BONNER GEOGRAPHISCHE ABHANDLUNGEN

Herausgegeben vom Geographischen Institut der Universität Bonn

durch Carl Troll
Schriftleitung: Hans Voigt

Heft 32

J. N. Jennings and M. M. Sweeting

The Limestone Ranges of the Fitzroy Basin, Western Australia

A Tropical Semi-Arid Karst

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with 10 figures and 18 photos

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INTRODUCTION

Within the field of karst morphological studies, much attention has been given to the characterisation of the various karst styles and to the rates of limestone erosion, which relate to different climatic conditions. The karsts of temperate, sub-polar and tropical humid climates have so far provided the chief bases for these comparisons in climatic morphology. Little attention has been given to the limestone terrains of tropical arid and semi-arid zones, one reason being that the lack of water results generally in retarded karst development, with a consequent reduction in their intrinsic interest. Though „dry“ karst may not differ so much as humid karst does from neighbouring relief of different lithology within the same morphoclimatic system, it is important that it should not be overlooked; conclusions drawn from such limestone country may have lessons of significance for the understanding of karst in general.

It was with this point of view that the authors carried out field work during May—July 1959 in the Limestone Ranges of the Fitzroy Basin. This area was chosen because it possesses larger extents of thick, pure limestone than anywhere else in tropical Australia, together with an available relief, which meagre at it is, is also as great as any to be found there.

The Limestone Ranges extend over 180 miles and little has been previously written on their geomorphology. The field work was therefore bound to be of the nature of a reconnaissance, especially in such matters as underground exploration.

Topographical maps of the area are poor, the best for the present purposes being on a scale of 1/253,440. Relief is inadequately represented by schematic hachuring on the Lennard River and Mount Ramsay Sheets (Lands Department, W. Australia) and by contours at a 250 feet interval on the Noonkanbah sheet (National Mapping Office). The scatter of height fixes is extremely thin. Vertical air photographic cover on a scale of 1/31,680 is complete and generally good. The loan of the relevant prints by Dr. N. FISHER, Chief Geologist, Commonwealth Bureau of Mineral Resources, Geology and Geophysics, is gratefully acknowledged.

Surface geology is shown on the Lennard River and Noonkanbah sheets of the 4 mile Geological Series of the Bureau of Mineral Resources; we are grateful for access to an unpublished draft of the Mount Ramsey sheet on a scale of 2 miles to an inch. Solid geology of the whole area appears on the 8 mile Fitzroy Basin map of the same Bureau. We have also been privileged to see unpublished detailed maps of parts of the Oscar Range and of the vicinity of the Windjana Gorge prepared by West Australian Petroleum Party Ltd. (WAPET). We are glad to acknowledge help of varied type from this organisation; in particular we wish to thank Messrs. M. H. JOHNSTONE, P. E. PLAYFORD and D. N. SMITH, geologists of WAPET, for valuable dis-

cussions. Certain chemical analyses specified in Appendix I were carried out for us by Mr. P. and Mrs. I. A. SERGEANT, to whom we are very grateful. This research was carried out from the Australian National University, one of us (M.M.S.) holding a Visiting Fellowship at the time.

2. OUTLINE OF THE PHYSICAL GEOGRAPHY

Rising abruptly from the surrounding plains, the Limestone Ranges consist of a series of low ridges and plateaux along the belt of Devonian rocks on the northern side of the Fitzroy Basin. This belt runs about 180 miles from Alexander Creek in the N.W. to a little beyond Bugle Gap in the S.E. where the Devonian rocks plunge beneath Permian strata (Fig. 1, see appendage).

The Napier Range, parallel with the N.W.—S.E. trend of the Devonian belt, is about 60 miles long and broken only by gorges and narrow gaps. For the most part it is only half a mile to a mile wide, but broadens to a maximum width of 5 miles towards its northwestern extremity. At this end, the limestone extends in front of the rather higher Van Emmerick (formerly Paterson) Range, developed in an interfingering conglomeratic facies of the Devonian. Mt. Behn, also in Devonian conglomerate, similarly rises higher than the neighbouring parts of the Napier Range towards its southeastern end (Fig. 2).

The Napier Range merges on the S.E. with the Oscar Plateau, which is really only the inner part of the Oscar Range. Together, the Oscar Range and Plateau constitute the largest limestone outcrop in the area, some 50 miles long and 10—12 miles across over most of its length, though it is narrower in the N.W. where it is separated from the Napier Range by the Fairfield Valley. The Oscar Range, however, includes a substantial inlier of Proterozoic rocks. Here quartzite and conglomerate ridges, aligned along the N.W.—S.W. folds of the King Leopold Beds, lie near the S.W. front of the Oscar Range and rise somewhat higher than the surrounding limestone.

To the S.E. the Oscar Range is continued without a break by a slightly lower limestone plateau and then by the Geikie Range; the plateau and the Geikie Range are separated by the discordant Geikie Gorge. The Napier, Oscar and Geikie ranges constitute a single physiographic unit, due to the fact that they are fashioned from a linear barrier reef complex, which has been almost undisturbed tectonically since its formation (Rade 1961).

South east of the Geikie Range, however, there is a more complex arrangement of small ranges and plateaux, separated by small plains or broad valleys. Although the predominant trend is still N.W.—S.E. e. g. in the Pillara, Home, Emanuel and Hull Ranges, there is much more variation; thus the Horse Spring Range runs S.W.—N.E. and the range east of Bugle Gap is mainly aligned N-S. An additional difference is found in the greater role played by the Devonian conglomerates in the relief; the Sparke and Barramundi Ranges are two of the most substantial of all the ranges in this part. This greater complexity has at least two causes; first, it seems

