SYNGENETIC KARST IN AUSTRALIA

J. N. Jennings

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This paper was presented by Joe Jennings in 1964 to the Karstic Phenomena Symposium of the Twentieth International Geographical Congress, held at Settle and Buxton, England. As publication of the proceedings was excessively delayed it was published in 1968, along with a companion paper by P.W. Williams, by the Department of Geography, Australian National University.
In the meantime studies had continued, so this published version has many footnotes commenting on subsequent work.

As copies of the paper are becoming dificult to locate, this electronic version was produced by K.G. Grimes in 2006 by scanning and OCR of a printed copy. I have checked the text, but some OCR errors may have remained. I have retained the original page breaks and pagenation for ease of referencing but have let the text reflow within paragraphs (the software did that without my permission!). Underlining has been replaced by italics and I have done some other minor formatting changes and corrected a few typos in the original. The 'footnotes', some of which actually appear in the middle of a page, have been rendered in italics to make them more distinctive.

The frontispiece opposite shows part of the large chamber of Aiyennu Cave near Stockyard Gully, Western Australia. The roof is a thin arch of caprock in aeolian calcarenite perforated by many solution pipes, each a source of daylight. On the left there is a soil horizon below the roof and a river flows at the foot of the blockpile. From roof to river is about 25 metres.

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SYNGENETIC KARST IN AUSTRALIA

J.N. Jennings

ABSTRACT

The ideas of various Australian speleologists, including the author, on the peculiarities of karst geomorphology in some parts of the dune limestones of the southern and western coasts of this continent are reviewed. To a certain degree karst processes have gone on concurrently with the consolidation of calcareous shell sand into aeolian calcarenite, i.e. the karst is partially 'syngenetic'.

Pipes are not solely solutional in origin; calcite deposition accompanying their formation has helped to lithify the sand, and taproot growth is involved also in some cases, Engulfment of allogenic drainage is less frequent than in normal karst because of the development of 'gorges of construction'. In this context any theory of collapsed cave origin for a gorge must be viewed sceptically, though short gorges due to retreating inflow cave arches are known and there is one probable steephead valley, now inactive. Amongst closed depressions, only soil subsidence and collapse dolines are found, and these occur sporadically, not in close-set fields.

Caves are well developed and in the main the result of lateral solution at the water-table. In many cases cave excavation has accompanied lithification and collapse has dominated more of their history than is typical of consolidated limestone caves. Differential lithification is reflected in cave form in some cases. Linear caves seem to be associated with irregular relief of a buried impervious basement, whilst inclined fissure caves are more prevalent where there is

a level basement beneath the dunes. Vadose action has usually been dominant, though there are certain phreatic systems of special type, the cause of which is not yet ascertained. Absence of known outflow caves may be due to seaward burial by young dune invasion or to precociously early achievement of saturation by underground waters in these incoherent and porous limestones. A few radiometric dates published since the preparation of this paper in 1964 indicate that at least some of the caves have developed rapidly in the late Quaternary.

ZUSAMMENFASSUNG

Die Meinungen einiger australischer Höhlenforscher, einschliesslich des Verfassers, über die Eigenschaften der Karstgeomorphologie in einigen Teilen des Dünenkalksteins der südlichen und westlichen Küste dieses Kontinentes werden erörtert. Zu einem gewissen Grade sind Karstprozesse mit der Konsolidation von kalk-igem Muschelsand in äolischen Kalkarenit Hand in Hand gegangen, daher ist der Karst zum Teil "syngenetisch".

Die geologischem Orgeln haben ihren Ursprung nicht ausschliesslich in Lösungen; Kalzitablagerung, als eine Begleiterscheinung ihrer Entstehung, hat zur Versteinerung des Sandes beigetragen, und Pfahlwurzelwuchs war in einzelnen Fällen auch mitwirkend. Infolge der Kntstehung von "aufgebauten Schluchten" ist das Verschlungenwerden von Fremdlingsflüssen weniger häufig als in normalem Karst. In diesem Zusammenhang muss jegliche Theorie des Höhleneinsturzursprunges von Schluchten skeptisch betrachtet werden, obwohl kurze Schluchten, die auf das Zurückweichen von Eingangshöholenbogengängen zurückzuführen sind, bekannt sind und es ein wahrscheinliches Karstsacktal gibt, das gegenwärtig nicht aktiv ist. Von ringsumschlossenen-, Vertiefungen werden nur Bodeneinsinken - und Einsturz-dolinen angetroffen, und diese kommen nur sporadisch, nicht in dichten Feldern, vor.

Höhlen sind gut entwickelt und rühren hauptsächlich von seitlichen Lösungen am Grundwasserspiegel her. In manchen Fällen ist die Versteinerung von Aushöhlung begleitet worden, und in manchen Fällen war Einsturz mehr charakteristisch für ihre Entstehungsges-chichte als es für Höhlen in verfestigtem Kalkstein typisch ist. In einigen Fällen ist differentielle Versteinerung in der Höhlenform ausgeprägt. Linienförmige Höhlen scheinen im Zusammenhang mit dem

unregelmässigen Relief einer unterirdischen undurchlässigen Unterlage aufzutreten, während geneigte Einsturzspaltenhöhlen dort vorliegen, wo eine ebene Unterlage unter den Dünen vorliegt. Vadose Wasserwirkung war gewöhnlich vorherrschend, obwohl es gewisse phrea-tische Systeme eines besonderen Typus gibt, deren Grund noch nicht erkannt ist. Der Mangel an bekannten Ausflusshöhlen düfte auf seeseitiges Begraben infolge jüngerer Düneninvasion zurückzufüren sein, oder auf frühzeitige Sättigung der unterirdischen Gewässer in diesen lockeren und porösen Kalksteinen. Einige wenige radiometrische Daten, die seit der Zusammenstellung dieses Artikels in 1964 publiziert wurden, weisen darauf hin, dass zumindestens einige dieser Höhlen sich im späteren Quartär rasch entwickelt hatten.

INTRODUCTION

Karst usually develops in marine limestone which has consolidated previously. Indeed a long time interval is common between the diagenesis of a sedimentary body and its emergence to form part of a land mass and its exposure to exogenic processes. Consequently rock consolidation and karst development have usually been considered as successive events. But in aeolian calcarenites - terrestrial limestone - lithification and karst phenomena are likely to be produced simultaneously, for the same agents are responsible for both.

Bermuda is one of the few areas where karst in aeolian calcarenite has been investigated. Yet the two major discussions (Swinnerton, 1929; Bretz, 1960), though differing in interpretation, are both conducted in terms of a successive relationship of karst to diagenesis. This sequence cannot be assumed even though Bermudan caves are restricted to dune limestones and absent from unconsolidated calcareous dune sands. Bretz' position is the more defensible in that he argues that the dunes were emplaced during interglacial high sea level periods when in his view there was not a large enough body of groundwater to produce caves and related phenomena. These are supposed to have developed in subsequent glacial periods when the islands were larger and so also groundwater storage. This sequence allows time for lithification before the onset of significant karst development.

However this inference of Bretz has little or no force for the dune limestone belts of Australia, which has probably the most extensive deposits of this kind of all continents. In the absence of adequate superficial geology maps, the area of calcareous dune sands and dune limestones must be estimated as lying between the broad limits of 50-100,000 km^2 . Here the context allows the possibility of *syngenetic* karst development and so an enquiry is warranted into the extent of its occurrence and its morphological consequences.

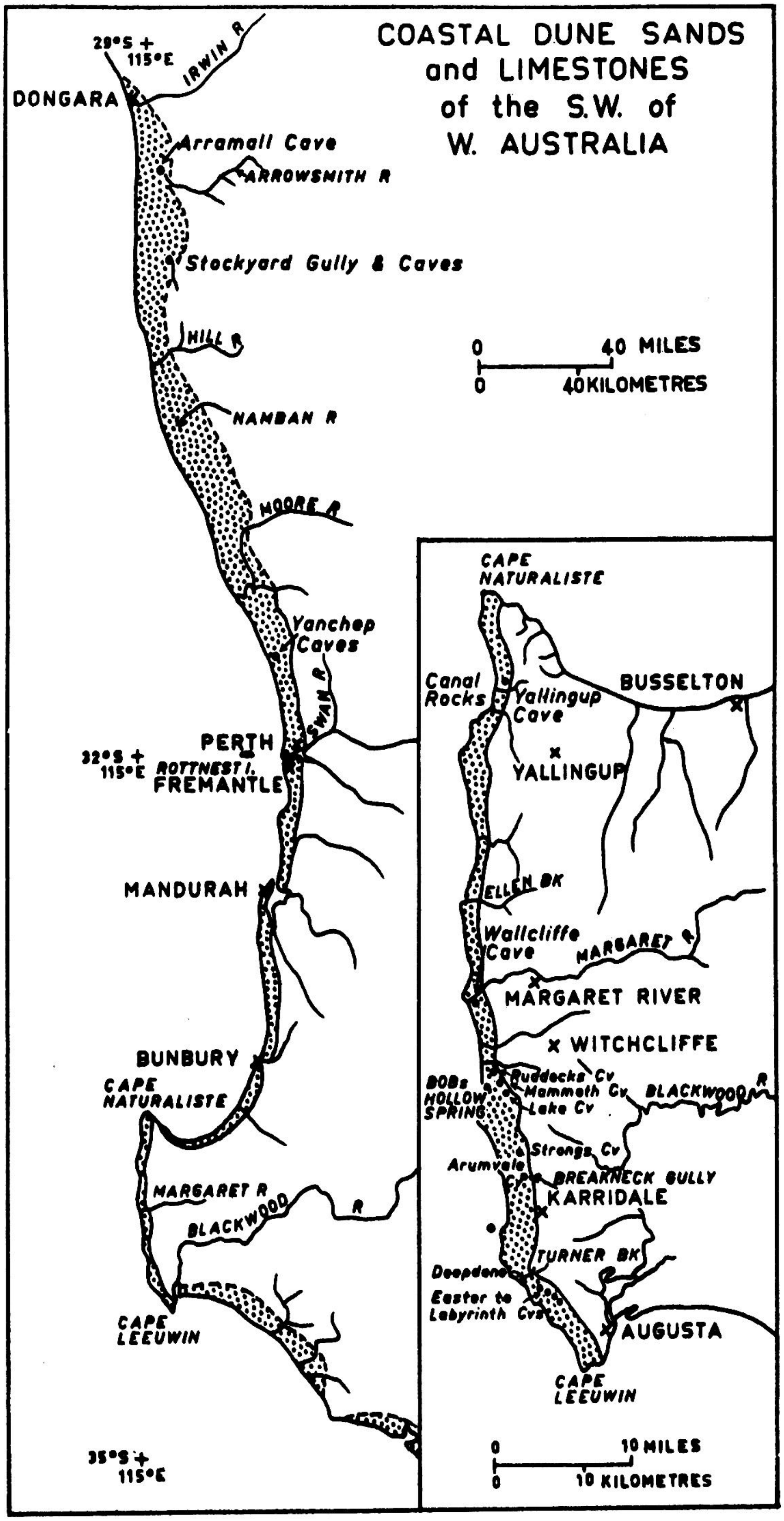
The exploratory essay in this direction which follows is based on field work in the Southwest of Western Australia (Fig. 6), the Nullarbor Plain, Kangaroo Island (Fig. 7) and the Southeast province of South Australia and King Island, Tasmania, in Bass Strait (Fig. 9). Included is a discussion of caves, which owes much to my fellow-speleologists, not simply through the inevitable teamwork of cave exploration but in particular through the writings and surveys of T.D. Bain, L. Bastian, A.L. Hill, B.C. Lowry, and R.T. Sexton with whom I have had much discussion, which I trust has been mutually profitable. I have also had the privilege of access to the records of the West Australian Speleological Group.

AUSTRALIAN CALCAREOUS DUNES AND DUNE LIMESTONES

Calcareous dune sands are found along substantial lengths of the coasts of Australia from Shark Bay in Western Australia to N.W. Tasmania, and associated with them are older dunes lithified to aeolian calcarenite (Fairbridge, 1950; 1954; Fairbridge and Teichert, 1952). Along with their distribution pattern, the calcarenites retain sufficient of their dune form, despite varying degrees of degradation, to confirm coastal origins.

Comminuted shells, calcareous algae and foraminifera, together with varying proportions of inorganic sands, are cemented to different degrees by secondary calcite to make up the calcarenite. The inorganic sands are chiefly quartz, partly felspar on occasion, plus a heavy mineral fraction. Intercalated in the

FIG.6


COASTAL DUNE SANDS and LIMESTONES of the S.W. of W. AUSTRALIA
29°S + 115°E
IRWIN R
DONGARA
Arramall Cave
ARROWSMITH R
Stockyard Gully & Caves
HILL R
NAMBAN R
MOORE R
Yanchep Caves
SWAN R
PERTH
ROTTNEST I.
32°S + 115°E
FREMANTLE
MANDURAH
BUNBURY
CAPE NATURALISTE
MARGARET R
BLACKWOOD R
CAPE LEEUWIN
35°S + 115°E
0 40 MILES
0 40 KILOMETRES
CAPE NATURALISTE
Canal Rocks
Yallingup Cave
BUSSELTON
YALLINGUP
ELLEN BK
Wallcliffe Cave
MARGARET R
MARGARET RIVER
WITCHCLIFFE
Ruddocks Cv
Mammoth Cv
Lake Cv
BOBs HOLLOW SPRING
BLACKWOOD R
Strongs Cv
Arumvale
BREAKNECK GULLY
KARRIDALE
TURNER BK
Deepdene
Easter to Labyrinth Cvs
AUGUSTA
CAPE LEEUWIN
0 10 MILES
0 10 KILOMETRES

aeolian rocks are thin marine limestone members, usually towards the base, and also fossil soil horizons (Pl. 7, Pl. 11). These soil horizons, varying from a few centimetres to as much as 3 m thick, include fossil land snails, e.g. *Bothriembryon* sp. and insect pupal cases (*Leptops duponti*). Some of the soils resemble rendzinas; others are red loams, called 'terra rossa', but often differing very much in mechanical composition from the red residual clay soils of S. Europe, which gave rise to this term.

