved from downward extension of these solution pans. On some moderately sloping slabs on the cliffs shallow *kamenitza* have developed, occasionally with poorly developed rounded runnels associated with them. The development of such coastal karren results from muricate weathering in the spray zone that causes pitting, solution by rainwater and spray, and biogenic corrosion (Bird 1976).

Large detached masses of aeolianite occur at the foot of the cliffs at Fotheringate Bay. The largest slabs are several metres across. Production of these slabs appears to be the result of a process akin to slab toppling, in this case associated with sapping of the subjacent rock material by marine or groundwater erosion. The rate of retreat of the cliff is constrained at this site by the calcrete that caps the cliff. The development of a hardened cap atop relatively friable dune sands is common on aeolianite coasts and in Australia (Jennings 1968, Gill 1972, White 1989, Ford and Williams 1989). At Fotheringate Bay the calcrete is 1 m thick. Examination of a specimen has revealed clastic sediment of similar kind and in similar proportion to that in the underlying limestone. One portion contains iron oxides and a much higher proportion of non-carbonate grains indicating loss of a considerable amount of carbonate by solution followed by re-cementation by ferruginous carbonate, roughly consistent with a calcrete (S. Stephens, pers. comm.).

A notch fundamentally different in form from the present intertidal notch has developed beneath the calcrete layer. This notch is up to 2-3 m deep and up to 3 m high. It exhibits no consistent apex, the inner wall often having an irregular profile. Sandy textured breakdown and some detached angular rock fragments are evident. In a few cases calcrete talus has accumulated on the threshold of the notch. Cavities extend down to the caves at the marine notch level in some cases. The general form of this upper notch is suggestive of its having resulted from the presence of the calcrete rather than its being the product of marine erosion focussed at this level when the sea was at a higher level relative to the land than is the case at present. The nature of the notch profile and breakdown sediments suggests mechanical weathering has played a major role. Given that intertidal notch formation on carbonate coasts can be very rapid (Trudgill 1985) and that the aeolianite on Flinders Island is very soft, it seems improbable that a marine notch dating from the Last Interglacial would have survived, even in modified form.

DISCUSSION

The development of carbonate coastlines is influenced by four principal factors. These are wave energy, tidal range, the lithology and structure of the rocks that form the coastline, and the climate of the area (Ford and Williams 1989). The erosional landforms that occur along these two calcarenite shorelines bear testimony both to marine processes and to normal karstic erosion by groundwater. The morphology of the coasts at Cave Bay and Fotheringate Bay bear considerable overall resemblance to other calcarenite coasts in Australia (Bird (1976 plates 27 and 28, Hills 1971). However, the presence of granite slabs beneath the aeolianite at Flinders Island has served to focus marine erosion and slow groundwater flow, thereby counteracting to a degree the tendency for diffuse flow to occur in carbonate rocks of high intergranular porosity. Case hardening reduces the intergranular porosity of rocks and represents a form of vadose diagenesis due to chemical precipitation (Ford and Williams 1989). That the presence of calcrete can significantly condition the morphology of a limestone or dolomite karst, has been shown by workers such as Panos and Stelcl (1968) in their study of the mogotes of Cuba that are capped by calcrete and display asymmetry due to the presence of resistant calcrete on their leeward side. On Flinders Island the presence of calcrete both as horizontal layers and extending down solution pipes, including the presence of calcified tree remains, has provided foci for solutional activity in the aeolianite.

Shore platforms are relatively common features of the Tasmanian coastline but there are few examples formed on limestone. The most notable of Tasmania's limestone coastal platforms are at Point Hibbs on the west coast where the importance of biological and biochemical processes in platform evolution on Devonian limestone was recognised by Sanders (1968); and on Maria Island off eastern Tasmania where a platform has formed on Permian limestone. In general terms, shore platforms may comprise a sloping surface that extends to below LWM formed by dominant wave action in the intertidal zone; a subhorizontal surface close to HWM produced by wetting and drying; or a surface around LWM produced by biological and solution processes (Bird 1976). The prominence of broad intertidal platforms on limestone coasts and their relative scarcity in other geological terrains has led to their recognition as archetypal coastal karst landforms. At least in part their conspicuous presence may be due to an absence of obscuring sand (Jennings 1985). Hills (1949) has suggested that intertidal platforms on aeolianite coasts coincide with a relatively resistant indurated horizon that has been produced by the precipitation of carbonate from groundwater at its interface with sea water. Hills further suggested that the plinths he observed to floor intertidal notches might be related to the height above the shore platform to which water is drawn by capillary action. The development of notches and shore platforms across fallen blocks of aeolianite at the foot of marine cliffs at Warrnambool in Victoria is recorded by Gill (1972), irrespective of the disturbed attitude of the bedding and free of the complicating affects of emerging groundwater. Some abrasion has been invoked to explain certain aspects of the morphology of intertidal platforms and associated cliffs, including the presence of ramps behind platforms at the Head of the Bight, Nullarbor Plain, and Warrnambool, Victoria (Jennings 1985). While the coasts at Cave Bay and at Fotheringate Bay are both relatively protected ones, facing away from the sea towards the mainland of Flinders Island, sand has been swept into coves and caves at both sites, and small calibre gravels are also present in caves. Hence, abrasion has undoubtedly played at least some role in the evolution of the platforms, notches and caves on Flinders Island.