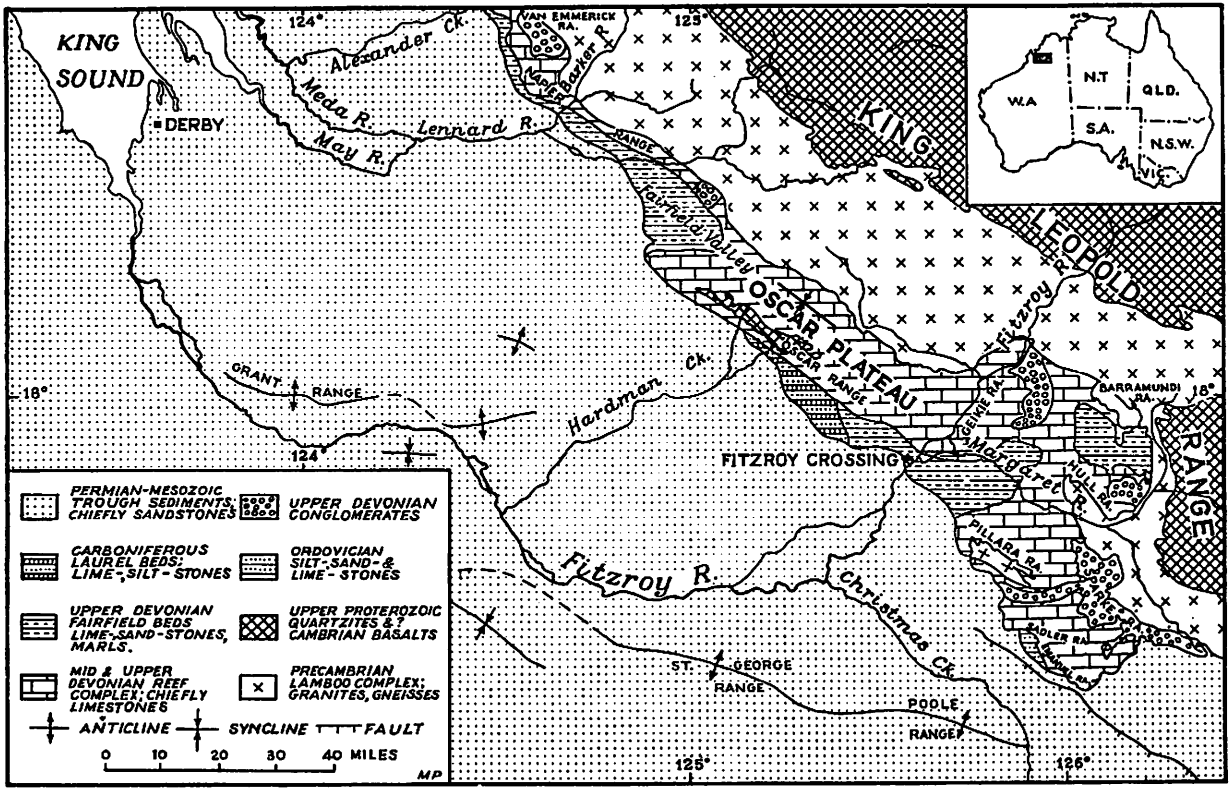

Fig. 2. Generalised geological map of the Limestone Ranges and their vicinity.

that a series of reef patches, rather than a more or less coninuous reef, provides a more elaborate initial framework, and secondly, it seems that there has subsequently been more faulting and tilting. Much less attention was given in the field to this S.E. area than to the Napier, Oscar and Geikie unit and this account chiefly rests on the landforms of the latter area.

Northeastwards from the Limestone Ranges lies the Precambrian heart of the Kimberleys, the old land along the coast of which the Devonian rocks were laid down as torrent deltas, fringing and barrier reefs, and perhaps also atolls. The high King Leopold Range, rising to over 3,000 feet with ‚Appalachian' ridge-and-valley relief in the strongly folded Upper Proterozoic quartzites, overlooks a much lower foreland in the Lamboo Complex. This metamorphic basement of schists, gneisses, quartzites and plutonic intrusives gives rough, hilly relief; yet the low hills appear to conform to an erosion surface sloping gently up to the foot of the steep scarps of the King Leopolds.

Southwest of the Limestone Ranges, the axis of the Fitzroy Basin is occupied by Permian and Mesozoic sediments, predominantly siliceous sandstones, the final fill of this sedimentary basin. This country is mainly low and gently undulating, much of it covered by Quaternary sands still retaining dune landforms. A higher land surface apears to be preserved in the summits of the Poole, St. George, Grant and other ranges. The same surface seems to be continued in more or less horizontal Permian beds to the S.E. of the Devonian outcrop and scattered hills and mesas throughout the basin may be residuals from this surface as well.

Broad alluvial plains of the major rivers, in particular of the Fitzroy and of the Lennard-Meda, traverse this sandstone and dune sand region, with unbroken and gentle gradients. Less obvious from the maps is the presence of a depression, continuous but of variable width, between the higher country of the full length of the Napier, Oscar and Geikie ranges on the one hand and of ther Permian sandstone and Quaternary dune sand region on the other. This depression will be referred to as the ‚outer marginal plain'. It is almost entirely covered by superficial deposits-alluvium, residual black soils and caliche; outcrops are sufficient to show that it is largely, though not entirely, developed on the Fairfield Beds, the uppermost Devonian formation, and the Lower Carboniferous Laurel Beds.

Not quite so continuous is the ‚inner marginal plain' between the Napier, Oscar and Geikie ranges and the Lamboo Complex hill country. This is in three segments, interrupted where Mt. Behn abuts on to the metamorphic hills and more substantially where the Oscar Plateau does the same between Tunnel Creek and Mt. Wilson. Again in the inner marginal plain there is much cover of alluvium, caliche, black soil and other residual soils. Small hillocks of Lamboo Complex project through here and there to show that it is mainy floored by the Pre-Cambrian basement; however, other parts are developed on the Devonian rocks. The various parts of the inner marginal plain are graded smoothly to the outer marginal plain through the river gaps and the underground course of the Tunnel, all of which have low, uniform gradients.

Planation surfaces in limestone are recognised as being amongst the most perfectly developed. The Limestone Ranges of the Fitzroy Basin conform to type. Whether dissected or undissected at the present time, where broad and where narrow, the tops of these ranges present a level skyline and belong to a single erosion surface truncating the complex reef structures with a remarkable precision. Fixed heights are scanty but they indicate that the surface varies gently between 600 and 850 feet, the highest parts being on the Oscar Plateau and in the Emanuel Range, significantly sited farthest away from the major drainage lines of the present day. Only the Devonian conglomerates and the Oscar Range Proterozoics rise above this surface by a maximum of 300—400 feet. Mt. Behn, with its coarse conglomerates, rises gently with concave slopes from the flat top of Napier Range. The Oscar Range quartzite ridges rise more abruptly 200—300 feet from the top of the surrounding limestone.

The inner and outer marginal plains (partly developed in the same rocks as the Limestone Ranges proper and encroaching on them), are graded to present sea level along the alluvial plains of major rivers. The marginal plains vary between 300 and 550 feet above sea level close to the ranges.

Intermediate plains of erosion are rare in the Limestone Ranges, though the alluviated plains, with residuals, inset into the Oscar Plateau east of Leopold Downs Homestead and draining northwards to the Fitzroy via Pigeon Creek, constitute one example. Another may be found in the plain between the Sadler and the Emanuel ranges.

However, the two major planation surfaces predominate in and around the Limestone Ranges, with a local available relief varying between 100 and 300 feet, if the monadnocks are excluded. Parts of the upper surface remain untouched by rejuvenation and the lower surface of the present cycle is already perfectly planed in close juxtaposition. Despite the small available relief the dissected portions between the two surfaces provide an excellent basis for determining the sequence of karst development in these climatic conditions.

Adequate means of dating the upper surface, whereby a time scale for the karst evolution might be obtained, are lacking. Small, shattered masses of quartzitic sandstone occur on the upper surface and within the dissected parts. They have been let down by solution from a higher level and may represent the fill of former enclosed depressions in the limestone. These sandstones belong to the Permian, Grant Formation, which was undoubtedly laid down widely over the Devonian, probably after a good deal of the upper stories of the reef structure had been removed by erosion. This is the only direct dating evidence from the Devonian area and merely sets an upper age limit to the surface, which undoubtedly antedates its final fashioning considerably.

There are several substantial unconformities in the Carboniferous-Permian-Mesozoic sequence in the Fitzroy Basin but it is the later ones, which are most probably associated with the removal of the Permian cover and planation of the limestone. The Cretaceous sandstones of the Dampier Peninsula to the west are nearshore deposits. The coarse sandstones and fine conglomerates of the Meda Formation, a thin formation unconformable on the Trias, are restricted to the central coastal parts of the basin. These could well be associated with of the surface with which we are concerned. Unfortunately the age of the Meda Formation is not known with certainly, it is variously given as Jurassic and as ‚Cretaceous-Tertiary' in GUPPY et al. (1958). The fact that the upper planation surface cuts across several fault-lines is of no help since the faults themselve are not closely dated.