Since the eastern coasts of Australia from Fraser Island to E. Tasmania are characterised by quartz sand dunes, often extremely large, the broad distribution of the two kinds of dune sand suggest an ocean current explanation. Subantarctic waters are carried to the western and southern coasts, whereas tropical waters move down the east coast. The higher nutrient status of the subantarctic waters may induce greater biological productivity offshore and account for the higher proportion of biogenic sand relative to quartz sand along the neighbouring coasts. This hypothesis is faced with the apparently contradictory fact of prolific organic calcareous growth in tropical waters along the Barrier Reefs of Queensland, even though distinctly different biota are involved there. Various factors are probably involved in this pattern of quartz and calcareous coastal dunes and many more data are required before the distribution can be understood.[A]

A *Fairbridge has pointed to the opposite contrast between the richness of the Queensland coast in coral reefs and the poverty of northwestern Australia in this respect. Equatorial currents set westward, sweeping planktonic coral larvae to eastern tropical coasts, whereas western ones are impoverished. Nevertheless*

FIG.7

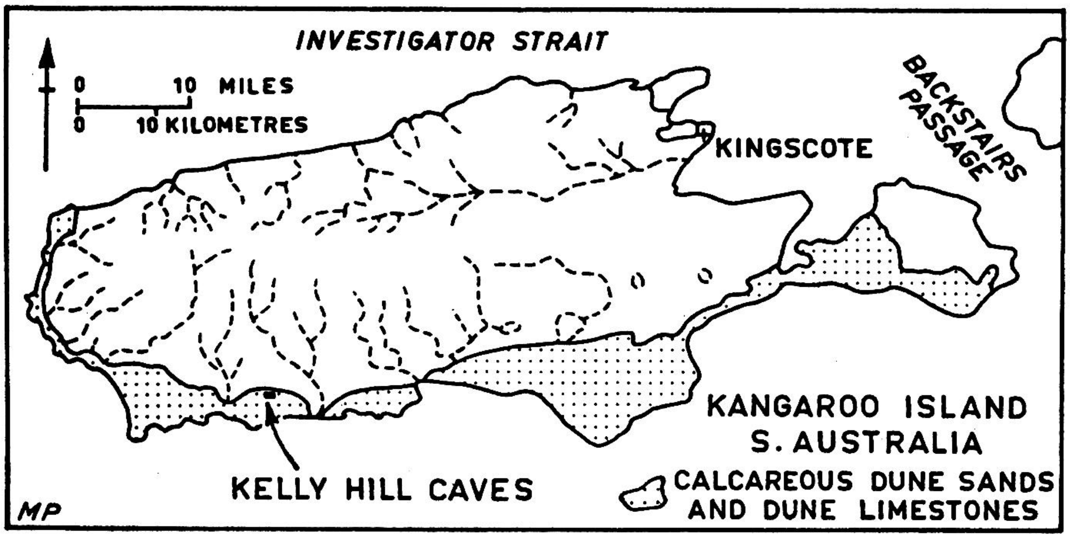
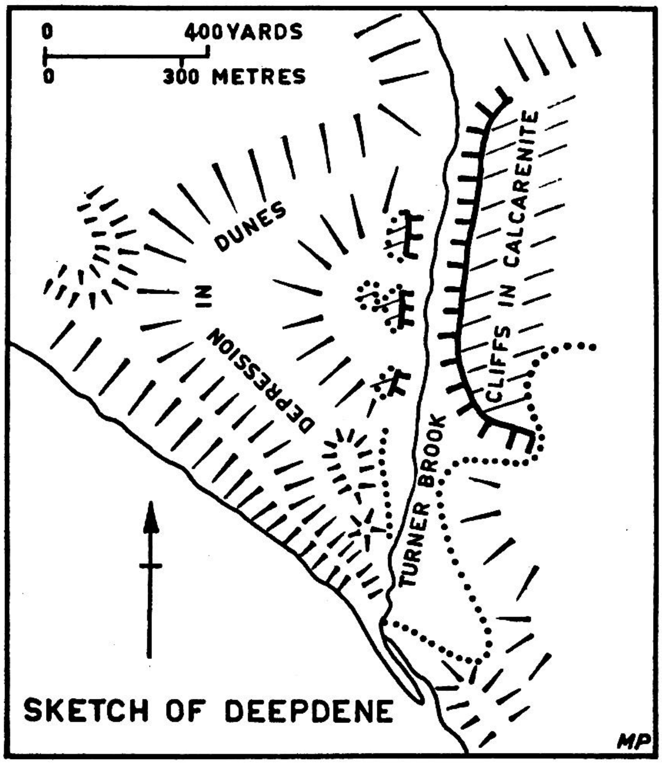

INVESTIGATOR STRAIT
0 10 MILES
0 10 KILOMETRES
BACKSTAIRS PASSAGE
KINGSCOTE
KANGAROO ISLAND
S. AUSTRALIA
KELLY HILL CAVES
CALCAREOUS DUNE SANDS AND DUNE LIMESTONES
MP

FIG. 8


0 400 YARDS
0 300 METRES
DUNES
IN
DEPRESSION
CLIFFS IN CALCARENITE
TURNER BROOK
SKETCH OF DEEPDENE
MP

Fairbridge considers that no imbalance in nutrient status is produced by oceanic upwelling so this explanation of the tropical coastal contrast is not completely consistent with the one offered here for the extra-tropical one.

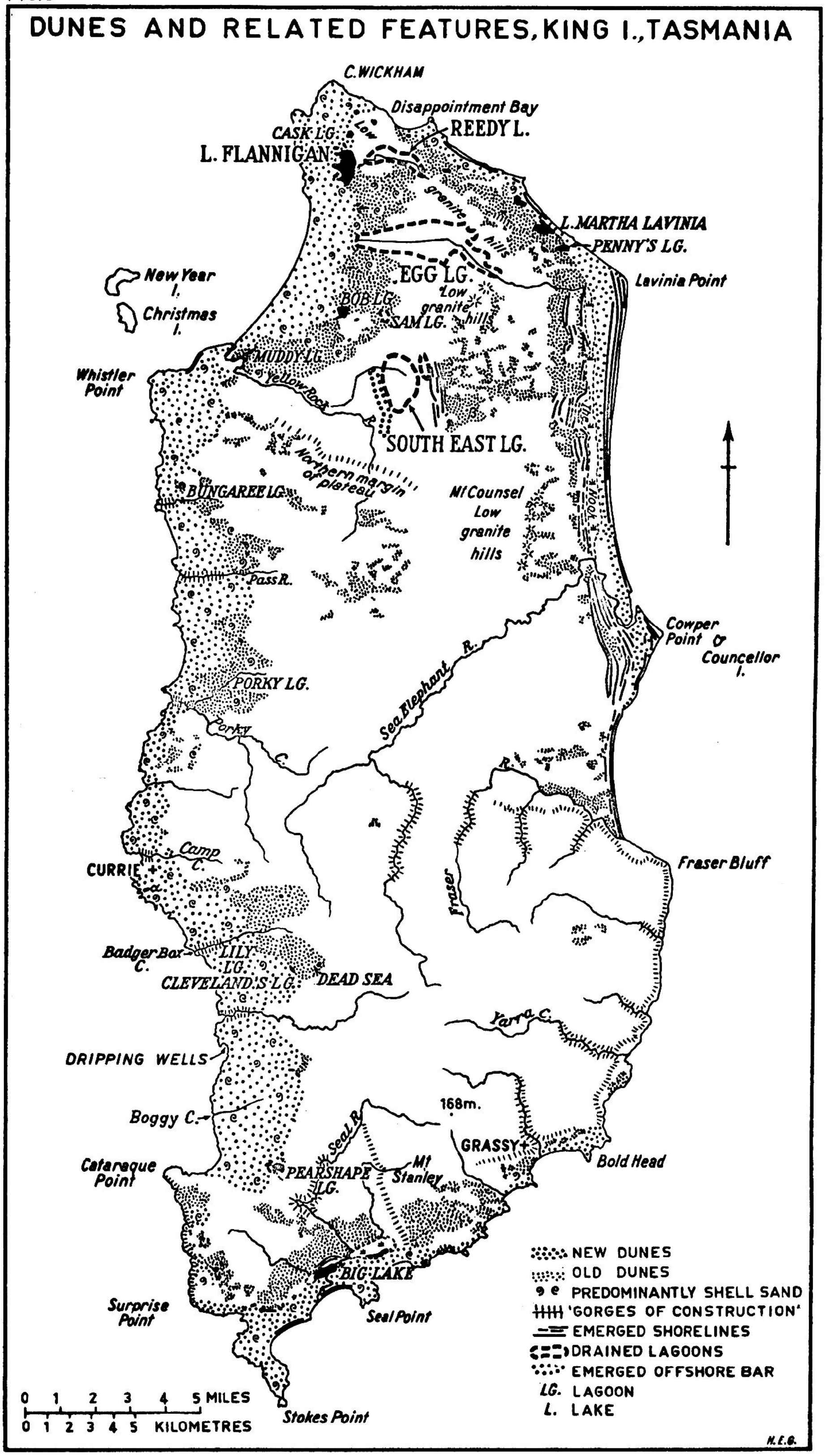
In a paper given at the ANZAAS Hobart Congress in 1965, J.M. Bowler suggested that a possible source of biogenic sand for the western and southern coasts of Australia might be the reworking of offshore Tertiary limestones. The pattern of Tertiary limestones roughly parallels that of the Quaternary calcareous dune sands and limestones and the question arises whether the same background of oceanic water masses and currents could not lie behind both.

Bird (1967) has discussed a different mechanism which might explain the pattern of quartzose and calcareous sands in the southern parts of the continent, namely the wave energy factor. The south-easterly swell dominant on the east coast has significantly less energy than the southwesterly swell of the southern and western coasts (Davies 1964); this could contribute to a variation in the amount of shell material driven onshore.

The whole question remains an open one of absorbing interest to many disciplines.

The calcareous sands and aeolian calcarenites have thicknesses up to at least 160 m, though usually much less than that. Where the dunes have advanced inland over a rising hilly basement, absolute elevations of 200 m and over are known. In these circumstances successive dune systems generally overlap one another in complex fashion e.g. on the west coast of King Island and the Cape Naturaliste-Cape Leeuwin sector of the Southwest of Western Australia (Fig. 6). Where, on the other hand,

FIG. 9


DUNES AND RELATED FEATURES, KING I., TASMANIA
C. WICKHAM
Disappointment Bay
REEDY L.
CASK LG.
L. FLANNIGAN
Low granite hills
L. MARTHA LAVINIA
PENNY'S LG.
Lavinia Point
New Year I.
Christmas I.
EGG LG.
BOB LG.
SAM LG.
Low granite hills
MUDDY LG.
Whistler Point
Yellow Rock R.
SOUTH EAST LG.
Northern margin of plateau
BUNGAREE LG.
Mt Counsel
Low granite hills
Pass R.
Cowper Point & Councellor I.
Sea Elephant R.
PORKY LG.
Porky C.
Camp C.
CURRIE
Fraser Bluff
Fraser
Badger Box C.
LILY LG.
CLEVELAND'S LG.
DEAD SEA
Yarra C.
DRIPPING WELLS
Boggy C.
168m.
Seal R.
GRASSY
Bold Head
Cataraque Point
PEARSHAPE LG.
Mt Stanley
BIG LAKE
Surprise Point
Seal Point
Stokes Point
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETRES
NEW DUNES
OLD DUNES
PREDOMINANTLY SHELL SAND
'GORGES OF CONSTRUCTION'
EMERGED SHORELINES
DRAINED LAGOONS
EMERGED OFFSHORE BAR
LG. LAGOON
L. LAKE
H.E.B.

the dunes have accumulated on coastal plains, sequences of separate dune ridges may develop and a relative chronology is more readily established, e.g. Swan Coastal Plain, Western Australia; Southeast Province, South Australia.

In the Southeast Province of South Australia, there is a very elaborate array of parallel ridges of aeolian calcarenite reaching as much as 100 km inland behind the unconsolidated sands immediately along the coast. Hossfeld (1950) and Sprigg(1952) agreed in regarding them as related to Pleistocene high sea levels of interstadial and interglacial age and in assigning them to the whole spread of the Pleistocene, but differ radically in dating individual ridges. De Mooy (1959) finds a somewhat simpler situation in the Lake Alexan-drina area. Some of the dune limestone ridges extend into the Portland district of western Victoria, where Boutakoff (1963) also thinks they belong to both the Lower and the Upper Pleistocene but that they formed in the glacial periods; a tenuous link in his chronology is the altitidinal correlation of an erosion surface truncating the older dunes with the Tyrrhenian level of Europe, itself by no means a certain datum. Moreover the existence of additional ridges of parallel pattern but of quartzose material, reaching as far as 240 km from the present coast (Blackburn, 1962), underlines the uncertainty attaching to all efforts of dating in this area up to the present.[B]

B. The most important addition to the literature on dune limestone since this paper was prepared is by Blackburn et al.(1965). It deals with many matters treated in the present study and several footnotes refer to it. These authors have presented similar and additional criticisms to those presented here of earlier efforts to date relatively the coastal dune ridges of the Southeast. In Blackburn (1966) initial efforts at absolute *dating of the sequence are to be found. C-14 dates of 24,950 ± 300 and 30,600 ± 450 for shells belonging to relatively young ridges close to the present coast in the Southeast suggest that the whole series must reach well back into the Pleistocene.*

Gill (1967) divides the calcarenites of southwestern Victoria into the Port Fairy Calcarenite and the Warrnambool Aeolianite, and attributes them to the Last Interglacial and previous interglacials respectively. A marine shell from the younger formation gave an ionium dating of 125,000 years.

The situation is simpler in the Swan Coastal Plain where there are only three major parallel dune systems: the oldest quartzose, the intermediate of well consolidated dune limestones, and the youngest of unconsolidated or slightly consolidated calcareous sands. MacArthur and Bettenay (1960) ascribe these three to the Riss-Wurm interglacial, the Wurm interstadials, and the Holocene respectively. However their dating also depends on long range eustatic correlations on an altitude basis, which cannot carry much conviction; moreover Bastian (1964) claims four dune systems in the same area.

In the southernmost part of the Cape Naturaliste-Cape Leeuwin sector, there are three dune systems (Bain, 1962). Most inland are found well consolidated dune limestones of very subdued relief beneath red loams (Deepdene Soil Association of Smith, 1951). Intermediate in position and nature are found dune limestones of more vigorous relief but lacking the depth and continuity of soil cover found in the previous belt.