The deep intertidal notches are perhaps the most spectacular features of the aeolianite coasts of Flinders Island. Ford and Williams (1989) suggest that notches in limestone or dolomite coastlines are confined largely to tropical and warm temperate waters. However, the notches around cool temperate Flinders Island are very well developed and are comparable to the most impressive notches described from tropical coastlines (Trudgill 1976, 1977, 1985, Kiernan 1988). A variety of processes contribute to notch formation on carbonate coasts. Rock dissolution is permitted by the fact that sea water may not be completely saturated with respect to all forms of carbonate and because its aggressivity may increase at night when photosynthetic activity is diminished and biogenic CO_2 accumulates. In addition, nightly cooling of near-shore water increases its capacity to take up CO_2 (Hodgkin, 1970; Schneider, 1976; Trudgill, 1976). Bird (1976) has argued that sea water off limestone coasts and emerging groundwater is generally saturated with respect to calcium carbonate. However, there is also the foreign ion effect whereby the solubility of calcite can be enhanced through the addition of ions such as Na and Cl. By this means, sea water can become an effective solvent (Back *et al.* 1984). The mingling of fresh water and sea water also favours mixing corrosion. Palmer and Williams (1984) and Proctor (1988) discuss cave formation at the base of freshwater lenses underlain by seawater. Cave formation at Flinders Island is likely to have been favoured where groundwater discharged at the coast. This seems to be confirmed by the relationship between some of the caves and springs at Cave Bay and the confirmed intersection of a pre-existing cavity by coastal notch formation at Fotheringate Bay.

The additional association of springs with some small embayments at Cave Bay suggests the embayments may have evolved from caves. This is consistent with observations from elsewhere that the presence of karst on coasts that have been subject to sea level transgression has significantly influenced the subsequent coastal morphology. Factors such as the nature of the bedrock surface, spring discharge, and the gradient of the topography are important influences (Back *et al.* 1984, Hutton *et al.* 1984). The brackish character of the water that emerges from the springs at Cave Bay probably reflects tidal influences through the porous aeolianite. Jacobson and Hill (1980) indicate that in Niue tidal affects through porous limestone are measurable 6 km from the coast, with the fresh/salt water transition lying 0.5 km inland. The inland extent of tidal influences through the aeolianite on Flinders Island is likely to be controlled in part by the altitude of the interface between the aeolianite and the interglacially wave-eroded granite surfaces upon which the calcareous dunes accumulated.

In addition to solution processes, a number of biological agents of erosion have been implicated in the development of intertidal notches on limestone coasts. They include the ingestion of the rock and the secretion of acids by the bivalve mollusc *Lithophaga*; the action of boring sponges and boring algae; grazing molluscs that rasp the limestone to get at their prey; and respiratory processes of other organisms in contact with the carbonate rock (Neumann 1968). Newell and Imbrie (1955) suggested that biogenic processes might account for up to 50% of the rock removed in notch formation on carbonate coasts. Rates of notch formation are controlled by many factors and, hence, are very site specific. Neuman (1966) indicated notch recession at 1-1.4 cm/yr on aeolianite in Bermuda. Trudgill (1976) has measured rates of 1.0-1.25 mm/yr in the development of notches in limestone on Aldabra Atoll where grazing was responsible for 0.45-0.6 mm of this notch recession. No lithophage molluscs have yet been recognised on the aeolianite coasts of Flinders Island. However, there is evidence suggestive of abrasion by molluscs, as well as deep algal penetration of the rock that must undoubtedly imply chemical weathering.

The altitude of the notch at Flinders Island is reasonably consistent with the observation by Hodgkin (1964) that maximum notch development occurs just above mean sea level. The notch on Flinders Island appears slightly higher above sea level than recorded from Aldabra Atoll by Trudgill (1977) who depicts HWM as being located at the top of the visor. Whether some uplift may have influenced the altitudinal range of the Flinders Island notches may warrant investigation, but no evidence for more than one apex was observed. The shorelines at Cave Bay and Fotheringate Bay where notches have developed are both protected, which is consistent with the suggestion that the sharpest notches develop on protected coasts, being replaced by ramps on exposed coasts (Guilcher 1958, Trudgill 1976). The reasons advanced for this relate to a general decrease in the relative significance of biological and chemical processes as energy increases. Trudgill (1985) proposes that on aeolianite, due to its being relatively poorly cemented, less recrystallised and less metamorphosed than most limestones, direct bioerosion is of paramount importance, with the height of the notch controlled by the intertidal zonation and competitive advantages and adaptions of the bioeroders. He proposes that whereas in the tropics notch position coincides with the presence of bioeroders, notches in the temperate zone are most marked where barnacles and mussels are present, together with the excavated pools of erosive echinoids. Hills (1971) has suggested that the form of the visors on aeolianite coasts in South Australia may be due in part to induration from seawater in voids. This is a suggestion that warrants further investigation.