The upper surface of the Limestone Ranges seems to correspond with the upper surface of the Permian residuals and plateaux; this is most evident in the Bohemia Downs-Christmas Creek area. This latter surface is lateritised and seems to be part of the most widespread laterite of Northern Australia (the ‚Great Australian Pediplain' of L. C. KING (1950). The final fashioning of this surface before rejuvenation is variously dated as Miocene (WOOLNOUGH, 1927 ; DAVID and BROWNE, 1950), early Plicene (WHITEHOUSE, 1940) and late Mesozoic-early Tertiary (HILLS, 1955; TWIDALE, 1956). It is likely that this very ancient surface persisted until different times in different areas before major interruption (HILLS, 1955). For the area under discussion, it does not seem possible to say more than that the upper surface ceased to be part of the current cycle working to the general baseleved of the sea at some time between the Oligocene and the Pliocene (WRIGHT, 1961) 1).

In the subsequent period, the present-day cycle has penetrated far into the Ranges. The Warrimbah Conglomerate (GUPPY et al., 1958), river boulder-beds in terrace remnants, rises at least 80 feet above the fine sediments of the present Fitzroy flood plain between 30 and 80 miles below the Geikie Gorge. They are regarded as late Tertiary-Pleistocene, and must relate to an intermediate phase of planation between the two major surfaces, which, as has been said, finds meagre representation now in the vicinity of the Limestone Ranges. It is unfortunate that the exact provenance of the find of *Diprotodon australis* (HARDMAN, 1884) is not known, other

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1) Since this account was prepared. R. L. WRIGHT (1961) has published some preliminary results of a geomorphological survey of a wider area than that of the authors, including the whole of the Kimberleys and the Fitzroy Basin. The Older Planation Surface of our account constitutes part of WRIGHT's Lower Kimberley Surface, which is deeply weathered and lateritised except on limestones. In WRIGHT's view this surface developed from Cretaceous times into the lower Tertiary until it was uplifted and gently warped in the Upper Miocene. Our Intermediate Plains apparently have no general equivalent in the wider context of WRIGHT's study and may be local features due to structural influences.

The Inner and Outer marginal plains discussed in the present paper would appear to belong to WRIGHT's Fitzroy Surface, which he thinks has suffered a slight rejuvenation in the Fitzroy Basin. In the Limestone Ranges, our Modern Planation Surface undoubtedly belongs to the current cycle encroaching on to the Ranges, but it may not be completely in adjustment to present day base-level. Below Alexander Island, WRIGHT finds that the Fitzroy river has entrenched its flood plain clearly below the Fitzroy surface.

References.

R. L. WRIGHT, 1961, A Deeply Weathered Land Surface in Part of North-Western Australia. C. S. I. R. O. Land Research and Regional Survey Division. Technical Memorandum 61/19. Canberra, 1961.

J. RADE, 1961, The Geology of the North-Eastern Margin of the Fitzroy Basin between Hawkestone Creek and Oscar Range. Journ. Roy. Soc. West Austr. 44, pp. 90—95.

than it was found in the Lennard River just below its debouchure from the Napier Range. This fossil is not known earlier than the Pleistocene.

Climatically the Limestone Ranges fall into a single hot, semi-arid type, BSwh in Köppen's system, DAw' in the early Thornthwaite classification (Johnson, 1950). Derby is the nearest station with temperature records. Its coolest month is July, with an average daily maximum of 84.2° F and daily minimum of 58.3°. Inland in the Ranges the daily range is slightly greater with the average daily mean slightly lower than the 71.3° of the coastal station. Frosts are not experienced however. The hottest month is December before the heaviest rains; Derby's average daily mean of 88.3°, for that month, with average range reduced to half that of the cooler season, will be close to the conditions in the limestone country. In the east of the Ranges, the air temperature probably rises to 100° or exceeds it on over 100 days in the year and the number will not be much smaller elsewhere in the Ranges. The estimated annual evaporation is high, between 100 and 110 inches *(Commenwealth Year Book,* 1958).

The average annual rainfalls and average number of raindays (with falls of 0.01 inch or more) for stations in or near the Ranges is as follows:

	Mean Annual Rainfall	Mean No. Rain days
Kimberley Downs	25.35 inches	32 days
Napier downs	28.2	44
Leopold Downs	23.39	30
Fitzroy Crossing	20.47	56
Fossil Downs	18.38	41

The seasonal concentration is high; only December to March may be said to be rainy months. About 85% falls within them, when the rainfall is effective vegetationally. The number of raindays is small and the average intensity ranges between 40 and 80 points per rainday; this is high even for Australia as can be seen from Prescott's map of intensity (Prescott, 1931). Thunderstorms are frequent (Barkley, 1934) and heavy rain-falls occur. Thus at Napier Downs, 15 inches fell in three days (24—27 March, 1949) and 19.35 inches on two days (3—4 March, 1943). Estimates of extreme precipitation by various methods (e. g. Walpole, 1958; *Report of Stormwater Committee,* 1958), class this region as one where heavy rates are to be expected. On the other hand the variability of the annual rainfall is not very high for Australia, the average deviation from the mean being about 30%.

The undissected parts of the Ranges and much of the plains alongside and between them are covered by black soils (grey and brown soils of heavy texture, Prescott, 1931). These carry a grassland vegetation, including *Chrysopogon, Dicanthium* and *Astrebla* species, often tussocky and not forming a closed cover. The alluvial plains have more variable soils; parts are in *Eucalyptus* woodland, with a ground flora chiefly of grasses, parts are solely in grassland. On the dissected limestone, both soil and vegetation are patchy and exiguous. Spinifex *(Triodia* sp., *Plectrachne* sp.) dominates and there are also scattered trees, chiefly baobab trees, and scrub, including *Acacia sp.*

3. GEOLOGICAL STRUCTURE OF THE RANGES IN RELATION TO LANDFORMS.

The Devonian rocks of the region have been divided into 18 formations of late Middle (Givetian) and Upper (Frasnian-Famennian) Devonian age, some of which have several facies (GUPPY et al., 1958). In the Oscar Range, additional formations have been recognised by WAPET geologists (McWHAE et al., 1958; SMITH et al., 1957). Even though 6 formations consist entirely of torrent conglomerates, the remainder include carbonate rocks in varying but generally high proportion. The position is simplified by the recognition in the later WAPET studies (SMITH et al., 1957; PLAYFORD and JOHNSTONE, 1959) of the occurrence of a limited number of reef facies within them. Detailed work in other parts of the Ranges is likely to reveal a similar position. It is these facies, often revealed clearly in the walls of the river gorges, which are the most significant units, with their chracteristic lithology and structure, for the geomorphology.

This later work also revises the dating of the Pillara Formation, which is now known not to be restricted to the Givetian but to extend upwards into the Frasnian and Famennian. Some of the contacts of the Pillara with other formations, formerly regarded as unconformities, are now considered to be rapid transitions between contemporary reef facies.

In the Oscar Range and the Windjana Gorges neighbourhood, the following reef facies predominate; they can be seen to occur also in other gorge sections, e. g. Geikie Gorge, Mount Pierre Gorge.

a) Barrier Reef Facies.