Coastward of them are unconsolidated calcareous sand dunes of fresh appearance but fixed by vegetation for the most part (Leeuwin Soil Association of Smith, 1951). A correlation of these three systems with MacArthur and Bettanay's three of the coastal plain to the north cannot yet be other than a suggestion.[C]

C. Coral underlying Coastal Limestone from Rottnest Island, has been dated radiometrically as 100,000 ± 20,000 years (Teichert, 1967). Teichert attributes the whole of this formation to the Last Glacial low sea level on this evidence, but the composite nature of the Coastal Limestone renders such a simple ascription unconvincing.

Whatever their age, the terrestrial calcareous sands of Australia's western and southern coasts have been subjected from the moment of their emplacement to the elements, which have simultaneously consolidated and karstified them. The climatic conditions governing the geomorphological processes range from almost tropical to the verge of cool temperate and from semi-arid to humid, with either a well distributed regime or a winter concentration. In addition to their direct influence, these climatic differences are significant indirectly through their effect on the runoff from adjacent impervious rock areas. Certain climatic elements of the areas to which most reference will be made are set out in Table 3.

Natural vegetation varies with climate. Now largely cleared, King Island had its dunes and dune limestones covered by open eucalypt woodland or boobyalla - manuka shrubland. In South Australia, the sands carried coastal wattle and boobyalla shrubland with mallee-broom-bush and mallee-heath on the calcarenites. A greater range in type occurred in the Southwest of Western Australia with its strong decline in rainfall northwards. In the high rainfall of the south, wet sclerophyll forest with karri covered the calcarenites, with heath-scrub, including peppermint (*Agonis*) and blackboy (*Xanthorrhoea*), on the sands. Northwards dry sclerophyll woodland replaced the wet sclerophyll forest but in the areas north of Perth heath-scrub still dominates nearly the whole coastal limestone belt.

TABLE 3

REPRESENTATIVE CLIMATIC DATA FOR SELECTED AEOLIAN CALCARENITE AREAS

AREA	MEAN DAILY TEMP °C			MEAN ANNUAL RAINFALL MM	KOPPEN CLIMATIC TYPE
	JAN	JULY	ANNUAL		
King I.,Tasmania	16	11	13.5	700-1000	Cfb
Southeast Province, South Australia	18	10	14	500-750	Csb
Kangaroo I., South Australia	18	12	15	500-630	Csb
The Southwest, Western Australia (Augusta -Dongara)					
(a) South	18.5	14	17	900-1150	Csb
(b) Centre	23	13	18	750-900	Csa
(c) North	24	15	19.5	500-750	Csa

LITHIFICATION AND SOLUTION PIPE DEVELOPMENT

When vegetation has fixed calcareous dune sands, the downward percolation of rainwater becomes an effective lithifying agent. 'Biological' carbon dioxide from root respiration, vegetal decay and soil micro-organisms greatly magnifies the aggressiveness of rainwater which contains only moderate amounts of this gas when it reaches the ground surface. Acidic percolation water leaches surface layers of calcium carbonate and deposits it lower down, cementing the loose sand grains with a calcite matrix. The mechanism of precipitation of the carbonate in the dunes does not seem to have been closely investigated. Negative variations in CO_2 content in the air in voids in the dune sand could cause such precipitation but it is not known whether such variations occur. Capillary rise of soil waters through the drying out of the surface could certainly result in evaporation and the precipitation of carbonate, but capillary rise of this type is thought to operate only over very short distances and close to the surface. More important may be the simpler process of the retention of thin films of water around sand grains through surface tension as water descends to the groundwater table and the subsequent drying out of such carbonate-rich films.

In the early stages of consolidation, at least, much of the precipitation of calcium carbonate takes place along roots (Fletcher, 1934). This is evident from sections in partially consolidated dune sand, e.g. in coastal cliffs, blowouts or road cuttings, where very often branching calcite bodies are freed of the loose sand between and can resemble dense thickets as Darwin (1845) observed (Pl. 8). Darwin and others claimed that calcite has also accreted round and replaced stems and trunks of vegetation buried by the incoming sand. This idea fostered the appellation given to the so-called 'petrified forests' e.g. near Seal Rocks, King Island. Boutakoff (1963) has maintained that this second process does occur in the Portland area of Victoria. However secretion round the roots of vegetation growing down into the sand seems to be more common.[D]

D. Blackburn et al. (1965) give a valuable discussion of pipes in the calcareous dune ridges of the Southeast of South Australia. They dispute interpretation in terms of buried tree trunks because of the rounded bottoms of pipes and regard them as due solely to solution under gravity with soil infill following. They correlate maximum depth of soil pipes with both relative ages of dune ridges and depth of caprock.

Consolidation proceeds from the building of this more resistant framework within the sand to the overall lithification of layers and ultimately of the whole bodies of dunes. Sections frequently show that lithification of an horizon parallelling the surface or of the surface layer itself is succeeded downwards by less consolidated sands; for this frequent development the term 'caprock' has long been used and 'kankar' more recently. The common process seems to be one of case-hardening, accompanied by some loss of volume and reduction in vigour of dune form.

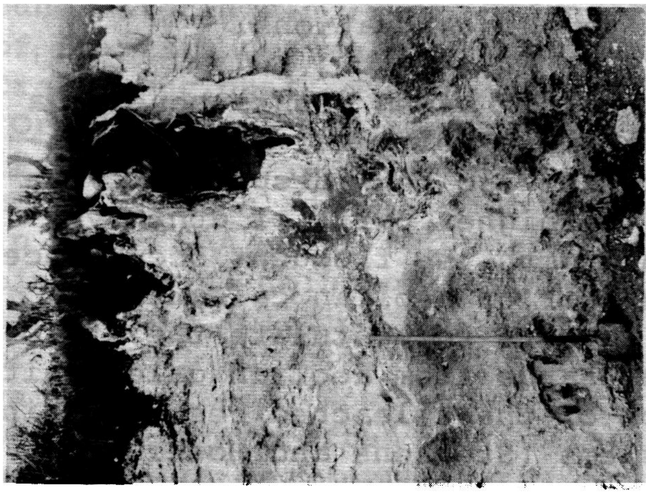
Caprock has not in general developed in the zone of oscillation of the water-table, either seasonal or longer term. In the Augusta caves area of the Southwest of Western Australia, the considerable depth to the water-table and its very flat nature there preclude such an explanation (D.C. Lowry, pers. comm.). Moreover the caprock has quite strong relief in many areas whereas water-tables in dunes generally have the form of broad gentle domes (e.g. Willis et al., 1959;

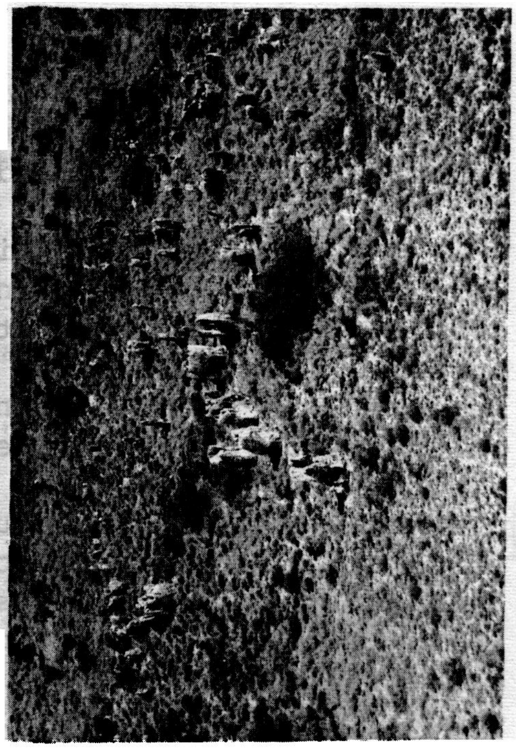
Bottom left - PLATE 7. Two aeolian calcarenites, each cross-bedded, separated by a buried rendzina soil at Hamelin Bay, Western Australia.

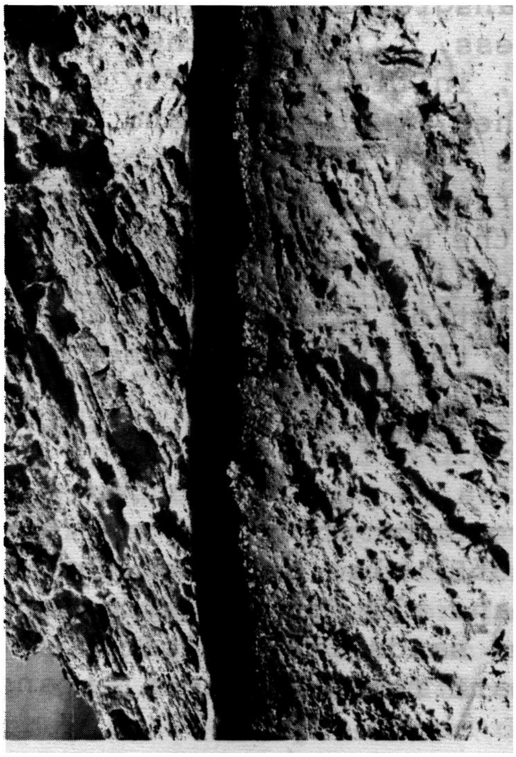
Bottom right - PLATE 8. 'Calcareous branching bodies' such as Darwin described in 1845. In partially consolidated calcareous dune sands at Green Head, Western Australia.

Top left - PLATE 9. Three stages of solution pipe development near Cape Leeuwin, Western Australia. The right hand one shows the rendzina soil fill with living roots and the calcrete surround and prolongation

Top right - PLATE 10. The Tombstones north of Jurien Bay, Western Australia. Calcrete or kankar walls of solution pipes remain standing after wind removal of surrounding unconsolidated sand. (By courtesy of West Australian Newspapers Limited).







Ranwell, 1959). Only in waterlogged hollows does the groundwater reach the surface periodically and caprock formation is not confined to such situations.

Compacted dune limestone often occurs beneath a soil cover e.g. in the innermost belt near Augusta mentioned above; however it can also be widespread at the surface, especially over the higher parts of dune systems. This fact, combined with the frequent occurrence of siliceous dunes in the rear of aeolian calcarenite systems, has led several authors to postulate the stripping of residual siliceous sands from aeolian calcarenite cores and the accumulation of these leached residuals inland as separate dune systems (Stephens and Hosking, 1932; Crocker, 1941; Boutakoff, 1963). Since many of these siliceous dunes form ranges parallel to the seaward calcareous dune ridges, it seems unlikely that these are secondarily derived since transgressive systems are to be expected from such a process. Instead they are either earlier primary dunes, initially chiefly calcareous but now very deeply leached, (Macarthur and Bettenay, 1960) or primary dunes always of siliceous composition (Jennings, 1959). The occurrence of compacted dune limestone at the surface in the more seaward belts can then be regarded as due to local deflation and short distance transport to accumulation sites in nearby dune hollows.[E] The net result on the latter hypothesis is a loss of original steepness and sharpness of individual forms but little loss of sand from a given dune system as a whole.

E. Blackburn et al., (1965) also consider that the siliceous sands are by no means all derived from long distance transport of leached sands from calcareous dune ridges seaward but in part represent local transportation.

Closely related to the process of lithification is the problem of 'solution pipes' in these calcareous dune materials. Under this name are included a range of features resembling the 'solution pipes' of the Cretaceous chalk of W. Europe (Kirkaldy, 1950), the '*Orgelpfeiffen*' in tougher, more compacted limestones (Penck, 1924), lapies wells (Cvijic, 1924) and open potholes in such rocks. But they also differ from them in important ways, for instance in their lack of association with joint planes, and in the fact that they are not solely solution phenomena. They are cylindrical or conical forms, either soil-filled or hollow, and of varying size. Most often described from the coast, where they are often seen in section and are to be measured in decimetres to at most a few metres e.g. at Point Peron, Western Australia (Fairbridge, 1950), they also occur inland, where they are known up to the size of Arumvale Pipe, which is an open pipe 27 m deep.

This variety itself suggests that more than one process is involved but individual occurrences show this also. Thus in a road quarry in young and only partially consolidated dunes on the west coast about a kilometre north of Cape Leeuwin is a series of pipes filled with black humus-rich rendzinas and much penetrated by the roots of scrub growing in the dune surface (Pl. 9). The pipes vary from short, blunt cones projecting downwards from the general soil cover to irregular cylindrical forms of somewhat greater length up to about 2.5 m long. These pipes are defined by a surround cemented by secondary calcite, which forms a much more consolidated envelope than the lightly consolidated sands into which the whole features are inset. This envelope sometimes projects farther down than the soil-filled pipe itself but roots in some cases penetrate this solid continuation. It is hard to envisage a mechanism whereby hollows developed first, to be filled later with soil and penetrated by roots; a simultaneous development of all elements is indicated. Root growth down into the unconsolidated sand provides aggressive solutions which preferentially leach the calcareous material around them. This produces a greater depth of soil along the pipes, extends their length and causes precipitation of calcite around to form the walls. In the earlier stages at least, this association of pipe, soil and walls is a syngenetic one.

Hollow pipes occur in two main kinds of situation, coastal and inland. Along the coast open pipes occur chiefly within the spray zone and the passage of much of this spray as well as rainwater seepage through soil and rock would seem to have been responsible for the evacuation. Some of the topsoil may have been stripped in these exposed positions by aeolian erosion to promote the removal downwards by percolation of corrosive waters. Enlargement by spray and rain would follow evacuation of the soil fill.

Inland open solution pipes seem to be associated with caves. They usually narrow downwards and then open into cave chambers normally at roof level, as in the natural entrance to Jewel Cave. Arumvale Pipe already mentioned is 3 m by 2.5 m at the surface and slightly angular through fracture but this form is quickly replaced downwards by a smooth rounded tube, 2.5 m in diameter to begin with but reducing to 1.5 m at the bottom where it opens laterally into a cave about 100 m long. Easter Cave, Augusta, has three solution pipes close together leading from the bottom of a do-line into the roof of its entrance chamber about 8 m below. There is a large flowstone and earth pile beneath the pipes but it is chiefly composed of soil which the pipes have fed into the chamber, not of rock debris.

Further on in the cave in the 'Chamber of Tresses', is a similar pile of earth and flowstone, which in this instance leads upwards into a pipe in the caprock some 3-5 m before a complete soil blockage is met. The 'tresses' to which the chamber's name refers are tree roots, some of which come down the pipes.