In coastal environments solution cavities provide foci for mechanical processes that have undoubtedly been important at Fotheringate Bay, including compression, decompression (implosion) and abrasion (Jennings 1985). In most cases the caves at Fotheringate Bay are floored by granite that has provided a resistant base level to erosion by the sea or by emerging groundwater. However, some of the caves in this locality exhibit floors of aeolianite that mimic the form of granite floors in immediately neighbouring caves. Hardening of the basal zone of the aeolianite by redeposition of calcite in strata where groundwater is perched immediately above the granite is one possible explanation. However, the caves at Fotheringate Bay do not seem as reliant upon calcrete for roof support as has been described from other Australian aeolianite karsts (White 1989).

Miotke (1972) emphasises flow dynamics of the solvent in explaining karren development on carbonate-cemented dune sands in northern Puerto Rico. In this context karren formation is complex as there is solvent flow both up and down rock surfaces due to the influence of the swell and tides. The generally smoother form of the aeolianite surfaces in the wave zone relative to that in the spray zone is consistent with the observations of Neumann (1966) who stressed the role of interstitial algae in producing the pitting in the latter zone. The algal factor is also considered relevant on Flinders Island given the deep algal discolouration of the aeolianite there. Honeycombed rock on coastal limestone cliffs has been attributed by Bird (1976) to alveolar weathering as a result of wetting and drying, associated solution of the rock, and precipitation near the surface to cause case-hardening. The almost horrific morphology of some of the karren that has formed on the Flinders Island coast, particularly on the southern-most stack at Cave Bay, bears comparison with the black phytokarst described by Folk *et al.* (1973) from the aptly named Island of Hell in the Caribbean and with other coastal phytokarst depicted by Ford and Williams (1989 - fig. 9.10).

The undercut walls of solution pans at Fotheringate Bay bear comparison with those described from the Burren, Ireland, by Lundberg (1977). However, Bird (1976) has observed that the zonation of landforms on the calcarenite coasts of southern Australia generally bears more resemblance to that described from limestone coasts in warm temperate environments, albeit with wider platforms in Australia, than to the zonations described from cool temperate and tropical environments by Guilcher (1958). Trudgill (1985) argues that on horizontal surfaces maximum relief is correlated with the balance of moisture retention and the adaptation of bioeroding organisms, hence pools deepen, partly due to changes in solvent aggressivity with tidal movements, and residual eminences develop between the pools.

Analogies between the aeolianite coastal landforms of Flinders Island and those landforms popularly considered more characteristic of warmer environments is not confined to the morphology of the shore platforms and intertidal notches. The presence of a calcrete capping on the aeolianite on Flinders Island allows the development of some features that bear comparison with those that form in duricrust landscapes in tropical and subtropical environments (Goudie 1973). However, whereas a duricrust generally controls the rate of slope retreat by protecting the underlying strata and inhibiting the reduction of the lower slopes, this situation is modified in a coastal context by marine erosion at the foot of the slopes. "Breakaway" scarps characteristic of duricrust terrains develop by sapping of the underlying softer material. This causes the production of steep talus slopes in a similar fashion to the cliff collapse and slab accumulation at Fotheringate Bay. However, because the marine erosion in the latter locality is relatively vigorous and dominates over the erosion caused by emerging groundwater the development of a significant calcrete talus is impeded. This situation is comparable to that described by Gill (1972) from Warrnambool in Victoria where aeolianite atop marine limestone cliffs is capped by calcrete that is undermined by erosion of the softer subjacent rock, but fallen slabs are rapidly subjected to marine erosion, including the cutting across them of intertidal platforms. Hence, much of the breakdown is removed in solution by the sea (Jennings 1985).