This is a narrow, winding strip of unbedded limestone and dolomite, consisting largely of in situ remains of calcareous algae, sponges and stromatoporoids, with some clastic calcareous deposits. In section, the massive limestone, traversed by vertical joints only, is seen to have grown chiefly upwards. This, the reef proper, provides but a small proportion, perhaps 10—15%, of the whole contemporary reef complex.

(b) Forereef Facies.

This consists of successive talus slopes, formed of debris due to active erosion of the reef front during growth. The facies consists chiefly of calcarenite and calcirudite, interspersed with small, compact masses of fine-grained crystalline limestones, which represent algal bioherms. The forereef facies is well-bedded, with primary depositional dips usually between 20—30° but in places both greater or less. Oolites occur in this facies. The rocks are generally purely calcareous, but can be dolomitised near the reef proper and may become impure in parts, when calcareous sandstones occur.

(c) Algal Reef Facies.

This forms masses of fine-grained crystalline limestones larger than the forereef bioherms. They are virtually structureless and probably represent secondary reef formation on the foreslope of the main reef.

(d) Backreef Facies.

In the lagoons behind the reefs, well-bedded calcarenites and biostromal limestones have accumulated. The clastic fragments came from erosion of the reef and of sessile organisms in the lagoons. These organisms, chiefly stromatoporoids, also built the biostrome. Noncalcareous debris from the land was also swept into the lagoons so that parts of the backreef facies are impure, including calcareous sandstones and siltstones. Although the backreef beds might have a fairly substantial depositional dip close to the reef, they were in general laid down in nearly horizontal attitude. which they have not lost during subsequent tectonic movement.

The Pillara, Sadler, Fossil Downs, Copley, Geikie, Brooking, Oscar and Napier Formations, Mt. Pierre Group and Bugle Gap Limestone (Guppy et al., 1958) all belong the the reef complex. Yet, each does not necessarily represent a single facies. Thus, although the Pillara is chiefly back-reef in the Oscar and Napier Ranges, and the Oscar Formation is forereef, the Napier Formation includes all four facies in one part or another of its mapped outcrop.

The uppermost Devonian formation, the Fairfield Beds (Famennian), does not belong to the reef complex and it formed in substantially different sea conditions. Sandy, and silty calcarenites predominate and marl and calcareous shale are also important in the sequence. The similar Laurel Beds of the Carboniferous are probably conformable.

From the point of view of karst morphology, the most important characteristic of all these Devonian formations in which carbonate rocks predominate is their degree of purity. Where the limestone members are impure and become interbedded with calcareous sandstones, siltstones and shales, the hills and spurs become convexly rounded to a marked degree, somewhat reminiscent of chalk terrain in N.W. Europe. Many karst features are lacking or poorly developed, though surface solution features and caves are not entirely absent. A close-set V-shaped valley system prevails, with continuous downward and outward gradients along the talwegs; in plan, such valleys show unusually strong joint influence. The landforms are dominated by surface drainage and possess a rock waste mantle interrupted to a limited extent only by rock outcrops. Cvijic's term ,merokarst' will be employed for this terrain, but this paper is not concerned with the landforms of the impure calcareous formations.

A detailed analysis of the air photographs in conjunction with the field work reveals that karstic and merokarstic relief can be found on nearly every calcareous formation (contrast this with Table 3 of Guppy et al., 1958).

The complex relationships between the major landform types and the various formations is set out in Table I. This complexity has several causes. Within a given formation there may occur more than one reef facies and, as has been mentioned, some individual reef facies may range from high purity to pronounced impurity in terms of limestone and dolomite content. Moreover, dissection proceeds inwards from the margin of the ranges and from the transecting allogenic gorges so that some parts remain undissected and lack obvious karst phenomena. Similarly, the extension of the modern surface of planation eliminates typical karst landforms from some outcrop areas.

Table I

Major landform types in relation to calcareous Devonian formations.

	Undissected surfaces		Dissected topography	
Formation	Upper (Cret.-early Tert?)	Lower (Pleistocene-Recent?)	Karstic	Mero-Karstic
Fairfield Beds	—	+	+	+
Napier Fmt.	+	+	+	+
Oscar Fmt.	+	+	+	—
Brooking Fmt.	+	—	+	—
Geikie Fmt.	—	+	+	+
Copley Fmt.	+	+	+	+
Fossil Downs Fmt.	—	+	+	+
Bugle Gap Lst.	—	—	+	+
Mt. Pierre Group	—	+	—	+
Sadler Fmt.	—	+	+	+
Pillara Fmt.	+	+	+	+

The lithology and structure of the various reef facies play a significant role in the karst morphology. It has already been pointed out that generally speaking the Ranges rise with remarkable abruptness from the surrounding plains. But the nature of their margins varies with the facies. The most striking of all of these margins coincides with the massive algal reef facies. Here are found cleancut, nearly vertical walls, which rise as much as 300 feet in height and look boldly out across the outer marginal plain. The cliffs near Morown Yard on the orther face of the Oscar Range, the Napier Range cliffs near Windjana Gorge and the cliffs on both sides of the promontory from the Napier Range ending in Barnet Spring, provide examples.

The more widespread forereef facies give almost equally rocky but less wall-like margins; steeply inclined bedding-plane surfaces due to the depositional dip alternate with nearly vertical clifflets corresponding with the biohermal masses. Varying with the primary dip of the beds, their thickness and the frequency of bioherms, the overall slope of the forereef margins can range from around 15° to over 40°. However, at some points erosion of the thicker-bedded forereef facies has given rise to cliffs as nearly vertical as those of the algal facies but more irregular in detail. Similarly steep cliffs occur on the inner sides of the ranges where encroachment is against the dip of the forereef beds, though here a talus slope tends to intervene between the cliff and the plain.

The algal reef and forereef margins tend to possess a simply curving or straight course in plan, and this corresponds with the strike of the forereef beds, that is, the original trend of the barrier reef. The later stages of dissection break down this simple plan, and it may never develop in areas where the forereef facies is impure, e. g. at the head of the Fairfield Valley in the Napier Formation. Here the margin is intricately cut up by valley development.

Where the margin of the ranges is found in nearly horizontal backreef facies it is nearly always intricately indented by valley systems, both where the backreef is giving rise to karstic or to merokarstic relief. Where the rocks are impure, the margin remains steep but curves convexly down to the plain, interrupted in a minor way by ribs of the purer limestone members. Where, however, the horizontal backreef beds are predominantly pure, they tend to give rise to nearly vertical cliffs, in which the weaker beds are etched out to give an aspect different in detail to that associated with the algal reef facies. In addition, a short talus footslope or a ‚haldenhang‘ in rock is more common.

The markedly linear marginal scarps to some of the ranges are etched out along certain faultlines[1]). Some of these faultline scarps are backed by a karstic facies, as in the western side of the Northern Hull Range and the north face of the Home Range, whilst others are in merokarstic sequences, for example the north face of the Virgin Hills and both flanks of the fault-defined Wedge Hill.

The Limestone Ranges are not universally margined by rock walls or scarps. In particular, there is no such clearcut edge at two pronounced ‚noses‘ in the range margins, found at the N.W. extremity of the Oscar Range and at the bulge west of Geikie Gorge ending around Brooking Spring. At present it is uncertain the cause of this but the possibility of a structural factor cannot be overlooked.