F. Since this paper was prepared, Lowry and Bain (1965) have described the main pipe here as 'travertine-lined' i.e. differentially cemented.

Whether these deeper pipes are due mainly to solution of the caprock after consolidation or developed from top to bottom during lithification by the combination of leaching along a descending water thread through the sand and associated cementing of the surround is uncertain. In the well forested part of the dune limestone in the Southwest of Western Australia, it is evident from many caves that large tap roots of such trees as karri and tuart commonly pass through solution pipes into cave chambers below e.g. one of the Easter Cave pipes mentioned above has a karri taproot along it. There are the two possibilities (a) that the taproot followed a pre-existing, soil-filled pipe downwards or (b) that the growth of the taproot has proceeded *pari passu* with the downward extension of the pipe and that the root has guided water down the developing pipe. It must be remembered here that with forest trees a substantial proportion of the precipitation falling on the crown is carried down the trunk and seeps into the soil immediately around the stool with a possible concentration of subsurface moisture beneath the trees. Root respiration and organic acids associated with roots would increase the aggressiveness of water seepage down the root. Fine growing roots can be seen in Lake Cave, Witchcliffe in sand nearly 60 m beneath the surface; many similar instances at lesser depth can be seen in this area, showing that the possibility that root development accompanies and promotes solution pipe development is a real one.[G]

G. Lowry (1967) has cast doubt on this process of concentration of vadose water by trees but does consider root 'exudates' important in the attack on the limestone.

Surface exposures of caprock often show former solution pipes largely or completely infilled by concentrically disposed calcite. Gentilli (1963) has suggested that the pipes developed beneath the surface in a 'humid phase' and the infilling in a succeeding 'dry phase'. It is not clear whether Gentilli means substantial phases of climatic history or short term phases of season and of weather. Fresh sections in young, soil-filled, small pipes such as those near Cape Leeuwin mentioned above certainly give the impression that leaching and precipitation are both going on at the present time and favour a theory of short term phasing in their development. There is in fact no reason why leaching and precipitation should not be going on simultaneously in close proximity.

So instead of the familiar solution phenomena along joint intersections, characteristic of older limestone compacted long before their development, solution pipes in aeolian calcarenite are involved also in the process of lithification through precipitation of calcite along the walls of leached passageways through the sands.

Root growth both promotes and is promoted by pipe development. Furthermore mechanical evacuation of deep pipes of their soil and sand fill can accompany cavern formation below.

A different aspect of the solution pipe phenomenon is found in the limestones north of Jurien Bay in the coastal plain of the Southwest of Western Australia. The Tombstones, which are as much as 2 m high, represent the calcite walls of solution pipes, standing free at the surface through the removal of the surrounding unconsolidated sand by wind transport (Pl. 10).

It is possible that joints as opposed to bedding planes are not as completely lacking from aeolian calcarenite as this account so far might suggest. Where caprock is exposed over substantial dune surfaces, not only the projecting tops of partially or entirely calcite-filled solution pipes are to be seen but also linear, narrow ribs, a few centimetres high and several metres long, with cracks along them. These are suggestive of accentuated lithification along a joint produced at an early stage in consolidation perhaps through differential leaching in neighbouring sand masses. Such incipient joints would promote both flow and calcite precipitation along themselves.

Where caprock is exposed directly to rainwater solution at the surface in conditions of little or no disturbance of the natural vegetation e.g. in the heath-scrubs north of Perth, the characteristic result is a quite irregular corrosional pitting. Only very occasionally are there to be seen poor incipient *Rillenkarren* (solution flutings) e.g. around collapse dolines on the top of the dune ridge northwest of Stockyard Gully Cave. Similar absence of gravity-controlled rainwater solution features has been attributed to low rainfall in the Nullarbor Plain (Jennings, 1963) but here the rainfall seems to be too great and too well concentrated seasonally for this explanation to apply. This is supported by the fact that the caprock shows the same surface characters where it is exposed between open canopy woodland on the intermediate dune limestone belt in the Deepdene-Augusta area of the Southwest where rainfalls are quite high. The corrosional irregularity may have its origin in the porosity and the irregular lithification in detail of the calcarenite. Artificial removal of soil cover from the oldest calcarenite near Jewel and Moondyne Caves, Augusta, has exposed smooth subsoil solution surfaces in solid caprock. This might be attributable to greater consolidation were not similar smoothed subsoil surfaces including *Rundkarren* (rounded solution grooves) and *Kluftkarren* (grikes or solution slots) found over the roof of Aiyennu Cave and around Moore's Cave, both near Stockyard Gully Cave, in the same calcarenites mentioned above as carrying incipient *Rillenkarren*. It seems instead that subsoil solution is less sensitive to minor differences of lithification than rainwater solution, which etchs them out.[H]

H. It is apparent from illustrations in Blackburn et al. (1965) that this account of Karren applies also in the Southeast of South Australia. They also note vertical joints in the caprock.

DRAINAGE

When rain falls onto incoherent dune sands, it usually fails to produce surface runoff. In the case of calcareous sands, this condition persists into the later phase of conversion into limestone.

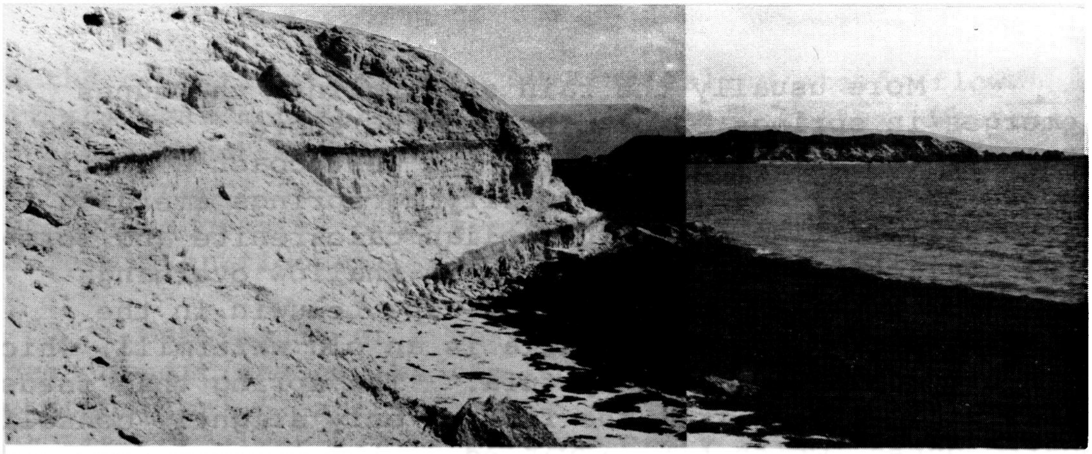
An exception is provided by certain calcareous dunes near Eyre on the Roe Plain south of the Nullarbor Plain. Here amidst a broad field of mallee-covered dunes of normal form, vertical air photographs revealed a small number of ridges with a herringbone pattern due to gullying on both flanks. Field examination of one of these, not the most extreme, showed there were shallow, widely flaring gullies, with active linear incision above and fan deposition below. The only instance of a comparable nature known to the author is in ferruginised and partly consolidated quartz dune sands, recorded by Coaldrake (1962) in the Teewah Sands of South Queensland. In the examples in calcareous sand, this gullying may be related to a particular intermediate stage of consolidation, which is sufficient to prevent the immediate percolation characteristic of incoherent sands and produce some concentration of surface runoff but not enough to provide the resistance to erosion presented by caprock. However, this hypothesis is open to the objection that such an intermediate stage of consolidation should occur widely, and provide plenty of examples of this kind of dune form, whereas this one area is all that is known so far.

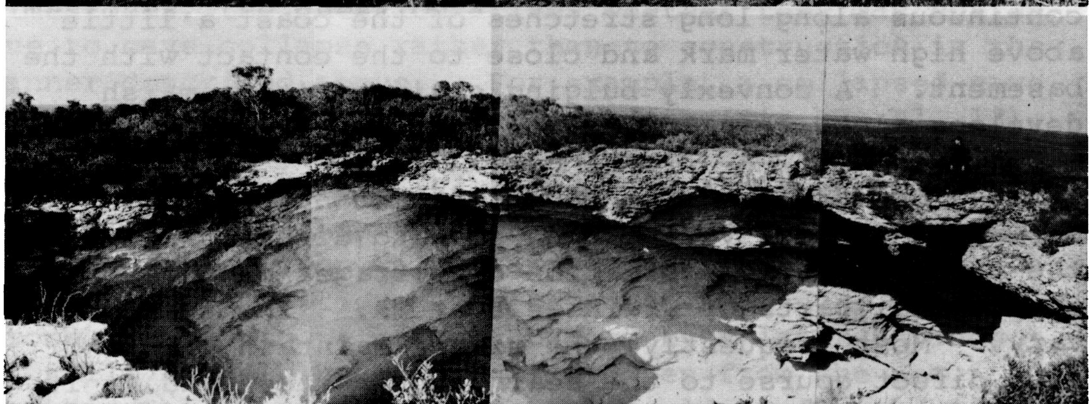
Climatic conditions and basement topography can combine to produce other exceptions. Thus the calcareous dune sands and aeolian calcarenites of King Island have a rather high effective precipitation for such areas in Australia, and here some swampy watercourses such as Boggy Creek are found within the west coast dune belt. In the case of Boggy Creek it is probable that a bedrock valley buried beneath the dunes helps gather underground flow, which gives rise to a short surface river course near the coast where the basement is not far beneath the surface. At the coast this stream has built a sequence of rimstone dams (Pl. 14) from about 3 m above high water mark down to levels between tidemarks (Jennings, 1956).

Top - PLATE 11
Aeolian calcarenite cliffs with two buried soil horizons at Hamelin Bay. Hamelin Island also of Coastal Limestone in background.

Centre - PLATE 12
Deepdene near Karridale, Western Australia. On the eastern (left) side aeolian calcarenite cliffs rise 60m. The crystalline basement outcrops in the channel of Turner Brook, which flows through the gorge to the sea which can be seen in the distance.

Bottom - PLATE 13
Collapse doline in crest of aeolian calcarenite ridge near Stockyard Gully, Western Australia. The caprock overhangs all round penetrated by solution pipes (bottom left), whereas unconsolidated crossbedded sands below are recessed.





More usually the rain soaking into the dunes emerges in springs on or close to the shore. In King Island, the Dripping Wells, on the west coast a little north of Boggy Creek, are petrifying springs emerging from a low marine cliff in aeolian calcarenite and forming stalactites and stalagmites in shallow overhangs (Pl. 15). Again just north of Cape Leeuwin in the Southwest of Western Australia is an old watermill, which has been cemented solid by tufa. The spring that feeds this mill emerges from the foot of only slightly consolidated dunes, which have advanced up the seaward face of a bedrock ridge; this spring's supply comes entirely from percolation into the dune surface. Percolation into dunes is general over their surface but exsurgence is usually localised in springs such as these examples discussed. Whether these springs are localised by bedrock topography beneath the dunes or whether they are linked to the development of joint planes in association with lithification of the incoherent sands is a matter for investigation. Along the west coast of King Island, the basement topography judging from its outcrop along the shore below the dunes seems to be part of a well planed erosion surface; as a result outflow can be continuous along long stretches of the coast a little above high water mark and close to the contact with the basement. A convexly bulging strip of 'tufa-marsh' develops along this line (Jennings, 1959).

Of more frequent occurrence than the complete burial of coastal valleys and seaward directed slopes is the tendency to the formation of barrages or dunes across the coastal parts of drainage systems. The consequences vary. Most frequently, the rivers maintain a more or less direct course to the sea, removing the sand as it blows into their channels. Big discharges and uniform regimes favour the preservation of previous courses.

In the climatic conditions of King Island steady flow all the year round is the more important factor, whereas in a case such as the Hill River well north of Perth maintenance of its course despite the emplacement of successive coastal dune systems has depended on few but large winter floods.

One result of a persistent surface course in these conditions can be the building of 'gorges of construction' (Jennings, 1957). Thus in King Island, the Ettrick River and Badger Box Creek flow through the dunes in steep-walled valleys up to 60 m high; these walls are not the result of river erosion but of aeolian accumulation on either side whilst sand blown into the river was removed.

On gently inclined coastal plains, though a surface course may be maintained, lateral deflection of the river is usually involved e.g. Seal River, King Island; Serpentine River, and Harvey River., Swan Coastal Plain, Western Australia.

Where gorges are found in consolidated dune limestones, the question arises whether they may not be due to cave collapse rather than to construction in the manner described above. For example, a collapsed cave origin may be considered for Deepdene (Fig. 8, Pl. 12), a cliffed valley through which Turner Brook reaches the sea in the southernmost sector of dunes along the Cape Naturaliste-Cape Leeuwin coast. But certain features of the physiography tell against such an interpretation. East of Deepdene there is a broad belt of dune lime-stone, though it is largely buried by a later advance of still largely unconsolidated dunes from the sea. In this calcarenite there is a long line of high cliffs up to 60 m high. West of the Brook, there is only a short length of steep wall in consolidated rock and it is also much lower. Bain (1962) has argued that this discrepancy between the two walls tells against a collapse origin. The discrepancy is certainly related to the fact that there is only a small patch of aeolian calcarenite on the western side of the river, surrounded by younger unconsolidated calcareous sand dunes. A depression in these dunes leads round the northern and western sides of this outlier of dune limestone, though it is separated from the sea by the outermost dunes, which in fact deflect the Brook slightly at its mouth. The high eastern Deepdene cliffs extend north of the junction of this depression in the new dunes with the Turner Brook valley. Viewed more generally, the new dunes blocked a gap in the older dune chain north of the Deepdene vicinity. If the older dunes represented by the aeolian calcarenite were formerly continuous across the line of Deepdene, the Brook would have been deflected only a short distance to the north to reach the sea unimpeded. There would have been little to promote the development of a cave, especially a big cave, across the northern nose of the old dune ridge. It seems more probable that Turner Brook persisted in surface flow through the old dunes as they accumulated. After consolidation and some cliffing on their seaward face, the old dunes were later partially swamped by a younger sand invasion, through which the river once more maintained its westward course. Though Turner Brook has only a small catchment, there are other streams in no more favourable climatic conditions and with even smaller catchments not far to the north which have continued to follow their earlier courses through dune barrages e.g. Biljedup Brook and Quininup Brook.

Though streams generally were able to remove the sands tending to block their path, there are cases where the drainage from the interior was unable to maintain a surface course through an accumulating sand barrier.