Other aspects of the development of karst morphology in inland duricrust, and particularly in calcrete terrains, are also pertinent to the present discussion. Small caves may develop beneath a hard calcrete and a subjacent softer layer due to solution, deflation by the wind and excavation by animals (Goudie 1973). The upper notch at Fotheringate Bay is considered to be more likely the result of contemporary weathering processes than of previous marine erosion and subsequent subaerial weathering and erosion. Bedrock disruption beneath calcrete is a well documented phenomenon, and it can lead to the breakdown even of quartzite. The exact mechanisms entailed are unclear but may include salt crystallisation, salt hydration and the thermal expansion of salt. The crystallisation of calcite can also split rocks and quartz grains where pore spaces and cracks are penetrated by capillary action. The likelihood of mechanical breakdown by such processes is probably enhanced by the tendency of calcrete to form discrete masses in favourable strata, in a manner similar to the segregation of ice within rock materials in periglacial environments. Calcite precipitation by vadose waters that penetrate fractures may also have an impact (Goudie 1973). Where a calcrete is relatively saline the expansion of water soluble salts such as sodium chloride is likely to assist in rock breakdown. The extent to which the high intergranular porosity of aeolianite might minimise this can only be speculated upon at this time. Similarly, the extent to which block detachment from scarps might be influenced by such processes or by the location of calcified tree remains that focus solution activity warrants further investigation.

Given the relatively rapid bioerosion rates measured from limestone coasts and the limited coherence of aeolianite, the survival of ancient relict landforms may generally be inhibited other than in situations where case hardening reinforces the rock or perhaps forms a cast of the karst. Sutherland and Kershaw (1971) recognised the presence of erosional landforms on Flinders Island related to old marine stands at 57-72 m and 27-33 m. They also identified marine sediments suggestive of other old sea level stands at 15-18 m, 5.5-6 m, 4.5 m and 0.6-1.5 m above MHWS. They recognised that the limestone was cut by their 4.5 m level which they attributed to the Last Interglacial, and was also cut by their 0.6-1.5 m level which they considered to be of late Quaternary age. However, studies from around Australia have consistently failed to reveal evidence of Last Interglacial sea levels more than 4 m above present (Murray-Wallace and Belperio 1990) which suggests that evidence of former shorelines that occur above that altitude are indicative of coastal uplift. This is confirmed by the Last Interglacial dating of sediments 24.5 m above present HWM at Mary Ann Bay in southeastern Tasmania (Murray-Wallace *et al.*, 1990). Morphostratigraphic evidence that deposits at up to 32 m altitude in northeastern Tasmania are also of Last Interglacial age, together with the circumstantial evidence provided by an historical record of relatively high levels of seismic activity centred near the edge of the continental shelf off northeastern Tasmania, are consistent with the possibility of locally greater uplift in the Flinders Island area than elsewhere in Tasmania due to hotspot activity (Bowden 1978, Richardson 1989).

However, even if one adopts the uplift rate implied by the data from Mary Ann Bay all but the uppermost of the former sea levels recognised on Flinders Island by Sutherland and Kershaw (1971) could relate to stands of Last Interglacial age. The 57-72 m level lies beyond the likely reach of the Last Interglacial sea. Its presence bears comparison with other elevated marine surfaces on King Island (Jennings 1959, 1961) although hotspot location probably implies rather different levels of neotectonic activity between King Island and Flinders Island. If uplift was continuous, the altitude of the Last Interglacial sediments at Mary Ann Bay would imply a mean uplift rate of 0.15 m/ka since the Last Interglacial maximum. On this basis, the 0.6-1.5 m level on Flinders Island could be explicable by present sea level without recourse to suggestions of higher sea levels at any period during the Holocene. A date of 3, 540 +/- 100 BP (SUA 413) obtained was by Gill (cited in Colhoun 1983) from shells in granite beach gravels 1.8 m above present sea level south of Whitemark and an assay result of 3, 970+/-90 BP (Gak 1102) has been obtained from wood at Yellow Beaches on the southern coastline of the island.

The truncation of the calcarenite at Fotheringate Bay by marine erosion during the Last Interglacial provides a minimum age for the rock. While the erosional landforms in the calcarenite are time transgressive for the most part they are likely to be primarily Holocene. However, the radiocarbon determination of 17,090±150 BP (Beta 43,947) obtained from the base of a stalagmite from close to present HWM in one of the caves at Fotheringate Bay implies that at least part of the cave had formed where groundwater was intercepted by the granite at the base of the aeolianite by the time of the late Last Glacial Maximum. Hence, unless the cavity formed during the high sea level stand of the Last Interglacial it must have been essentially a terrestrial karst feature.