Within the Ranges one of the most interesting instances of structural morphology lies in the expression in the landforms of the barrier reef facies itself. It has been pointed out (SMITH et al., 1957) that the ribbon of reef tends to weather more readily to a slightly lower and smoother belt between the neighbouring facies on the almost featureless flat top of the N.W. end of the Oscar Range and Plateau. In the dissected karst near Windjana Gorge, this differentiation is more marked, the reef proper forming a narrow trench, 50—100 feet below the forereef and backreef areas (PLAYFORD and JOHNSTONE, 1959). In both papers cited, the lesser resistance of the reef to denudation is suggested as due to the presence of more primary voids in the rock promoting the movement of solvent groundwaters. In surface outcrop, however, any such cavities are filled by secondary calcite. There are other instances of the occurrence of depressions along the reef line in the region, as for instance on either side of Bugle Gap, at the contact of forereef Sadler Formation and backreef Pillara Formation.

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1) Some earlier investigators, e. g. BASEDOW (1918), were so impressed by the wall-like character of the Limestone Ranges as to attribute a fault scarp origin to instances where subsequent work has failed to reveal any faulting at all, e. g. the Napier Range.

Another example is found in the narrow belt of Sadler Formation running south from the Mount Pierre Gorge to the broader limestone plateau east of Bugle Gap. Here there are two outwardly dipping steep cuestas or hogback ridges, formed in forereef beds and separated by a narrow medial depression along the line of the reef proper.

Not all such trenches are of this origin. Thus the remarkable linear depression on the south side of the Emanuel Range separating the horizontal Pillara from the dipping Sadler Formation and Mt. Pierre Groups lies along a faultline. There is also the case of the much larger and longer depression, which can be traced along the middle of the Napier Range almost without interruption from Mt. Behn to the Oscar Plateau. This was examined in the field at The Tunnel, where it is narrow, and at Dingo Gap where it is broad. It was seen to lie entirely within forereef facies; this medial depression seems to be simply a strike vale excavated along a thinner bedded and less purely calcareous sequence in the forereef facies of the Napier Formation. At Dingo Gap, the true barrier reef facies depression can be seen included within the inner or northeastern ridge of the Napier Range; this is not only much narrower and less deep than the strike vale, but it also shows the winding plan seen so clearly in the vicinity of Windjana Gorge.

The line of the reef proper is not always expressed prominently in the relief. For example the barrier reef facies visible in the cliff section of the Geikie Gorge about half a mile from its southern end cannot be followed continuously as a surface feature in the dissected plateau to the flanks. Nor can a reef depression be detected at all in the S.E. sector of the Oscar Range near Brooking Gorge. Moreover at the eastern extremity of the Pillara Range near Donalds Yard, there is a projecting spine in the Sadler Formation which seems to have along its arête a core of barrier reef facies. Here this facies seems more, rather than less, resistant compared with its neighbours.

4. THE KARST LANDFORMS AND THEIR SEQUENCE.

With some of the structural influences thus briefly assessed, the karst landforms can now be considered in themselves, as there does not seem to be any fundamental difference in this respect between the forereef and the backreef facies, which together provide the greater part of the area of pure calcareous rock.

I The Old Planation Surface

Although small areas of the upper planation surface remain unaffected by rejuvenation in the northern Napier Range east of Old Napier Downs Homestead, the one substantial area of untouched old surface is on the Oscar Plateau, with a tongue extending towards the N.W. extremity of the Oscar Range. Though gradients and local relief are small, the old surface has the form of a very gentle elongated dome, from which drainage lines run in all directions. This includes the S.W., where it results in discordant valleys through the higher quartzite ridges of the Oscar Range Proterozoic core.

In the inner parts of this major remnant of the old surface, there is a virtually unbroken cover of grassy black soil. There are widely spaced drainage lines, up to several miles apart, which are shallowly inset in the surface. Convex slopes lead gently down to the silt beds of intermittent wet season streams, which sometimes meander on a small scale. On the flat interfluves, ‚crabholes', small rounded depressions, 10—30 feet across and 1—2 feet in the soil, are widespread and can become very frequent. Such features cannot be regarded as true karst phenomena, since they are common enough in Australia in contexts unrelated the limestones (cf. David and Browne, 1950, V. 2, p. 26). Lines of floaters along the strike and occasional strike ribs at most a foot or two above the surface enable the broad geological structures to be determined, the grain being most obvious on the slopes leading down to the drainage lines. On the exposed rock surface, solution is most often expressed here in the form of solution pans (Frye and Swineford, 1947), up to a few inches deep and 2—3 feet across, rounded in plan, flat bottomed and with steep to overhanging rims. Their development tends to prevent the evolution of the strike ribs into more prominent features.

Outwards from the areas of continous black soil, drainage lines increase in frequency, though remaining but a few feet below the general level of the old surface. The soil cover is more and more interrupted by rock outcrops and rock rubble; solution pans can become very frequent. Occasional crabholes now reveal bedrock in their sides or bottoms and some strike ribs rise 5—10 feet high in bulky ‚tumps'. From their peripheral distribution, these characteristics seem to be the first effects of rejuvenation of the old surface, a good deal of which has this stripped character, yet retaining its essential form. This leads, usually somewhat abruptly, into vigorously dissected relief, whether this be truly karstic in the pure calcareous facies or the rounded merokarstic forms of the impure.

II The Dissected Karst

The dissected karst is predominantly a bare karst; rock and rock-rubble occupy most of the surface except at a late stage of development. Soil is limited and vegetation exiguous.

(a) *Minor Surface Solution Features.*

Most of the exposed rock exhibits pronounced effects of surface solution, both on a small and a large scale. The former are often superimposed on the latter but it is convenient to discuss them separately, especially as a well established and detailed terminology in English is lacking.

Steep to vertical rock surfaces are almost everywhere etched by nearly parallel solution incisions. These include solution flutings (Rillenkarren) at most a couple of inches across and an inch deep, separated by razor-sharp, hollow-ground partitions; solution furrows (Rinnenkarren) a few inches deep as well as wide; and solution gullies up to 4—5 feet deep, with ribs and buttresses between which may or may not carry the smaller forms on their surface. The small solution flutings are often subdivided into successive sectors the one above the other by small rainpits, tiny hemispherical hollows ½—1 inch deep. The marginal cliffs in algal reef facies and the gorge walls in barrier reef and algal reef facies are particularly liable to carry the large gullies. Here they may run unbroken up nearly vertical walls, to heights of between 100 and 200 feet. Where the bedding is pronounced in forereef and backreef facies, these planes of weakness are also etched out by solution and hinder such continuity of the vertically-directed solution. Often an upper bed projects beyond the one below by as much as several feet, giving an appearance of truncated pyramids set one on top of another. This is most common in the nearly horizontal backreef and the forereef beds where the primary dip is low.

Flatter surfaces are split up into clints (Flachkarren) by solution slots (FRYE and SWINEFORD, 1947) or grikes (Kluftkarren) along joints, but are generally pitted by ‚bird's nest hollows' (Napfkarren) and solution pans. The flat bottoms of the pans are usually coated with a thin film of loam or clay. This protects the bottom and directs solution laterally. Dried algal remains were often found in these pans and in the wet season the algae increase the CO_2 content of the contained water. The partitions between the pans and other hollows, themselves covered by flutings, are undercut, steepened and narrowed into knife-edged ridges and points. They become so thin that even rubber-soled boots constanly strike off rock flakes from them. Thus the minor karst solution features point to a strong tendency for solution to operate in vertical and horizontal directions, eliminating intermediate slopes.