These streams were blocked and their waters had to pass underground through the dunes. In a climate which is rainy throughout the year such as King Island's only small drainage basins are usually blocked in this way. These circumstances are likely to result in permanent lakes; for example, Lake Flanagan, the largest lake in King Island, is of this type (Jennings, 1957). In the seasonally dry conditions of the Southwest of Western Australia, the pattern is more complicated. In the high rainfall sector between Cape Naturaliste and Cape Leeuwin, conditions are rather like those of King Island. All the large rivers such as Margaret River, Ellenbrook, and Galgardup Brook retained their courses to the coast. A few smaller streams were blocked by the dunes, e.g. Nindup Brook, Breakneck Gully Creek. Swamps and intermittent lakes sometimes developed round the point of entry into the dunes e.g. near Ruddock's Cave. In lower rainfall country such as north of Perth, longer dry seasons and less frequent high stages during the winter season permitted much larger catchments to be barred by the coastal sands, e.g. Namban River. Large temporary lakes may form in such circumstances, e.g. at Stockyard Gully. Farther north still Arrowsmith River flows into a rather more persistent pondage, Arramall Lake, which drains underground.

So allogenic drainage may go underground in this context as in the more usual karsts in marine limestones. In the case of the latter, however, there is the possibility to be reckoned with that initially the allogenic streams flowed across the karst concerned and the disappearance developed later. In the case of the coastal dune limestones this kind of evolution is not involved.

As with the rain waters percolating vertically into the dunes, the waters entering laterally as drainage from neighbouring impervious rock terrain emerge for the most part either on or close to the shoreline. Thus, in King Island the Lake Flanagan waters reappear at The Springs, resurgences in collapsing loose sand a few yards from high water mark on the coast about 1.5 km to the west of the lake (Fig. 9). Along the Cape Naturaliste-Cape Leeuwin coast in Western Australia many springs on or near the shore are plotted on the parish maps; some of these must represent the resurgences of drainage entering the inner margins as well as exsurgences such as the Cape Leeuwin water mill spring. No such connection has yet been proven, however, although fluorescein testing has shown that the stream in Calgardup Cave at the inner margin of the dune limestone near Witchcliffe flows to Connolly's Cave about a kilometre and a half to the west and this in turn lies fairly close to Bob's Hollow Spring not many metres from the shore. It is likely that Nindup Creek and the stream entering Ruddock's Cave emerge here also. Bob's Hollow Spring rises at the foot of an aeolian calcarenite cliff about 6 m above high water mark, a height corresponding with that of an emerged marine platform just to the north. Along other stretches of the coast the dune limestones extend below sea level and there is the additional possibility of submarine springs; none has been reported as yet however.

Spring recession producing 'steepheads', characteristic karst features, has not yet been noted in Australian dune limestones, though a possible relict case is discussed below.

CLOSED DEPRESSIONS AND SOME RELATED FEATURES

In more usual kinds of karst, closed depressions are the product of karst processes, though in glaciated areas rock basins due to glacial scour can complicate the picture (Jennings, 1960). In calcareous dune systems, closed depressions occur as initial features due to the inequalities of aeolian accumulation. These persist through the lack of surface drainage, which would tend to produce integrated slope and thalweg systems. Even after leaching and lithification has greatly subdued the initial aeolian forms of dune country, the primary closed depressions remain significantly different in form from closed karst depressions. Broad inter-foredune swales and the axial hollows of parabolic or U-dunes are primary forms, which remain recognisable after considerable time has elapsed and much sharpness of form has been lost. Thus Strong's Cave is situated in a former U-dune axial hollow in the oldest aeolian calcarenites of the Cape Naturaliste-Cape Leeuwin sector of the Southwest.

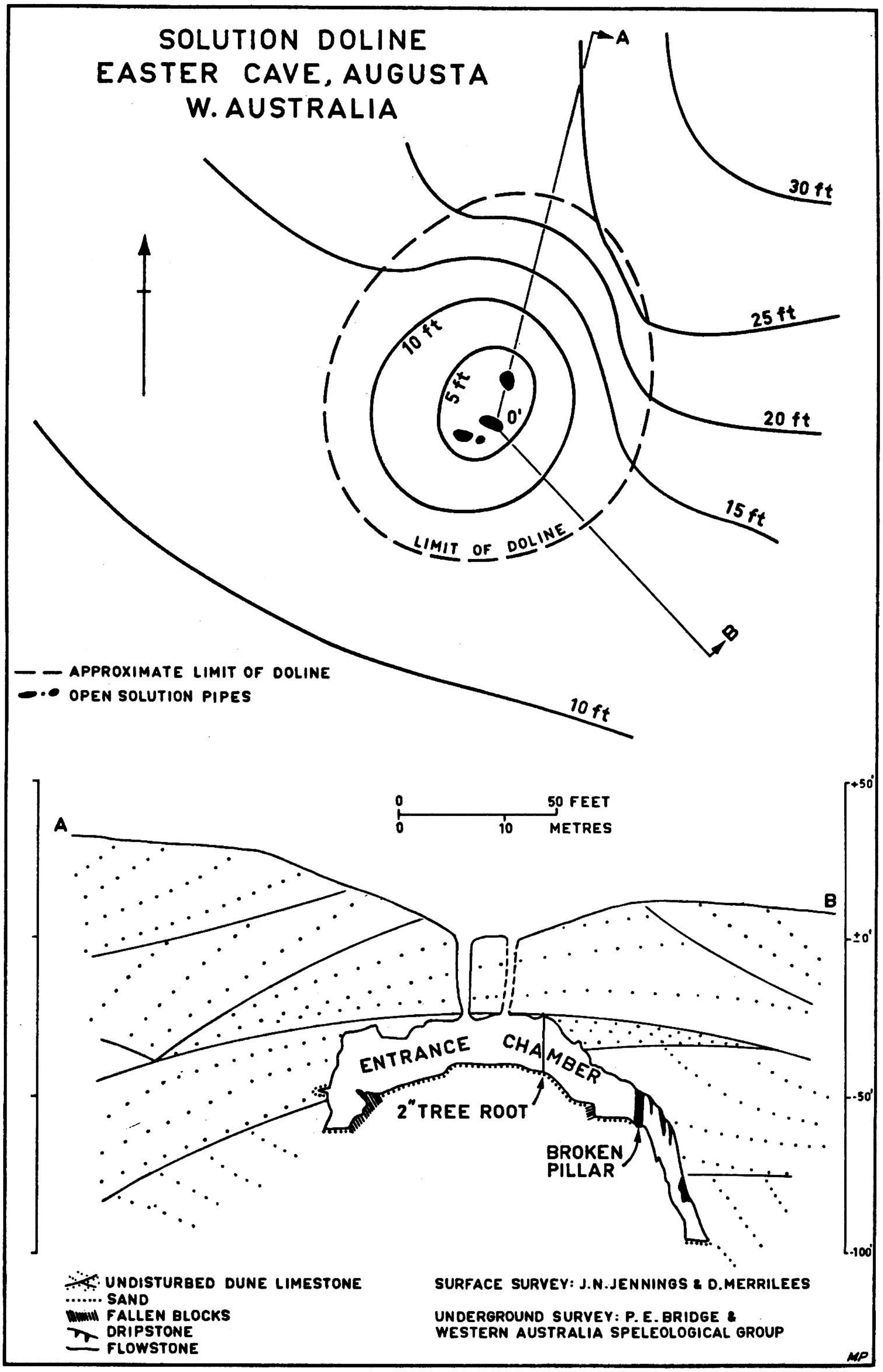
Superimposed on these primary forms are distinct features of karst origin. Thus in the Southwest of Western Australia there are solution dolines, collapse dolines and certain elongated collapse features. These are all found, of course, in old lithified dune systems,[J] at least to the extent of having a crust of 'caprock'. A corollary is that they are completely absent from King Island, where aeolian calcarenites are nearly everywhere buried by later dunes as yet unconsolidated.

J. Blackburn et al. (1965) map the distribution of closed depressions in the Southeast of South Australia; they occur in several dune ridges but mainly more inland ones.

In the Southwest, the solution dolines known to the writer are all small in size; such are found associated with Easter Cave, Jewel Cave and Labyrinth Cave near Augusta. The Easter Cave example may be cited in more detail (Fig. 3, Fig. 10; Pl. 1). Breaking a gentle slope, it is asymmetrically conical, being about 4 m from bottom to lip on the downhill side and about 7.5m on the uphill. In plan it is 35 m wide downslope and 29 m wide across the slope. From the base of the cone, three solution pipes lead down through undisturbed caprock into the initial chamber of Easter Cave. The smallest of these leads a taproot into the chamber though there is no tree directly above. The sides of the doline are almost entirely soil covered as is the general surface of this oldest dune system of the Southwest. There seems no reason to exclude the possibility of such solution dolines developing *pari passu* with the solution pipes and with the caprock. A more likely sequence may be the formation of the caprock and pipes with a soil fill first, then subtraction of the soil fill into a cavern below. The promotion of soil movement to the pipes would accompany and follow this, so bringing the surrounding top surface of the consolidated calcarenite nearer to the surface proper and subjecting it to greater subsoil solution; this concentration of solution would result in the development of a conical hollow in the caprock. **K**

K. Recently Lowry (1967) has augered around this doline and found that it is not a solution doline as proposed here; the depression is actually in a thick soil cover and the surface of the caprock in fact rises towards the pipes. This depression is due to soil slumping down the solution pipes. Other conical dolines in the vicinity are probably similar in origin. They do not fall easily into existing terminology and is proposed here that they be called 'soil subsidence dolines'.

FIG. 10


SOLUTION DOLINE
EASTER CAVE, AUGUSTA
W. AUSTRALIA
A
30 ft
25 ft
20 ft
15 ft
10 ft
5 ft
0'
10 ft
LIMIT OF DOLINE
B
APPROXIMATE LIMIT OF DOLINE
OPEN SOLUTION PIPES
10 ft
0 50 FEET
0 10 METRES
A
B
+50'
±0'
-50'
-100'
ENTRANCE CHAMBER
2" TREE ROOT
BROKEN PILLAR
UNDISTURBED DUNE LIMESTONE
SAND
FALLEN BLOCKS
DRIPSTONE
FLOWSTONE
SURFACE SURVEY: J.N. JENNINGS & D. MERRILEES
UNDERGROUND SURVEY: P. E. BRIDGE & WESTERN AUSTRALIA SPELEOLOGICAL GROUP
MP

Collapse dolines are not characteristic of this belt of low relief in which these Augusta caves are found, though the Big Hole within the belt is more of a collapse doline than a solution doline, both processes contributing to it. The Witchcliffe cave area, a little further north but still within the high rainfall belt, has the most prolific development in the Southwest of collapse dolines, both in number and size. The entrance to Lake Cave may be taken as representative and not an extreme case. It is about 45 m across and has nearly vertical to overhanging cliffs. On one side the cliffs are only some 7 m high above the top of a long talus slope which leads down to the base of stalactite-clad cliffs about 28 m high on the far side, whence access is to be had to the descending cave passage. Strong's Cave has a much smaller and asymmetrical collapse doline at its entrance. This is at the foot of 8 m cliff on one side with the remaining sides forming an amphitheatre of steep soil covered slopes; a 6 m blockpile beneath the doline leads down into the entrance chamber.

Though more common in the rainier south, collapse dolines are not absent from the drier northern part of the Southwest. A chain of such features in various stages of development are spaced over a line several kilometres long northwest from the beginning of the Stockyard Gully cave system. Right on top of the dune ridge northwest of the Stockyard Gully depression is one which appears the freshest and youngest, breaching the dune crest abruptly as if it were a cracked eggshell (Pl. 13). It is round in plan, approximately 25 m in diameter and about 12 m deep. Almost all the way round it, the caprock projects in an overhang of varying width. The recessed lower walls consist of much less consolidated, almost incoherently sandy calcarenite. The form of this collapse doline is thus closely related to the characteristics of this kind of limestone. Between 400 and 700 m to the northwest are four other collapse dolines in various stages of degeneration. The northernmost is oval (60 m by 45 m) and has nearly vertical upper margins only 4-6 m in height, below which talus slopes reach down 7-9 m more. Overhangs are small and only found at the ends of the major axis, which is related to the former underground drainage line. Collapse dolines must clearly postdate caprock development and so are not wholly syngenetic, though clearly the first example mentioned still has characteristics deriving from the fact that lithification is not yet complete.

Certain larger features are closely related to these collapse dolines and also owe their origin predominantly to collapse. Stockyard Gully proper is a short gorge in the dune limestone immediately in front of the first section of the cave, where the river goes underground. It was undoubtedly caused by recession of the entrance arch of the inflow cave through breakdown. Indeed in 1963 a substantial piece of the entrance lintel of the order of 7 m by 3 m by 2 m fell into the river channel. Beyond the first section of cave, there follows an open sinuous valley, some 10 m deep, the flaring sides of which are mainly of soil or of broken rock; only in parts do the sides culminate in slight cliffs. From one arch to the other at the ends, this valley is about 400 m long and is most readily explained by roof collapse of a cave along its length. It resembles in principle, though not in size, the Rak valley near Postojna in the Slovenian Karst.

Breakneck Gully near Witchcliffe is a short gorge in which a creek disappears underground in a boulder ruckle. It is another but smaller example of arch recession of an inflow cave as at Stockyard Gully.

Boomerang Gorge at Yanchep about 110 km north of Perth appears to be basically due to resurgence head retreat, though it no longer possesses a river and its head now closes in a gradual slope. However, a spring rises at its mouth, feeding into Loch McNess, which occupies part of an interdune swale and drains underground into the next seaward ridge, Gentilli (1963) has pointed to the absence of large collapse blocks in Boomerang Gorge as an argument for gradual 'steephead' development as opposed to general roof collapse along the length of cave.

Nothing akin to the larger kinds of closed depression of the classical karst of Yugoslavia - uvala and polje - has yet been recognised in Australia's dune limestones even in the rainiest parts of the Southwest of Western Australia, At first sight the interdune corridors might well be thought of as suitable loci for the development of poljes by lateral solutional undercutting and there may be the very beginnings of this process in the interdune corridor at Yanchep, in which the artificial Loch McNess has been made. Their general absence, however, may be a result of inadequate time for their formation since the emplacement of the sands. Other possible causes are insufficient material suitable for the formation of alluvial seals, which seem essential to polje formation, catchments which are too small, or insufficiently aggressive waters.