The age of this carbonate deposition is itself worthy of note. Speleothem dating from Europe and North America has indicated that deposition of speleothems occurred primarily during interglacial periods and that their deposition ceased almost entirely during episodes of cold glacial climate (Harmon *et al.* 1977; Atkinson *et al.* 1978; Gascoyne 1981). In contrast, the date from Fotheringate Bay indicates deposition during the late Last Glacial Maximum. It also compares closely to uranium series dates of 17±3 ka BP and 19±4 ka BP from a sea cave on King Island which although formed in quartzite contains abundant carbonate speleothems due the leaching of calcareous dune sands that overlie the bedrock (Goede *et al.* 1979). In addition, a result of 20±4 ka BP has been obtained on a speleothem from a cave at Montagu, close to the Bass Strait coastline in NW Tasmania (Goede and Harmon 1983). During the late Last Glacial Maximum both Flinders Island and King Island were hills that rose from the Bassian Plain exposed by low glacial sea levels. Bowden (1983) has interpreted linear terrestrial dunes in NE Tasmania, similar to those on Flinders Island (Kershaw and Sutherland 1972), as the product of a climate that was colder, drier and windier than today due to changed circulation patterns, topographic factors and increased continentality. More recent work by Blom (1988) indicates that during the latter part of the Last Glacial Stage Bass Strait existed only during the periods 49-43 ka BP, 41-37 ka BP and 29 ka BP. At other times once the sea level dropped below the sills on the Bassian Rise and King Island High at 55 m depth the Bass Basin was floored by a saline lake 110 x 260 km in extent and 11 m deep from which evaporation rates would have been high. Bass Strait was not fully flooded until 8 ka BP. Hence, local moisture availability may not have been a major difficulty, although the inception of speleothem deposition at this time may still require explanation. Goede and Harmon (1983) list five other Tasmanian speleothem dates from the period 30-10 ka BP and suggest that the inception of speleothem formation evident from six of these, four of them clustering at 15-19 ka BP, may be the result of rapid climatic amelioration. However, the Dante Glaciation in central western Tasmania did not commence until shortly after 18,800±500 BP (ANU 2533) (Kiernan 1983) while evidence from Kutikina Cave on the lower Franklin River, indicates that frost shattering continued until after 15 ka BP at low altitudes in western Tasmania, where moisture availability is never likely to have been a problem (Kiernan *et al.* 1983). This may be inconsistent with the suggestion by Caine (1983) that the cessation of frost shattering on Ben Lomond during the Last Glacial maximum may have been a response to increasing aridity rather than rising temperatures. It seems likely from the advent of speleothem deposition that precipitation increased rather than decreased at this time.

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A NEW TOPOFIL

Alan Warild

Abstract

A light, compact, reliable instrument for surveying difficult vertical caves has been a dream of cave surveyers for many years. The topofil described goes a long way toward fulfilling that ideal, although there are still problems of availability and user error. Even so, the author is of the firm opinion that topofils are ideal for expedition and deep cave surveys.

INTRODUCTION

The basic topofil consists of a small box containing a roll of thread and distance counter. In this simple form, topofils have been around for some time as measuring chains for rough terrain and for quick, simple surveying applications. Most commercially made units though, have been strictly distance measuring devices and inclinations and compass bearings have been taken with separate instruments.

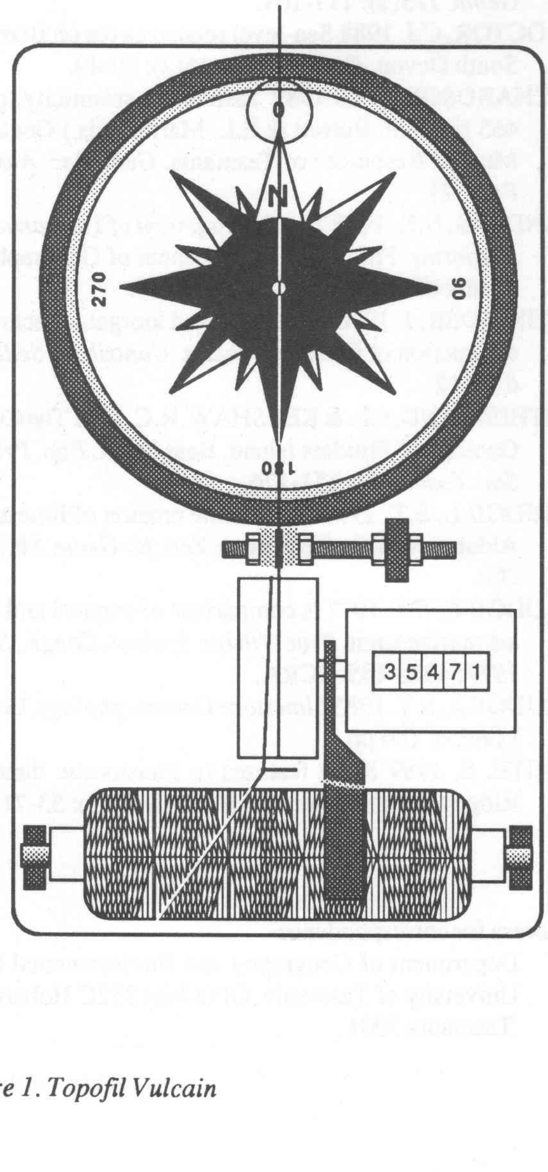


Figure 1. Topofil Vulcain

More advanced topofils use a compass and clinometer adapted to read along the thread laid from one station to the next. These can be carried as a separate unit or mounted on the topofil box provided it contains no magnetic components. Commercially available topofils specifically for caving use are restricted to two French models - Vulcain and Expé. The Vulcain model is a complete unit (Figure 1) with a large moving card compass inside and a 180° protractor and spirit level on the back as a clinometer. The "Topofil Vulcain" is made by the Vulcain speleo club in Lyon to raise club funds and always seems to be in high demand and short supply. Expé (TSA-Georges Marbach) makes less convenient separate counter and compass/clinometer units. Design limitations with both make constructing one a reasonable alternative.