Deep circular pits or lapiés-wells (Röhrenkarren) are present in the Limestone Ranges but are not of the first order of importance. Examples from 2—10 feet in diameter and up to 20 feet deep were examined. They had flattish floors of rock debris, were sometimes nearly vertically walled throughout, but at others widened both at the base and at the top. Trees were infrequent and most of the wells seem unrelated to their occurrence. It seems doubtful therefore whether they can be attributed to the effect of tree roots promoting soluion as has been suggesed for the deep but otherwise similar pits of the Bom de Jesus Lapa in Brazil (Tricart and da Silva, 1960); none the less a small roof window in an upper level of the Old Napier Downs cave appears to have been localised by the influence of massive tree roots.

Not all the pure calcareous rocks of the area give to these ferociously jagged surfaces of corrosion. The barrier reef facies in particular weathers into rounded and smooth surfaces, penetrated by similarly rounded and smoothed holes and tubes. Smoothness is also characteristic of the other facies when solution has gone on under a soil cover. This was revealed by soil erosion on the track from Brooking Homestead to Geikie Gorge. Again, a small doline near Moolee Spring at the edge of the Oscar Range showed smoothed grikes and solution tubes emerging from beneath silty clay soil in process of removal. The smooth, rounded surfaces due to subsoil solution of course well known from karst in many other climatic conditions (Bögli, 1960).

(b) *Major Landforms.*

The early stages of the evolution of the dissected karst in this area are completely dominated by the development of karst corridors or bogazi (Karstgassen). Systems of vertical joints are general in the limestone of the Ranges and these are etched out by solution on all scales up to 20 feet wide at the base, as much as 100 feet in depth and hundreds of yards in length. They occur in intersecting sets of parallel systems, though one joint system is apt to dominate in a given area. The walls are usually vertical, though there is some widening towards the top. The floors are generally flat, with buff silt-loam and clay-loam soil covers, including rock fragments. Debris ruckles may interrupt the floors giving slopes at the ends of some of the corridors. Wedged blocks bridge the chasms occasionally. Trees up to 20—30 feet high grow in the larger examples.

The most extreme development of this was seen in almost horizontal backreef facies, e. g. in the Pillara Formation west of the southern end of the Geikie Gorge. In the area examined, many of the big corridors were found to continue underground in cave fissure passages, and crosslinks at right angles were often completely underground. Closely comparable examples were often encountered in steeply-dipping forereef facies, e. g. in the Oscar Formation west of Brooking Gorge. In the flatlying backreef the ridges tend to retain a flat top, even though this is often reduced to two or three feet and cut up by minor solution features in the manner already described. In the steeply dipping forereef facies, blocks defined by vertical joints and inclined bedding planes more readily fall into the corridors from the ridges, producing knife-edged arêtes. Pinnacles and arêtes are however far from absent in the backreef also and the whole terrain is extremely difficult to traverse. The corridors often end in vertical walls and overhangs, and the ridges are broken by cross-chasms too wide to jump. Because the karst corridors grade upwards in size from small solution slots, they are regarded as chiefly due to solution from the surface, and only to a subordinate extent to collapse of blocks forming cave roofs. The writers, familiar with the Craven karst area of N. England, immediately referred to the relief as consisting of „giant grikes". But such karst corridors are in more ways comparable with the bogazi of Jugoslavia (Blanc, 1958). The corridor networks of the Fitzroy Basin are developed in bare karst and are clearly developing at the present time; the bogazi of Jugoslavia belong to covered areas and are regarded as relict landforms. Tle Fitzroy corridors are also deeper, wider and longer than the bogazi. Karst corridors, described by Tricart and da Silva (1960) from the Bom de Jesus Lapa, also seem fairly closely comparable, though not so grandly developed (Fig. 3).

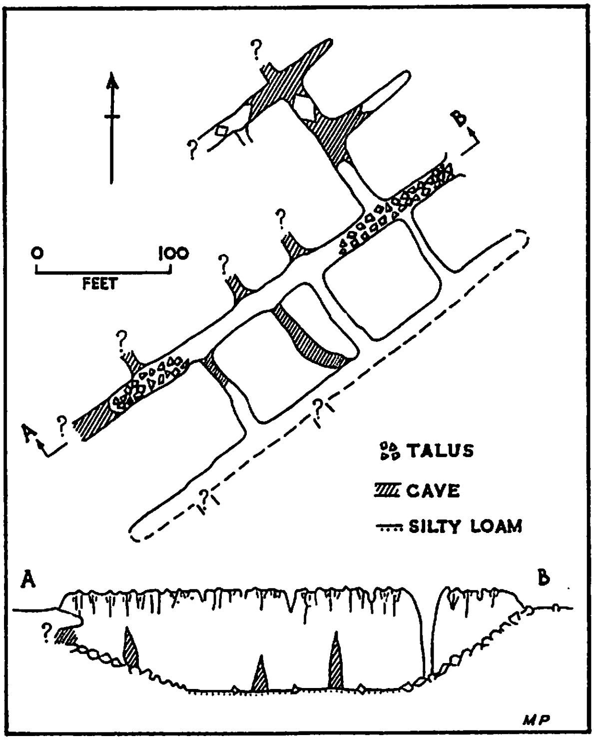

Fig. 3. Sketch of a small of „giant grikeland" near Geikie Gorge.

The areas of enclosed karst corridors are surrounded and penetrated by integrated valley systems of box-like cross-section. It is inferred that they are derived from the corridor networks. The roofs of the fissure caves collapse, and link more and more of the corridors into one system. The flat floors of the corridors extend both lengthwise and laterally, presumably by lateral corrosion. Some of the intervening ridges, which are seen in all stages of destruction, are eliminated in this way. When interconnected by these means, the box valleys retain a completely rectangular, joint-controlled branching pattern. Dry silty beds of wet season streams are inset at the most a few feet in their floors and form confluent systems. But streambeds are not universal; in other parts there are solely flat floors in rock and soil apparently subject to sheet flow only. The divides between different stream systems may be mere rises several feet only above the flat floors on either side, or else vertical walls of rock. The valleys are more continuous and confluent than the stream courses within them, which sink into the floors or enter small caves in the valley walls with some frequency. However, the downward gradients are scarcely interrupted by these watersinks, which usually occur in small clay or silt-floored hollows no more than 4—5 feet down amongst the floor outcrops or at the foot of the flanking walls. The longitudinal gradients of the valley systems at these points of sinking are generally so slightly reversed that the drainage disruption in this way is not discernible in the air photographs (Fig. 4).