CAVES

Perhaps nowhere else in Australia is there, area for area, such a great array of developed and potential 'tourist' caves as in the Yallingup-Augusta belt in the Southwest of Western Australia. Extensive caves have developed with elaborate calcite decorations (Pl. 17), particularly in the form of straw stalactites and helictites. What is thought to be the world's longest straw stalactite, 7.2 m long, is found in Strong's Cave and others, e.g. in Jewel Cave, fall not far short of this length. These facts give an indication of the propensity of aeolian calcarenite, given suitable climatic conditions, for underground development during lithification because the materials in which the caves are found are far from all being as completely and uniformly lithified as is possible under present conditions, (Simpson, 1906). Indeed quite loose sand is encountered in some cave walls.

Discussion of cave development in the dune limestones of Australia is hampered by the fact that very few of them have been surveyed in sufficient detail for morphological analysis, a notable exception being the Kelly Hills Caves in Kangaroo Island, South Australia (Fig. 7). Nevertheless germinative discussions have been written by Hill (1957), Bastian (1962; 1964) and Bain (1962) and the following account rests heavily on them.

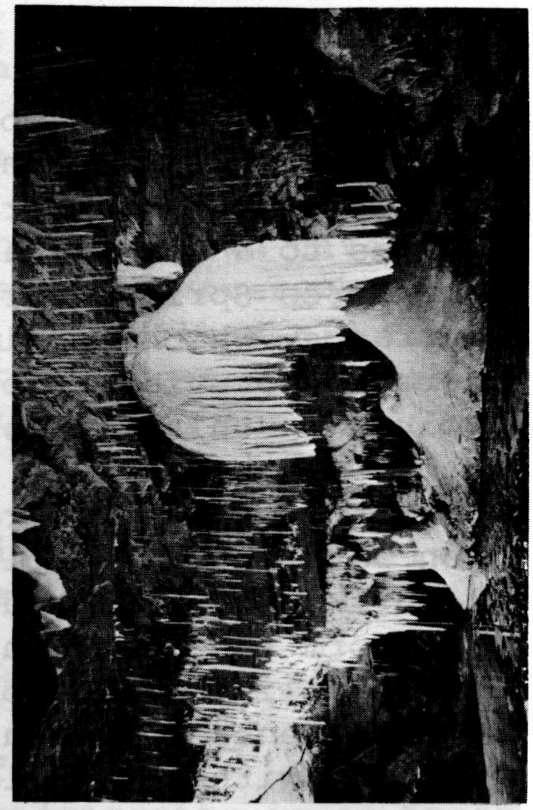
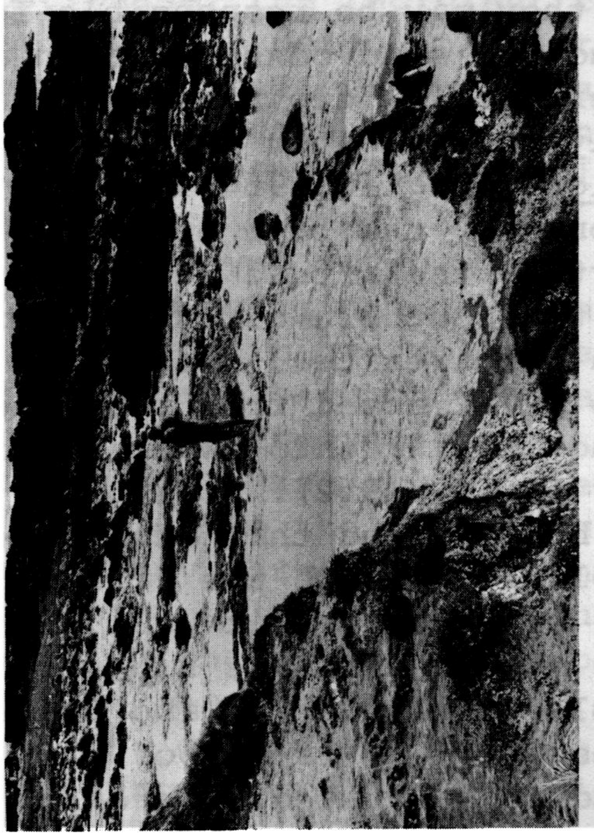
Both Hill discussing the Kangaroo Island caves and Bastian with regard to those of the Southwest of Western Australia have argued that the chief mechanism of cave formation is horizontal solution by water flowing into the dune belt laterally from the inland areas and not vertical solution by percolating rainwater. It is maintained that the high porosity retained after lithification and the absence of joints prevent downward percolating water from concentrating to promote cave evacuation. This point of view exaggerates the absence of joints; as an instance a very large fallen block defined on one side by a joint plane can be cited from Lake Cave, Witchcliffe. It also neglects the existence of solution pipes which can concentrate surface drainage as we have seen and so play a role in cave development. It is true that we are

Bottom left - PLATE 14. Rimstone dams and pools where Boggy Creek, King Island, Tasmania meets the shore.

Top left - PLATE 16. Exit from section of Stockyard Gully Cave, Western Australia. The collapse arching of this linear cave can be seen. The discharge is exceptionally great for this cave; the water's depth is 4 m on either side of the constriction.

Bottom right - PLATE 15. The Dripping Wells, King Island, Tasmania. Springs emerging from calcareous dune sands along the shore have built this cavernous cliff with mossy stalactites and stalagmites.

Top right - PLATE 17. The Judge's Wig and other calcite decorations in Strong's Cave, Karridale, Western Australia. In the foreground is the quartz sand floor of the cave. (By courtesy of D.C. Lowry).


chiefly aware of pipes where they are associated with cave breakdown e.g. the Chamber of Tresses in Easter Cave. However there seems no reason to preclude the possibility of solutional work prior to collapse being fed from pipes to a significant degree. Moores Cave near Little Three Springs north of Perth has a pothole type of entrance, which is simply an enlarged pipe and as yet there is no evidence of lateral stream solution being involved in this cave's formation.

Bastian finds a contradiction in allocating to percolation water the two roles of lithifying the sand into rock on the one hand and removing some of it in solution to form the caves on the other. This neglects the real possibility of seasonal or aperiodic variation in the aggressiveness or saturation of these waters, varying perhaps with the biological activity of the soil and vegetation cover so that they may be responsible for cave evacuation some times and for sand consolidation at others. Moreover these waters could help in cave formation by mixing with laterally moving water of different properties ('*Mischungskorrosion*', Bogli, 1964). The view that caves can be fashioned by the rain of the dune belt itself finds some support by the actual occurrence of the caves near Augusta in the southernmost sector of Cape Naturaliste-Cape Leeuwin calcarenite. Here the underground drainage seems to be directed from the dune belt itself towards its inland margin, into swamps, and thence to the Blackwood River (Bain, 1962). Despite this case, however, it is to be expected that after the dune belt rainwater has percolated through the calcareous mass and gathered into larger waterbodies, it will be much less aggressive than the stream drainage from acid soil country inland. In Table 4, samples 17 and 6 are perhaps indicative in this respect; 17 is a roof drip in Lake Cave, Witchcliffe, and is saturated, whereas 6 from the stream in the same cave remains aggressive, admittedly after a fairly short travel underground from the eastern margin of the dune belt. The fact that most caves are found near the inland margins of the dune belts argues strongly for Hill and Bastian's standpoint. Nevertheless there is the possibility that burial of caves on the seaward flank by younger, unconsolidated dune systems is partly the explanation also. Indeed the absence of any known caves from King Island could be because nearly everywhere younger dunes have advanced further inland than older ones along the west coast where the calcareous dunes occur. Moreover in the Southwest of Western Australia at least one cave - Connolly's Cave, Witchcliffe - is known at a distance of only about 1000 m from the coast. So Hill's and Bastian's views on horizontal and vertical solution need some qualification.

According to Bastian there is a sequence of three phases in the history of the lithifying dune sands with respect to cave formation. During the first phase, the incipient calcarenite is so incoherent that as water percolates laterally through it, any sand removed is replaced by falls from above, and the whole mass settles down and prevents cave formation. Then follows a period when some limited degree of coherence has been achieved. Barely coherent masses fall down and are removed in solution but coherence above is sufficient to permit cavities to form, small at first. In these conditions collapses follow quickly one after the other and cave enlargement is rapid. Bastian envisages that free surface streams are characteristic during this phase of rapid evacuation in semi-coherent material. So the caves are vadose in origin from the start; any phreatic phase has been one of movement through capillaries? in the unconsolidated sands. In the third phase, collapses become less frequent because the rock has become more strongly coherent. They do not cease completely because the cave stream meanders and undercuts part of the sidewalls, causing further wall and roof adjustment.

A possibility which needs to be considered, but for which the writer can offer no field evidence at the moment, is whether or not the development of a cavity with a free atmosphere in itself promotes the lithification on the roof through diffusion of CO_2 from percolating water into the cave air causing carbonate to be precipitated. This is, of course, the chief mechanism of stalactite formation but stalactites impose additional loads on the roof rather than strengthen it. On very steep walls calcite decorations may, however, act as strengtheners in some degree. The high primary porosity of partially consolidated sand may in fact induce a process of internal case hardening.

The dominance of collapse through virtually the whole history of these caves is their most distinctive trait and it is directly a consequence of lithification being accompanied by cave development. It continues to the present since substantial collapse between visits to certain caves have been reported by Bastian and others.

Hill has concerned himself particularly with the collapse process in relation to the Kelly Hills Caves, Kangaroo Island because so much of the system is of this origin (Fig. 11). Only a few shallow, flat-roofed rooms, e.g. Mud Chamber and Bone Chamber show signs of occasional current movement with fresh inwashed mud and water-washed walls about 25 m below the surface; these seem to represent primary solution cavities at the water-table. Most of the system consists of roughly circular collapse domes, 40-60 m in diameter, but with only a few metres separating floors from roofs. At the sides there are frequently cleanly broken fissures at 40-60 as a result of large scale roof fall, which are blocked off by rubble at the bottom; between are arched roofs 10-20 m across in roughly broken rock, with broken material lying below them. Collapse tunnels of lesser diameter link

TABLE 4

WATER ANALYSES FROM THE COASTAL LIMESTONE BELT OF THE SOUTHWEST OF WESTERN AUSTRALIA

No	Name	Date	°C	pH	$CaCO_3$ ppm.	$MgC0_3$ ppm.	State
Streams at entrance to inflow caves							
1	Arramall Cave	22.7.63	14	6.9	47	127	A
2	Stockyard Cave	24.7.63	14.5	(7.1)	12	22	A
3	Ruddock's Cave	29.7.63	12	(4.4)	23	94	A
4	Mammoth Cave	1.8.63	11	(6.6)	30	64	A
Streams in caves near eastern margin of limestone							
5	Calgardup Cave	29.7.63	14.5	(5.8)	12	19	A
6	Lake Cave	1.8.63	16	6.9	124	70	A
Streams in caves well within limestone							
7	White Grotto, Yanchep	6.7.63	19	7.5	122	76	E
8	Mambibby Cave, Yanchep	6.7.63	17	7.4	86	42	A
9	Aiyennu Cave (in flood)	24.7.63	14.5	6.9	13	37	A
Standing pools and lakes in caves							
10	Labyrinth Cave	15.7.63	15.5	7.2	343	501	S
11	Easter Cave	16.7.63	17	8.1	243	157	S
12	Jewel Cave	18.7.63	16.5	7.3	422	32	S
Spring not far from coast							
13	Spring in Deepdene	19.7.63	17.8	7.1	142	86	A
Springs on coast							
14	Cape Leeuwin Water race	16.7.63	14	7.6	224	106	S
15	Bob's Hollow Spring	29.7.63	17.8	8.3	204	110	S
16	Small spring Canal Rocks	3.8.63	18	7.6	284	598	S
Percolating water in cave roof							
17	Drinking Fountain Drip, Lake Cave	1.8.63	16	7.6	318	18	S

A = Aggressive E = Equilibrium S = Supersaturated

pH readings in brackets are laboratory determinations by potentiometric pH meter, carried out because peaty discolouration of the waters made colorimetric determinations in the field uncertain. Calcium and magnesium hardnesses were determined by the E.D.T.A. method.

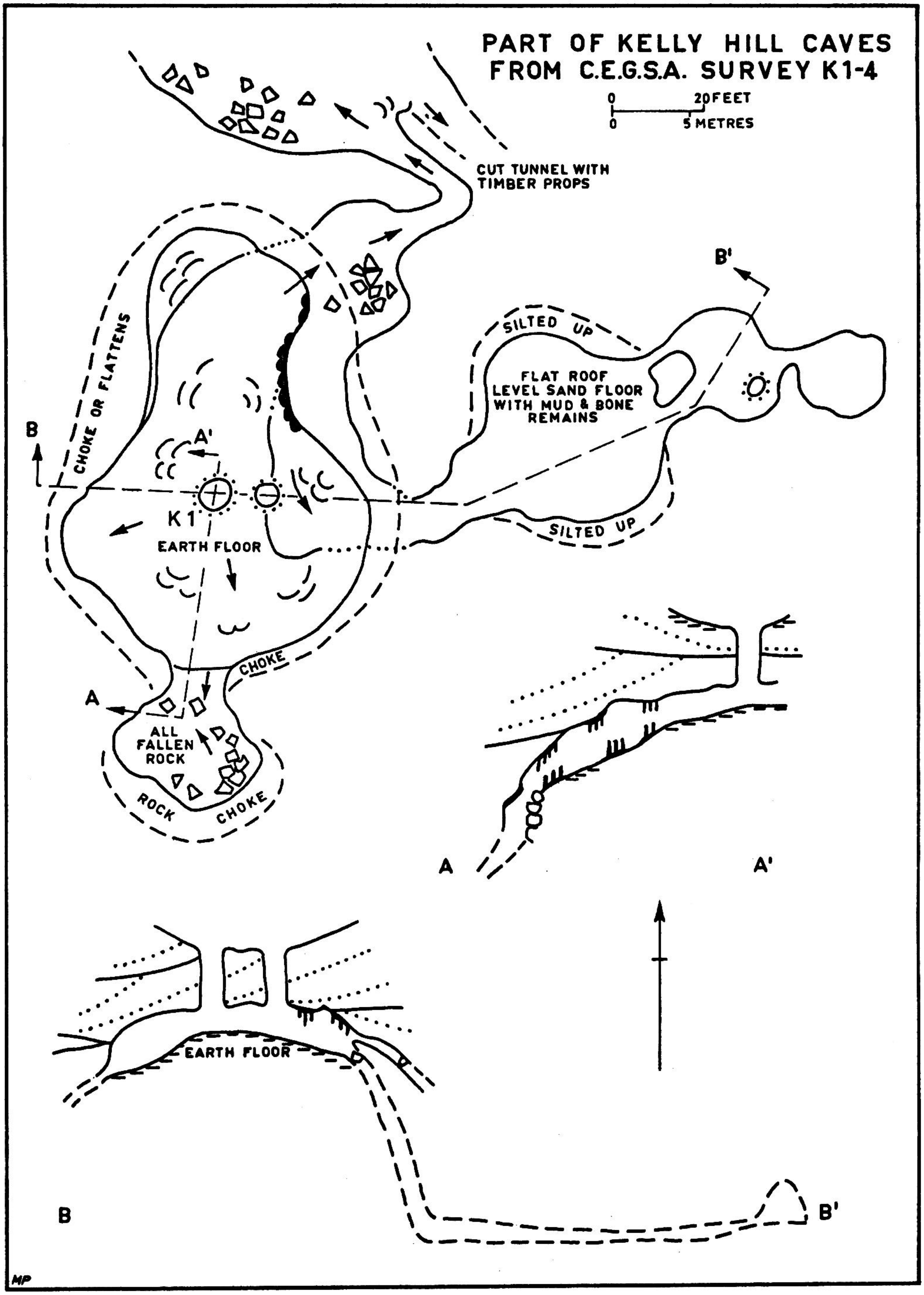
the domes, which are however scattered over a compact area and are not arranged in linear fashion. On the basis of carefully surveyed cross sections, Hill thinks collapse is a two-stage process of tension and shear (Fig. 12). The roof of a flat solution chamber at the water-table is regarded as a complex beam supported by a combination of tension and shear. First of all tension cracks appear towards the top of a tension dome so that this part affords no support. The load is transferred to the periphery where shear stress is increased. This builds up to the critical level of ultimate shear stress and then shear occurs along the periphery as a final stage of collapse. In this way structural stability is achieved for a time at least and the cavity is displaced towards the surface.