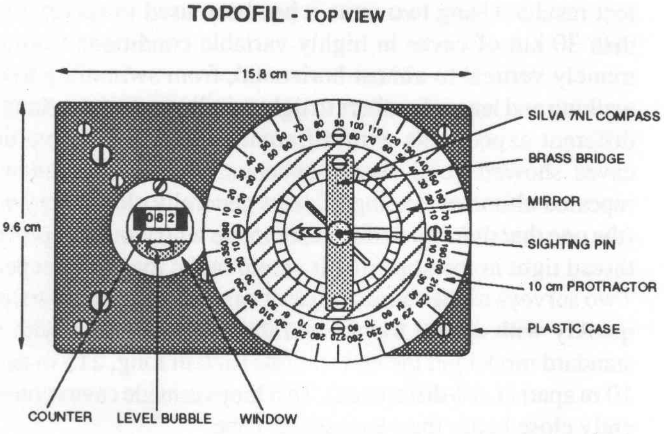
TOPOFIL "WARILD"

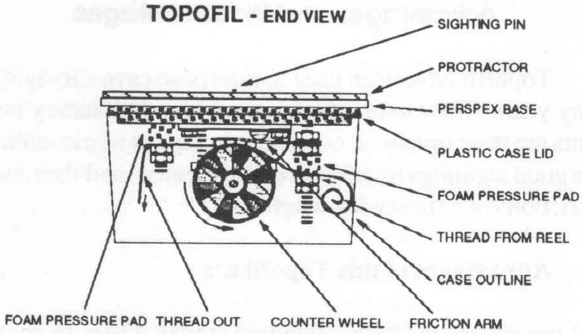
This topofil was redesigned using the Expé model as a basis for the counter. The sighting mechanism is a new invention. It solves some of the problems of earlier models by being an integral unit using the same 360° protractor to measure both bearing and inclination. The counter, compass and clinometer mechanism are built around a 16 cm x 9.5 cm x 5.5 cm plastic electronic component box. The topofil could be mounted in an aluminium box if an especially robust instrument was required, but the lighter plastic boxes have given no problems.

In pursuit of a truly compact surveying instrument, this 'standard' topofil has been further reduced to fit into a 13 cm x 7 cm x 4.5 cm box. The 7 cm diameter protractor is almost as easy to read as the larger version but the box only holds one roll of thread (400-500m).

Counter Mechanism

The ideal counter is a non-magnetic, 4 or 5-digit, direct drive decimal revolution counter. The topofil described uses a plastic 5-digit counter which must first be disassembled and the steel spindle replaced by a brass or stainless steel one to avoid magnetic effects on the compass. The centimetre digit at the right end and the 100's of metres digit at the left end are superfluous, so to make note taking easier and more accurate, they are masked. This has the effect of the counter always displaying a rounded down figure. Note however that this does not mean each survey leg is rounded to the nearest 10 cm. The counter still counts in single centimetres, but it displays in decimetres from the starting point.





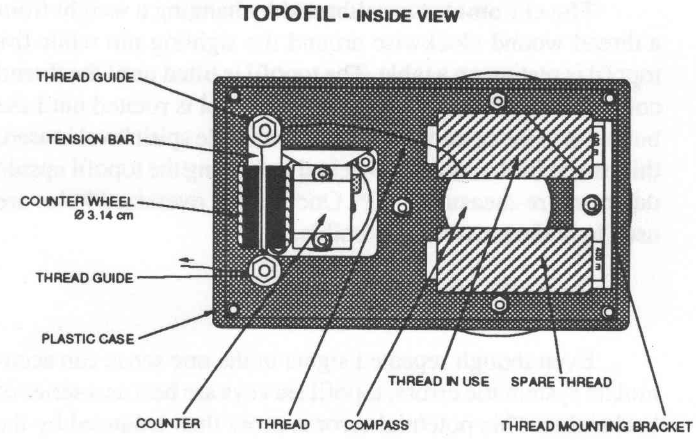


Figure 2. Topofil "Warild"

The counter wheel is a 10 cm circumference, 1.5 cm wide, rubber coated wheel that is turned down from nylon or polyester or made from a suitable sized plastic cotton reel. The wheel should be as light as possible so that its inertia is minimal. Heavy wheels tend to skid when started quickly and keep spinning after a sudden stop, introducing errors and possibly derailing the thread. Rubber coating (bicycle tube) helps reduce skidding and the friction arm dampens over-running.