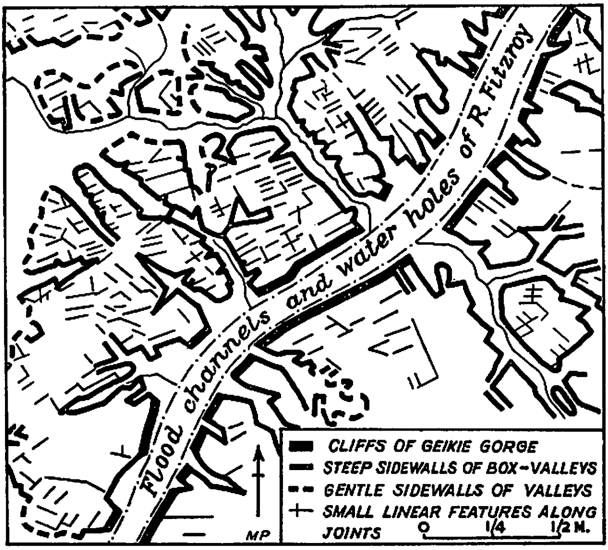

Fig. 4. An area of box-valley network near Geikie Gorge.

Secondary precipitation of travertine occurs fairly requently along the stream beds. Travertine „tongues‘ are found in a valley half-way between

Siphon Spring and Horse Spring in the Horse Spring Range. Such travertine levees end in a small enclosing dam and tend to occur in groups. These depositional features no doubt relate to the period of declining flow at the end of the wet season; the tendency to seal the valley floor in this way hinders sinking underground and promotes valley widening (BRANNER, 1911).

The course through the backreef Pillara Formation of the stream which emerges at Cave Spring (east of Bugle Gap), shows the various landforms already discussed in association (Fig. 5). Immediately this stream leaves

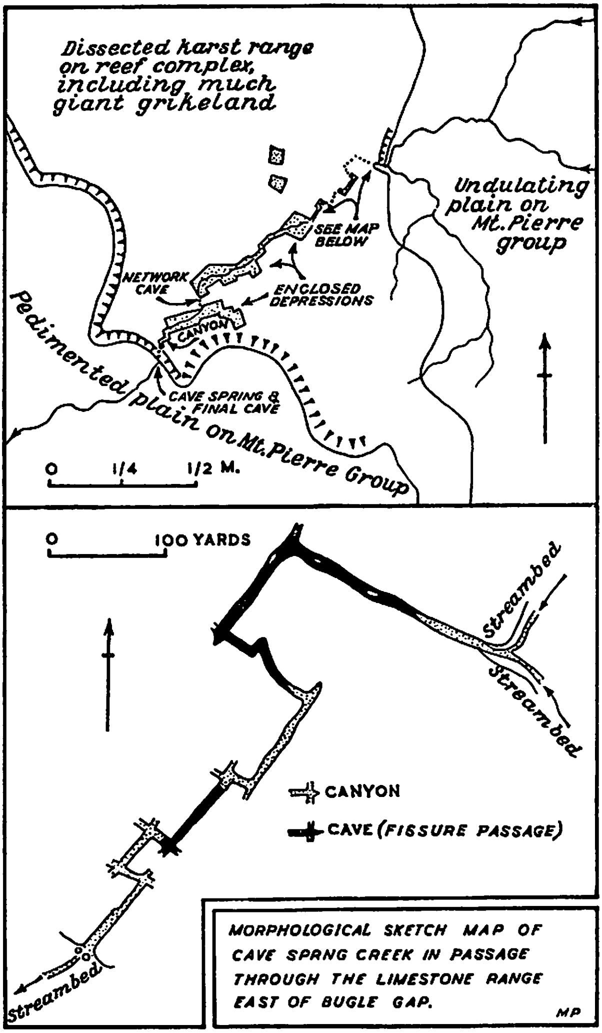

Fig. 5. The course of Cave Spring Creek through the limestone range east of Bugle Gap.

the gently undulating relief on the impure Mt. Pierre Group to enter the „giant grikes“ of the Pillara, its wide, open valley becomes a narrow vertical-sided gorge which in less than a hundred yards passes into a zigzagging fissure cave about 40 feet high, at the most 20 feet wide, and 250 yards long. There follow stretches of zigzagging slit canyons (100 feet deep and 10—20 feet wide) and stretches of vertical-walled depressions with flat alluviated floors. The stream then passes underground and the limestone mass is honeycombed with a network of fissure passages; there are pools in the cave passages during the dry season and it is clear that the river floods most of them in the wet season. The stream then traverses the W. half of an enclosed depression about 450 yards long and 100 yards wide; this shows a magnificent contrast between vertical, solution-furrowed walls and a flat floor, partly covered with alluvium and residual soil and partly by planed rock. A slit canyon leads the stream from this depression into the final cave of Cave Spring. From the cave, the stream emerges in the wet season to cross the flat plain of Bugle Gap, developed in the Mt. Pierre Group. The larger enclosed depressions along this stream are clearly due to the fusion of numerous giant grikes and the elimination of the intervening ridges. Floodwaters from the stream spreading over its alluvium and attacking the base of the surrounding cliffs are responsible for the process of enlargement.

Such branching, outwardly graded box-valley systems, are characteristic of the more advanced stage of the dissected karst. Two miles north of Windjana Gorge in the Napier Range such an elaborate system penetrates almost the full width of the range. From the broad mouth it is possible to drive a vehicle over planed rock floors up tributary after tributary until they narrow drown so much that it is necessary to back out between vertical walls of limestone. This integrated valley system penetrates deep into the middle of the most rugged ‚giant grikeland‘.

Not everywhere, however, are the valleys graded longitudinally in this way. In particular where the range wall is high and the undissected plateau reaches close to the margin, the stream courses show an alternation of gently graded reaches with steep waterfalls. This is typical for instance of the Morown Cliff margin of the Oscar Range and as this ‚storying‘ here occurs in steeply dipping forereef and in unbedded algal reef, it cannot be given a structural explanation. Nor does it seem the result of successive phases of rejuvenation. This ‚storied‘ relief is regarded as yet another expression of the tendency of solution to out either vertically or horizontally, a tendency operating at all scales in the relief.

Apart from the karst corridors already discussed, enclosed depressions are comparatively few, considering the substantial areas of dissected karst in the Ranges. It is significant that BLATCHFORD (1927) shows no enclosed depressions at all in a fairly detailed contoured map of part of the Emanuel (Rough) Range. Conical or basin-shaped dolines, typical of temperate karst, are rare, nor was anything comparable to the cockpits of tropical humid karst encountered. The biggest example of a doline is a special case; it is a large collapse doline leading down into the middle of The Tunnel, the largest known cave in the Ranges. A small conical collapse doline, 20 feet across and 20 feet deep was also met with just west of the inner end of Brooking Gorge, but this was an isolated example. There are, however, a number of enclosed depressions of rectangular plan, with flat floors and with steep or vertical walls, such as the one on the course of Cave Spring creek mentioned above. The floors are mainly covered in alluvium or residual soil but rock floors also occur in parts. Stream channels sometimes traverse the floors and disappear into small holes in the alluvium or enter caves in the surrounding walls. These depressions do not correspond well with any of the classical categories of enclosed karst depression, having the dimensions of dolines but some of the aspect of poljes.