This view of Hill's seems to presuppose a more general degree of lithification to permit large masses to collapse together than is involved in Bastian's interpretation. However it would be unwise to presume evolution will be everywhere the same with material as diverse in degree of coherence as the dune limestone.

The two main kinds of caves (Fig. 13) found in the Southwest of Western Australia - the linear and the inclined fissure types - are considered by Bastian more related to hydrological conditions than to variation in the dune limestones themselves.

The linear type e.g. Strong's Cave, Witchcliffe, is a long sinuous, arched cave along a well-defined underground watercourse (Pl. 10). There can be a good deal of height in these caves through removal of substantial amounts of collapsed material and the arching can be more rounded than that found in the domes of Kelly Hills Caves. Rubble piles shift the stream this

FIG. 11


PART OF KELLY HILL CAVES
FROM C.E.G.S.A. SURVEY K1-4
0 20 FEET
0 5 METRES
CUT TUNNEL WITH
TIMBER PROPS
B'
SILTED UP
FLAT ROOF
LEVEL SAND FLOOR
WITH MUD & BONE
REMAINS
CHOKE OR FLATTENS
B
A'
K1
EARTH FLOOR
SILTED UP
CHOKE
A
ALL
FALLEN
ROCK
ROCK CHOKE
A
A'
EARTH FLOOR
B
B'
MP

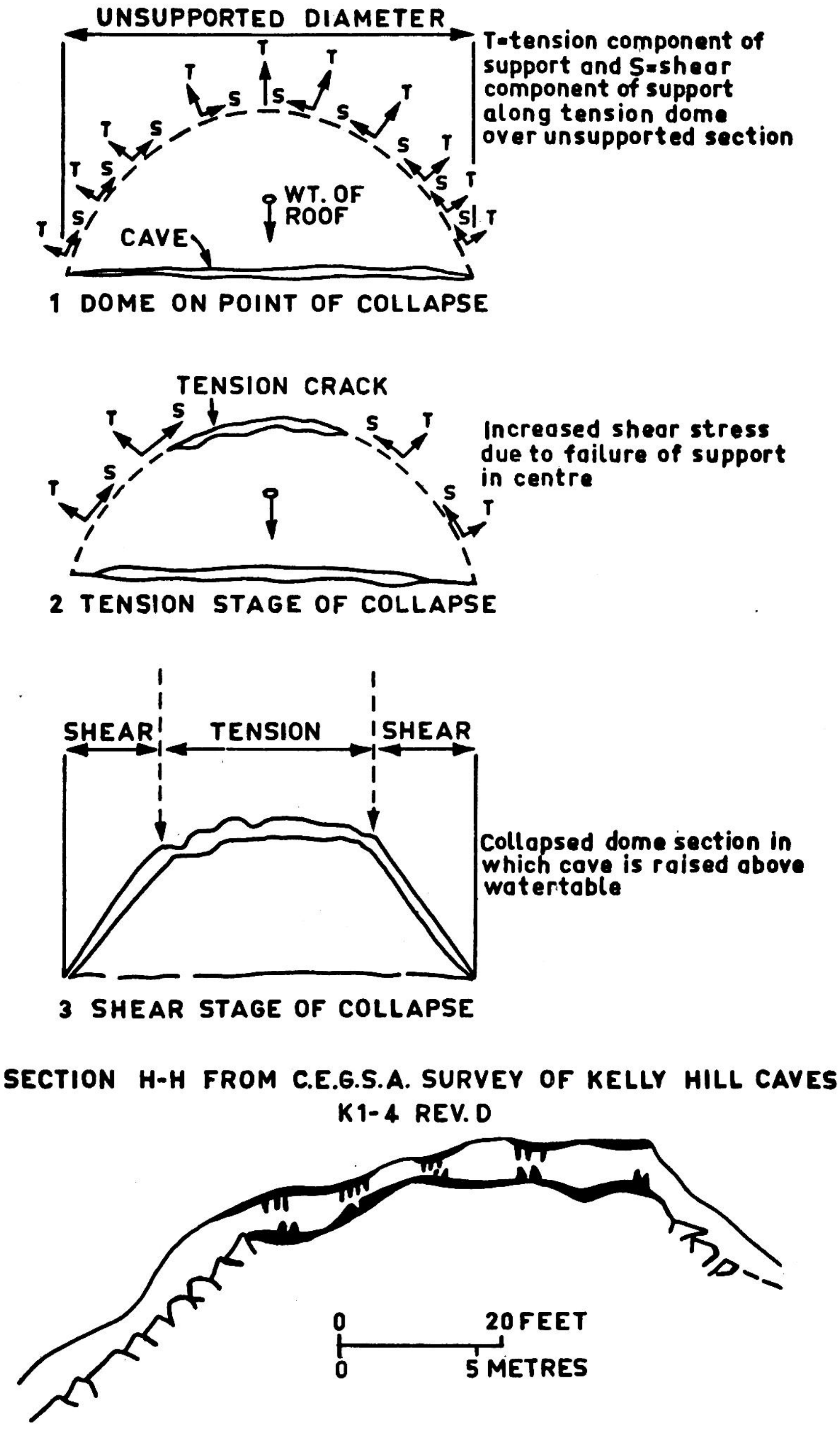
way and that and it is clear in some cases that streams are deflected permanently into fresh channels leaving large dome caverns to a flank. Crystal Cave, Witchcliffe is cited by Bastian in this connection where small tunnels link two domed caverns to an active stream passage on one side. Giants Cave in the same area is a linear arched cave with its floor completely littered with talus; here the stream presumed responsible for it can no longer be reached. In some of these linear caves the impervious basement rock over which the dunes advanced is exposed along varying lengths of the floor e.g. Ruddock's Cave, Strong's Cave, and there is some slight incision into it.

The inclined fissure type comprises generally small caves irregular in plan, normally with no great height and with floor and roof profiles paralleling one another because of the dominance of collapse. The resemblance of such caves to one side of a collapse dome as described by Hill is clear. Where streams are found in them, they are shallow and meandering, with very little gradient, e.g. in Mambibby Cave, Yanchep. Usually several fissured chambers of this type occur in rather unsystematic arrangement and Bastian attributes these characteristics to collapse upon diffuse flow or broad, ill-defined waterways. Such streams may be deflected laterally easily and so large areas of collapse can result.

Since both Hill's collapse domes and Bastian's inclined fissure caves in some degree assume forms which bear resemblance to the original dune shapes, the question arises whether they partly reflect those forms through the guidance of a coherent caprock developing in relation to the dune surface. Such data as are available with relation to this suggest that in this extreme form the hypothesis cannot be sustained. The

FIG. 12

FORMATION OF COLLAPSE DOME IN AEOLIAN CALCARENITE OF KELLY HILL CAVES, KANGAROO I., S. AUSTRALIA ACCORDING TO A.L. HILL



overall pattern of Kelly Hill Caves does not resemble a dune pattern. Nevertheless the contrast in coherence of caprock and core appears to affect cave form in particular instances. Thus several parts of the Stockyard Gully Cave system have very flat only slightly arched roofs, which consist of a caprock zone with weaker materials below.

This is shown particularly well in Aiyennu Cave to the northwest, which is probably part of the same underground river system (Fig. 14; Frontispiece). The main chamber, some 60 m long, 30 m wide and 25 m high, has a thin arched roof, which reduces to a thickness of 1.5-2 m in the centre and is perforated so much by close-set solution holes up to 1 m diameter that it looks like lacework from below. Immediately beneath this well lithified roof of caprock, there is a layer of 3 m of unconsolidated reddish sand containing root concretions; it is in fact a buried soil of the so-called 'terra rossa' type. Beneath an incline on this buried soil, well lithified calcarenites give rise to vertical walls, though there is another soil horizon lower down in parts of the walls.

The form of the very fresh collapse doline on the dune ridge top between Aiyennu Cave and Stockyard Gully Cave, which has already been discussed, is relevant here, since it implies the previous occurrence of a cave of Aiyennu type with its form influenced by caprock above and incoherent sands beneath. Also the entrance chamber to Easter Cave seems to have a caprock above and slip-slope bedding in less consolidated materials forming the walls. R.T. Sexton (pers. comm.) reports that Frosted Floor Cave at Kelly Hills, Kangaroo Island, has a roof congruent with flat bedding in the calcarenites and walls in crossbedded, less coherent materials below, and his survey of Marcollat Cave in dune limestone in

FIG.13

TYPES OF CAVE IN AEOLIAN CALCARENITE IN THE SOUTHWEST OF W.AUSTRALIA ACCORDING TO BASTIAN (1964)

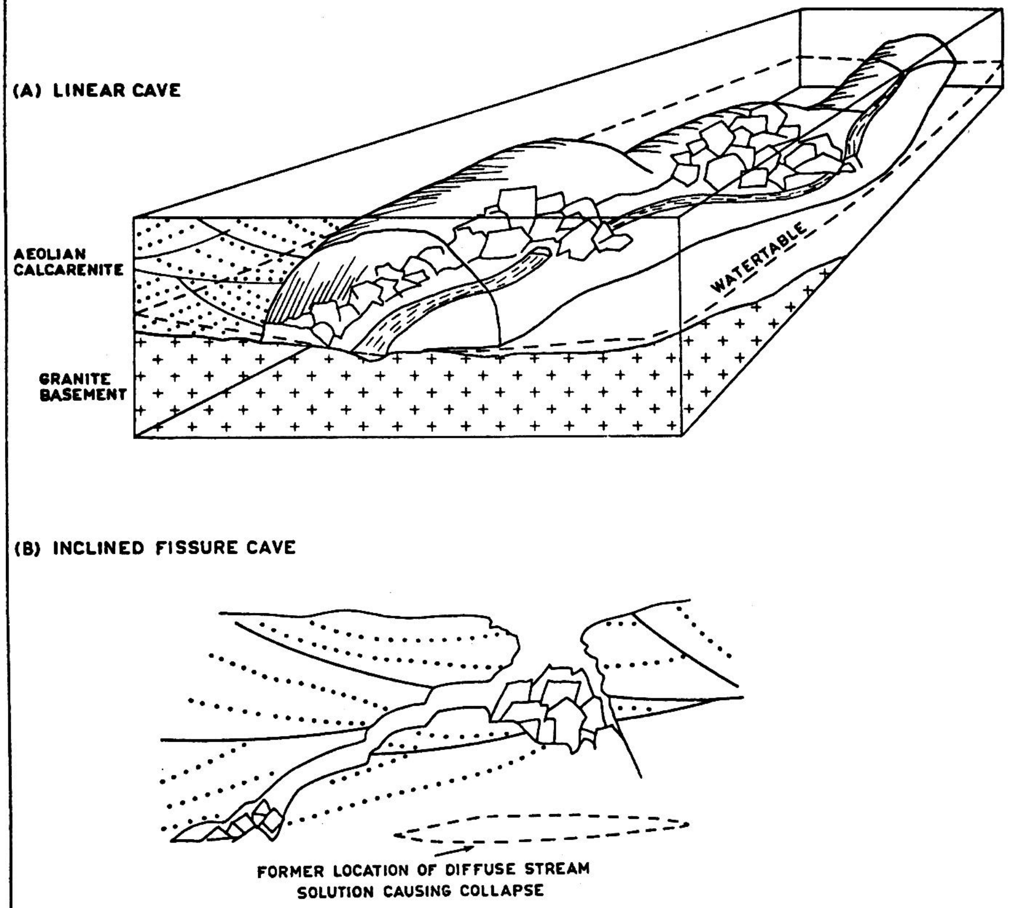
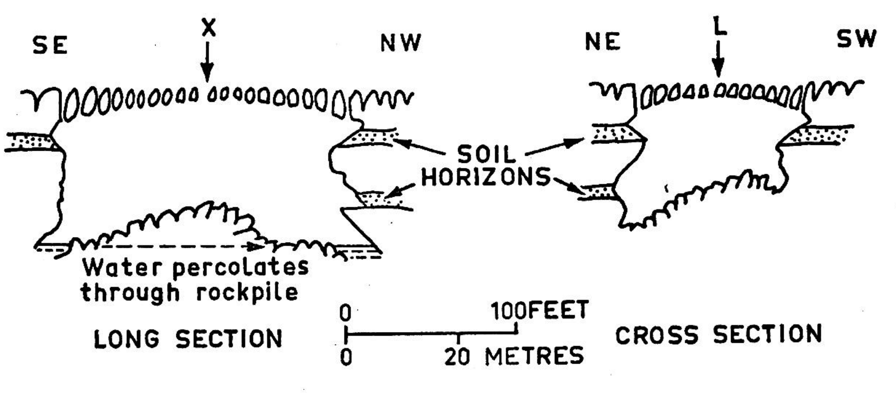


FIG. 14



SKETCH OF AIYENNU CAVE NEAR STOCKYARD GULLY

MP

the Southeast Province of South Australia suggests that cross-bedding is there influencing cross-sectional form. Similarly L. Bastian (pers. comm.) describes inclined room development in Wallcliffe Cave, Margaret River, in accordance with the aeolian bedding. The conclusion is that variation in consolidation of the aeolian calcarenites is a factor influencing the form of some of the caves in them. [L]

L. Since this paper was given, Lowry and Bain (1965) have pointed to control of direction of passage development by the strike of the aeolian cross-bedding in Easter Cave.