The counter mechanism is mounted on the back of the spirit level window from a builder's level which in turn fits neatly into a hole cut into the lid of the topofil box. A roll of cotton thread 400 m to 1000 m long is push-fitted onto a peg mounted on an angle bracket so that the thread pulls off the reel's end without the reel spinning. The thread then passes through a friction guide, takes 2 turns around the counter wheel, passes through another friction guide then out through a hole in the end of the box. A fur-coated damping arm rests against the counter wheel surface to eliminate over-run and to firmly hold the thread in place. There is room available in the box for an extra peg to carry a spare roll of thread.

Compass Sighting Mechanism

The sighting mechanism consists of the compass capsule from a Silva 7NL or similar compass (a needle rather than a moving card compass) set into a hole in the topofil box lid and held down by a brass bridge. At the centre of this bridge is a 1.5 mm diameter sighting pin surrounded by a brass washer "bullseye". Around this is a sighting mirror surrounded by a 10 cm protractor with a 0° to 360° outer scale and four 0° to 90° inner scales mounted on a 3 mm white perspex backing sheet to improve contrast and rigidity.

Clinometer Mechanism

The clinometer uses the same protractor as the compass in conjunction with a spirit level mounted on the inside of the counter window so that it operates when the protractor is in the vertical plane.

Calibration

The counter is calibrated by reeling out a metre of thread against a tape or ruler and seeing how close it is to correct. Changes are made by adjusting the diameter of the counter wheel. Turned wheels can be cut marginally oversize and the wheel carefully filed to the precise size. A wheel that is too small is built up using a strip of plastic adhesive tape, the length of which is adjusted until the correct size is obtained. Once the counter is good over a metre it must be fine tuned over ten metres. An alternative is to calibrate roughly then calculate a correction factor by which all distance measurements made with that machine are multiplied before reducing the data.

The compass assembly is calibrated in two steps. The sighting pin is locked over the centre of the compass. The protractor is then adjusted so that the sighting pin is at its exact centre by laying a complete protractor over the top of the topofil protractor and moving it until the sighting pin is under the crosshairs of the top protractor. The bridge and protractor are screwed into oversized holes in the topofil lid to allow for this. The second calibration is done by tying a thread between two stations and reading its bearing with a calibrated sighting compass or topofil. The topofil to be calibrated is set up so that the thread is wrapped around the sighting pin, then runs across the correct bearing on the protractor to the other station by rotating the entire topofil. The compass capsule is then rotated within the topofil until its needle lines up with the North arrow on the compass base and locked in position with a lock screw. Note that the diameter of the sighting pin induces a centring error into all readings but this is "calibrated out", provided the thread is always wrapped the same way - The author prefers clockwise. By taking the magnetic declination of an area into account, the topofil can also be set to read true or grid north.

The clinometer is calibrated by hanging a weight from a thread wound clockwise around the sighting pin while the topofil is resting on a table. The topofil is tilted until the thread coincides with the 90° mark then the level is rotated until the bubble is in the correct position. If a suitable spirit level is used, this can be further double checked by turning the topofil upside down and re-measuring 90°. Once again, oversized holes are used to make movement possible.

Using the Topofil

Even though repeated sights in the one sense can accumulate systematic errors, topofil surveys are best as a series of backsights. This potential error is more than balanced by the very low station error.

Distance is taken by noting the initial topofil reading at the first station, then running a straight line of thread and touching the thread outlet hole to the next station. The new reading (cumulative distance) can then be read off.

Bearing is taken by wrapping the thread coming from the first station clockwise around the sighting pin and pulling it taut. The topofil is held horizontal and in line with the station while it is rotated until the north arrow lines up with the arrow on the compass base. The bearing is the degree mark over which the thread passes. To take upward sights the thread must pass over the protractor some distance above it, making parallax errors possible. To reduce such errors the observer's eye is moved until the reflection of the thread in the mirror around the compass is obscured by the thread itself, the eye is then directly above and the reading is parallax free (in practise, the eye does this automatically). Should the mirror be unusable, it is necessary keep one's eye directly above the sighting pin - not too difficult with the aid of the 'bullseye' while looking end-on at the pin. Downward sights are more difficult and potentially less accurate. The topofil is oriented as above except that the thread now drops down over the side of the topofil. The thread must therefore be lifted with one finger a few centimetres out from the side of the box. It is then moved from side to side until it makes a straight line in the horizontal plane from the topofil to the station.

Inclination is taken by turning the topofil on its side so that the protractor is vertical with the thread just off its face. The instrument is then leveled using the spirit level and the reading taken. A suitable protractor can take inclination readings in all four quadrants.

Accuracy

The accuracy of any instrument is only as good as the surveyor who uses it. This Topofil has been designed to make it as foolproof as possible with special thought given to avoiding accidental misreadings by having logically organised, easy to see scales. A team of two cave surveyors skilled in the use of a good topofil will produce more reliable results in less time than a comparably trained group of three using Tape & Compass.

Like any good surveying instrument, the topofil can be tested periodically for accuracy and recalibrated as necessary.

The topofil and the described method of use have been field tested on several vertical caving expeditions with excellent results. Using two units it has been used to survey more than 30 km of caves in highly variable conditions from extremely vertical to almost horizontal, from swimming to dry walking and large chambers to tight winding passages, done on different expeditions with different people. All the vertical caves showed good correspondence when controlled with repeated altimeter readings. Loops generally closed very well (the one that didn't was due to someone who wouldn't pull the thread tight in the hope that it would make the cave deeper!). Two surveys of the same stretch of cave done a year apart, one quickly with a poor topofil and the other carefully with the standard model put the end stations (620 m long, 215 m deep) 10 m apart (1.6% difference). Test loops outside caves consistently close better than Suuntos & Tape.

Advantages and Disadvantages

Topofils have been used in European cave surveying for many years. Their main advantages over other survey instruments are their lightness, compactness, speed of use, ability to take good sightings in difficult circumstances and their lack of restriction over survey leg length.

Advantages of this Topofil are -

- Low weight and bulk - Standard model: 320 g, 16 cm x 9.5 cm x 5.5 cm.
  Mini: 190 g, 13 cm x 7 cm x 4.5 cm
  (Suuntos & Tape: 700 g, 25 cm x 18 cm x 3 cm.)

- It is fast to use with all scales on one instrument read by a single caver.

- All scales are read from left to right (clockwise). This greatly reduces the chances of taking a false reading by counting in the wrong direction on a reverse scale compass or reading the wrong scale on a dual scale clinometer (an accidental reading of the wrong clinometer scale is obvious during data reduction and is easily corrected).

- Very good precision on high angle compass shots. The thread is sighted along and aligned with the mirror allowing a high degree of accuracy even when approaching 90° (Sights of 20° to 90° with a sighting compass rely on increasing amounts of guesswork).

- Sights that would otherwise be taken as verticals can be measured - the bottom end of many vertical sights is very inaccurate, especially if water is falling down the pitch.

- Distance between stations is limited by the length of the roll of thread (usually between 400 m and 900 m), which is more than adequate for any big pitch.

- Minimal station error. Sighting instruments require the instrument reader's head to be behind the instrument. A topofil has a much greater latitude over where stations are set. "Floating" stations such as sighting to the light of someone standing in mid-passage are unnecessary. In low wet passages the topofil can be floated along like a boat on a string. For very awkward sights it is often better to hold the instrument in line between the two stations rather than as close to the station as possible. Topofils are easily held in line and their small size keeps the station error small when this is not possible.

- Easy to read in the low light conditions of a cave.

- Unlike direct sighting instruments, topofils have no optical sighting; there is never a problem with them misting up.

Disadvantages of this Topofil are -

- Not readily available.

- More working parts than tape and requires a "light touch" to run well. The thread must be run out carefully or it may break or snag. The instrument must be opened to insert a new roll of cotton when the old one runs out. If the thread is broken on a pitch or difficult passage that one sight can be left for the return trip rather than having to do the pitch or passage an extra time.

- Topofils leave a thread line throughout the cave that must be collected by the surveyors on their way out. Cotton thread should be used so that if any is accidentally left behind it will eventually rot.

- Once the thread is wet it will not run freely and must be replaced by a dry roll.

- Topofil length data is cumulative. Some sort of calculation is required to determine individual leg lengths, whether to aid sketching in the cave or during survey data reduction.

- Tape & Compass surveys never have to be abandoned when they run out of thread.

- Even a light crosswind will displace a topofil thread enough to give a compass error of several degrees. Surface surveys should be done with Suuntos or more accurate instruments and topofils only used to measure the distance component.

- There is the temptation to take sights longer than 30 m. The optimum leg length is a compromise between station error and instrument reading precision but is always well below 30 m. On pitches the difficulty of getting any sight may outweigh the need for accuracy.

- The thread can be wound the wrong way around the sighting pin. This will give a constant error for the compass which can be calibrated out, but because the clinometer can be read in four quadrants the error cannot be removed.

- The surveyer must get his head over and beside the topofil to take readings.

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WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain Caves. In: J.R. DUNKLEY and T.M.L. WIGLEY (eds), *Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain. Southern Austalia:* 32-34. Speleological Research Council, Sydney.

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