It is appropriate at this point to discuss the Augusta caves, which seem to stand genetically apart from the others in the Southwest. These caves - Easter, Jewel, Deonderup, Moondyne, Labyrinth - lie close together in the oldest and most inland calcarenite. Their natural entrances are by solution pipes, somewhat enlarged by collapse in one case, leading down into collapse dome chambers. The main extent of all of them, however, is horizontal within confined vertical limits of 3-6 m in low passages and rooms, with network mazes in some caves. Well developed spongework is prevalent and in places it is guided in detail by aeolian cross-bedding. Almost stagnant lakes are typical of this level of horizontal development, which relates to a very flat water-table. From the evidence of re-solution and submerged decorations, a water level oscillation of about 1.5-2 m has taken place.

Bastian (1964) has described these caves as of shallow phreatic origin. 'Shallow phreatic' is an American term implying strong current close to the water-table, an oscillating level in itself, of course. However the elaborate spongework of these Augusta caves precludes the strong currents, frequently under hydrostatic pressure, associated with the shallow phreatic or epi-phreatic concept. Instead we have characteristics associated with deep phreatic solution in the Davisian sense of mainly slowly moving water in completely waterfilled cavities. However here these characteristics seem confined to a very shallow zone; so perhaps a better designation is to describe the caves as of phreatic origin within narrow vertical limits. Water samples from three of these caves, samples 10-12 in Table 4, all show very high carbonate contents and are saturated. No solution could have been going on at the sample sites in the four day period covered by the recordings. Observations representative of much longer periods are required to ascertain the processes now operative in these caves. However, these samples were taken in the middle of an exceedingly wet winter, when waters might have been at their most aggressive level.

A second statement of Bastian's with regard to these caves commands more complete acceptance, namely the view that they must have developed after a greater degree of lithification had been reached than is necessary for the other types of cave. The very prevalent spongework can scarcely have formed at all otherwise. The almost perfectly horizontal and very large roof over the Flatroof Lake in Jewel Cave, which is 160 m long and up to 45 m wide without any support, argues even more strongly in this sense.

The form of the underlying crystalline basement may well have induced the special character of these caves through its control of groundwater movement and this form is well worthy of geophysical investigation.

There is great variation in the occurrence and nature of caves from one part to another of the long coastal limestone belt from Dongara to Augusta in the Southwest, and according to Bastian six factors contribute to this.

(a) Basement relief

From Busselton to Dongara the dunes have been emplaced over a flat coastal plain, whereas from Yallingup to Augusta the dunes advanced into hilly relief on igneous rocks. In these latter circumstances cave development tends to be guided and concentrated along the lines of the buried valley systems both by the feeding of inland water into the dunes along them e.g. Mammoth Cave, Witchcliffe, and by imposing a relief on the water-table within the limestone which reflects in subdued fashion the buried topography. As a result the caves are frequently of the linear type and tend on the whole to be of large dimensions. Water-tables are much flatter beneath the dunes on the coastal plain and here broad sheet-like water movements result in more inclined fissure caves e.g. in the Yanchep area north of Perth.

(b) Rainfall

There is a rough correspondence between the decrease in size and number of caves from south to north and the decline in mean annual rainfall from about 1150 mm at Karridale in the south to 500 mm at Dongara. There is also a northwards decline in the amount and variety of secondary calcite decoration.

(c) Sequence of Limestones

The younger the dune system the less time there has been for the necessary degree of lithification and also for the actual solution of the caves. Thus in the Deepdene-Augusta belt, only three caves are known from the intermediate dune belt - Old Kundardup, its unnamed neighbour and Bat Caves - whereas nine are known from the inner, oldest dune belt. In the Fremantle-Mandurah belt it is noticeable that despite an excellent development of caprock the underlying parts are very friable and there is scarcely a cave worthy of the name.

(d) Depth to the Water-table

The greater the thickness of limestone above the water-table the more substantial caves may be. In this respect Bastian contrasts Yanchep with the water-table 10-15 m below the surface with depths between 30 and 60 m in many parts of the Yallingup-Augusta belt.

(e) Inland Drainage

Where dunes block the course of rivers from inland areas and force them to seep underground, the most potent factor of all promoting cave development is called into play, as the preceding discussion on the relative importance of vertical and lateral solution indicated.

As it is in the drier parts where rivers flow less regularly that they are more liable to be blocked, this factor can counter the effect of rainfall on cave distribution. Thus Arramall Cave, receiving its water from Lake Arramall which is in turn fed by the Arrowsmith River draining a very large area in the low rainfall belt, is a very long cave for the Southwest. The Stockyard Gully Cave system further south seems likely to prove the biggest cave development in the whole area from the indication of the chain of collapse dolines and caves stretched over a line of several kilometres in length.

(f) Progress to Saturation of Groundwaters

Bastian maintains that as underground drainage from the interior moves westward through the dune-belts, there is progressive loss of power to dissolve limestone and fashion caves. There is a reduction of numbers of caves in this direction and the observations set out in Table 4 are in accordance too, showing a progress from very aggressive waters on the inflow side to saturated springs on the coast.

In some karst areas cave development may be as substantial on the outflow side as on the intake side, though often the outflow caves may be waterfilled and it is difficult to determine their size. For example, at Cooleman Plain in southern New South Wales, the inflow caves are much larger; it must be noted, however, that the main springs remain aggressive all the year round here. The common case may be that the outflow side is marked by fewer but larger caves compared with the inflow side.

If Bastian is right in thinking that saturation and with it ineffectiveness in cave formation is reached more rapidly than is the usual case with consolidated limestone areas, the explanation may lie in greater porosity and incoherence than is common with most karst areas.

A further factor additional to Bastian's six is variation in purity of the calcarenites; this is known to vary markedly and more caves can be expected in the purer limestone.

It is instructive to muster the caves of the aeolian calcarenites of the Southwest of Western Australia and South Australia in terms of a very simple classification into inflow, outflow, through- and between-caves.

Much the largest number fall into the last category, between-caves, (*Ger. Zwischenhohle*), in which entrance into a cave is effected from vertically above at some point in its length. Their entrances vary from simple solution pipes (Arumvale Pipe Cave, Karridale), solution pipes in solution dolines (Jewel Cave, Augusta), roof windows (Lake Hamilton Cave, Eyre Peninsula), and collapse dolines (Lake Cave, Witchcliffe). Inflow caves are fewer, their entrances being open arches (Ruddock's Cave, Witchcliffe) or collapsed arches at former points of entry (Arramall Cave). The through caves known are parts of inflow caves (the first two parts of Stockyard Gully Cave). No outflow caves are known as yet. This last fact can be regarded as due to the prevalence of burial of seaward parts of the aeolian calcarenite by unconsolidated dunes or to rapid saturation of cave waters or both in combination. Connolly's Cave, Witchcliffe, a between-cave fairly near to a coastal spring in Bob's Hollow, suggests the possibility that burial is more important than saturation of underground water. The comparative infrequency of inflow caves is due to the ability of many of the larger rivers from the interior to maintain surface valleys through the calcareous dunes as the latter are being emplaced. Moreover the smaller streams incapable of this spread out in swamps at the inner margin of the limestones. There is diffuse percolation into the limestone, which retains in any case a high porosity permitting such entry. Penetrable caves are not common on this inner margin in consequence.

Bain (1962) and Bastian (1962,1964) have claimed that the caves of the Southwest have developed especially fast because of their lithological characteristics and exposure to aggressive water action from the moment of their emplacement. Comparative data with which to test the matter are not readily available particularly from

Australia, where caves are often in very old rocks, and where late Tertiary and Quaternary geomorphological history is generally not well established. In addition there is, as has been indicated earlier, much uncertainty as to the precise age of the aeolian calcarenites themselves, though we can with some confidence regard them as belonging to the Pleistocene. If the whole of the Pleistocene were available for the caves of the Southwest to form, it does not need much consideration to come to the conclusion that there is nothing unusual about such a rate of development. Not only have large cave systems been developed within the Pleistocene but also the gross land-forms in which such caves lie. This is true for instance of the caves in the Miocene limestones of the central cordillera of Australian New Guinea where Pliocene rocks are involved in the orogeny; they are regarded therefore as mainly Pleistocene in age, though the limestones had been lithified prior to this period. If, as follows indirectly from Macarthur and Bettenay's reasoning, the oldest calcarenite in the Southwest of Western Australia belongs to the Last Interglacial, then the possible time involved is about 100,000 years and rapid development is an appropriate description.

There is a little support for this shorter history from the Southeast Province of South Australia, where the dozen known caves in the aeolian calcarenites occur in four of the dune ridges. In Sprigg's chronology (1952), these ridges range from the oldest to the youngest but one, i.e. from the beginning of the Pleistocene down to the Last Interglacial. Hossfeld's very different dating (1950) would still include one at least of the caverniferous dune ridges in the Last Interglacial. Therefore in either case some cave formation has taken place since the Last Interglacial.

Ollier and Tratman (1955-6) have argued strongly for regarding quite substantial cave systems in Carboniferous Limestone in part of County Clare, Ireland, as completely Postglacial in age but they regarded this rate of development as exceptional. It has similarly been claimed that some deep caves of West Norway in even older, crystalline limestone have developed since the last Pleistocene glaciation (Corbel, 1951) and this would be thought by many to be even more exceptional. There is considerable interest therefore in more precise dating of the dune limestones so that it can be determined whether or not the caves of the Southwest and perhaps other Australian dune limestone caves belong to [M] a comparatively small class of very youthful caves.

M. The various footnotes mentioning the beginnings of radiometric dating of the dune limestones in the last few years make it clear that some at least of the caves have developed within the last 100,000 years.

CONCLUSION

Many karst attributes are to be found in dune limestones of young geological age in the Southwest of Western Australia in particular and to a lesser extent in Kangaroo Island and the Southeast Province of South Australia. Some of them have been produced concurrently with the transformation of carbonate dune sands into aeolian calcarenite of variable degree of consolidation and certain special characteristics have resulted.

In this context solution pipes are not solely solutional in origin; calcite deposition also plays a part in their evolution. In consequence their formation contributes to the lithification of the sands. In some cases taproot growth contributes to pipe development and encrustation and replacement along rootlets is of general importance.

Though minor surface solution forms associated with subsoil conditions e.g. *Rundkarren* (rounded solution grooves) occur and may occasionally be found stripped at the surface, rock outcrops rarely if ever exhibit properly developed gravity-controlled sculpture due to direct rainwater solution such as *Rillenkarren* (solution flutings). Any caprock which has been exposed to direct rainwater action usually shows very irregular corrosional action. It is possible that slight variations in degree of lithification to be expected in young aeolian calcarenites are sufficient to find expression through rain solution but not through less sensitive subsoil solution.

Although some engulfment of allogenic surface drainage occurs, the proportion is less than frequently is the case with limestones consolidated prior to forming part of the landscape. This is due to the propensity of rivers from inland areas to remove dune sands tending to encroach on them, even though this results in quite deep and steep-sided valleys through the growing dune belt. Because of this, gorges in dune limestone must be even less readily assumed to be of collapsed cave origin than on limestones well compacted prior to karst development. Nevertheless some drainage from inland goes underground and resurgence as well as exsurgence types of spring occur on the seaward flank. Closed depressions of karst origin are present and are generally readily distinguishable from the somewhat degraded primary enclosed depressions of aeolian origin. They chiefly take the form of scattered dolines, and not close-set doline fields as can occur in karst on older limestones. However, as individuals, the dolines can be well developed and quite large. Some are demonstrably of surface solutional origin, though collapse origins are perhaps more common and give rise to the larger features. In their initial stages, the collapse dolines have a form related to the structure of the partially consolidated, case-hardened aeolian calcarenites. At inflow points of inland drainage, two instances are known of short gorgelike valleys produced by roof or retreating arch collapse. There is also one completely closed valley with a surface stream, which is due to collapse. There is one short steep-head valley, now relict and probably due to springhead recession. None of the more elaborate closed depressions - uvalas and poljes - is known; inadequate time for their development may not be the complete explanation of their absence.

On the other hand caves are well developed and regarded as chiefly the result of lateral solution at the water-table, though vertical solution associated with piping cannot be excluded altogether. In many cases cave excavation has accompanied lithification and collapse has dominated more of their history than is characteristic in consolidated limestone areas. Collapse forms are in fact particularly common in these caves and in some instances have been influenced by dune bedding through the factor of differential lithification, though more frequently collapse forms are those of optimal structural stability in a more or less isotropic, weak material.

Linear caves along well defined underground streams appear to result from the guidance of underground drainage by the relief of the impervious basement beneath the dune mass. Inclined fissure caves and collapse domes are more prevalent where a level basement beneath the dunes results in a more sheet-like underground flow in the porous calcarenites. The importance of collapse from an early stage implies a vadose history for these caves, but in a few Davisian phreatic phenomena dominate the morphology and imply a substantial degree of lithification before speleogenesis.

The absence of known outflow caves may be chiefly due to burial of the seaward flank by later and still incoherent dune sands, but, in these porous and incoherent limestones, underground waters may achieve saturation precociously and thus substantial cave development may be inhibited towards the seaward side of the coastal limestone belt.

The undertain age of the aeolian calcarenites make it difficult to verify or reject claims that these caves in terrestrial limestones have developed extremely rapidly. This is, however, by no means the only problem for future investigation which emerges from this discussion.

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