The largest of these depressions lies in the Napier Range about halfway between Barker Gorge and Old Napier Downs Homestead. It is about one mile long and has a maximum floor width of 200 yards, though the area draining into it is elongated along the strike of the forereef beds, and the eastern end follows a joint system cutting the strike at an acute angle. Apart from one or two cols, the surrounding walls rise 100—150 feet above the depression floor, which is itself 100 feet above the outer marginal plain. From that plain, it is separated only by a narrow belt of dissected plateau, which presents steep walls both to the plain and to the depression. The inner wall of the depression is much broken into ridges and pinnacles by corridor valleys. The western end of the depression consists of the fairly narrow valley of the main stream bed coming down from the plateau. The central, widest parts have a loam-covered flat floor about 500 yards by 150 yards and on the southern side, streams from east and west disappear into three small entries into the rock. The eastern end of the depression consists of a series of more or less circular dolines, which get deeper and more rocky eastwards towards the outer margin of the range. A fresh collapse hole, about 15 feet across and not far from the eastern end of the central alluviated flat, probably lies on the line of the main underground drainage from this ‚miniature polje' (Fig. 6).

S.E. of the depression, a major outflow cave occurs in the outer wall of the Napier Range and from this Old Napier Downs Cave runs the only stream issuing from this part of the range. It seems almost certain that this is the outlet of the depression. In the dry season no watertracing was possible. Nor was it possible to press to the limits of exploration of the cave, but survey of the parts explored showed it to a leading in the appropriate direction1).

Another type of landform characteristic of the dissected pure calcareous formations of the area is in some ways intermediate between the large enclosed depressions and the outwardly sloping and widening box-valleys; it deserves separate mention and can be designated as the ‚marginal amphitheatre'. Through a gap in the outer wall of the range, the marginal

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1) The cave is almost horizontally developed, a flow-stone staircase leading down to the plain, 20 ft. below. Rimstone barriers inside the cave enclose still, clear pools, the last one emerging from a water-trap, which halted exploration. Calcite crystals form on these pools in the dry season, but it is clear that this level of the cave is regularly used as an outflow in the wet season. Water also emerges from tubework at the base of the cliff at plain level and the more regular wet season outflow takes place at this lowest level.

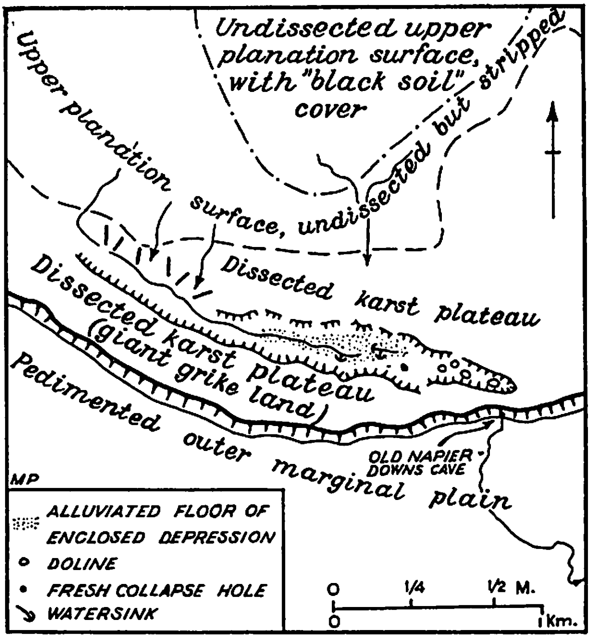

Fig. 6. Enclosed depression in Napier Range close to Old Napier Downs Station.

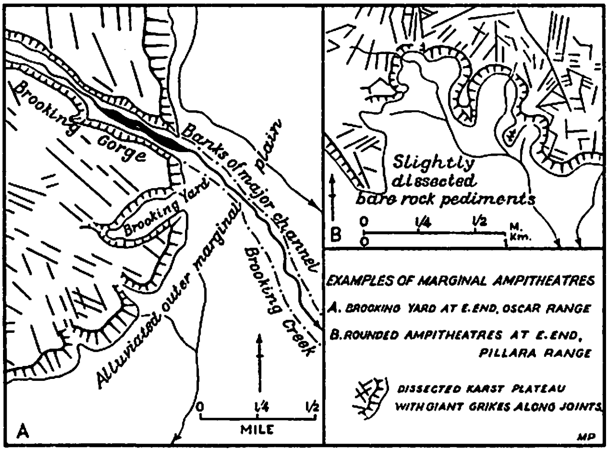

Fig. 7. Examples of marginal amphitheatres.

plain enters into the range and expands over a wider area, which is generally angular in plan but in some cases is round and somewhat cirque-like. Brooking Yard, a few hundred yards west of Brooking Gorge in the Oscar Range, provides an excellent example (Fig.7). Examples are also found in the southern flank of the Pillara Range just east of the Home Range. The rock or soil-covered floor may be flat or slope gently upwards from the entry to the steep or vertical surrounding walls. Sometimes the entry is so narrow and the interior expansion so immediate and substantial that the conversion of a former enclosed depression by collaps of an exit cave or arch seems to be indicated. This may apply to two instances in the Morown Cliff. In others, the gap in the marginal wall is so wide that such a conversion, if it ever happened, must have taken place much earlier in the evolution. Streams cross the floors of some of these marginal ampitheatres, generally entering by a waterfall down the inner wall. Spring activity is sometimes involved, one instance being the square-cut marginal ampitheatre, about two miles S.S.W. of Brooking Yard. In the dry season of 1959 no springs were active but two groups of low travertine terraces in front of small recesses in the backwall were clearly sites of two springs in the wet season. The building up of these terraces may have the effect of deflecting laterally the point of emergence of the spring, thus causing the locus of undercutting of the inner wall to move.

More restricted than the assemblages of landforms in the dissected karst so far described, are areas of separate towers, pinnacles and narrow ridges, scattered over an almost flat rock plain, which is often thinly and patchily veneered by soil and rock debris. This is a type of tower karst (Turmkarst), though admittedly on a small scale, because of the strictly limited available relief. About 150 feet was the maximum height encountered in a tower in the Limestone Ranges and most are much lower, but this is not sursprising in view of the available relief. The abruptness with which the towers rise from the surrounding surfaces and the steepness of their sides, are however fully characteristic. The box-valleys, the somewhat polje-like enclosed depressions and the marginal ampitheatres enlarge nd intersect to produce the fields of pinnacles and arêtes. Every transitional assemblage between the networks of huge bogazi to the stage of scattered towers is represented in the area.

The advanced stage of tower karst is most widespread in the narrow belt of steeply dipping Oscar Formation forereef on the S. E. flank of the Proterozoic inlier of the Oscar Range. This development has been significantly promoted by runoff from the impervious quartzites behind, and spreads of quartz sand and quartzite pebbes from the inlier occur quite frequently over the flat surfaces between the towers. Mechanical abrasion by streamfloods and sheetfloods is playing a more significant role here than it would do in a purely karst situation (cf. Carlsbad Cavern area, U.S.A.; Horberg, 1949). However, it is not a necessary element in the production of tower karst, because it develops in other situations. Thus, tower karst is found along the southern flank of the Oscar Range both to the N.W. and S.E. of the Proterozoic inlier well beyond any possible influence from the presence of the insoluble rocks. There is some variation of form of the residual limestone projections. Where the beds dip, the down-dip side is usually less steep, with inclined bedding plane surfaces in evidence, though they are usually undercut and steepened at the base; the tops are dominantly sharp pinnacles or knife-edged arêtes. Where the bedding is nearly horizontal, flat-topped symmetrical towers result. This is true of the N.W. tip of the Oscar Range and also of a field of towers developed in the Fossil Downs Formation and located about one mile S.E. of J. K. Yard east of the Geikie Range. At Castle Rocks east of the Hull Range, the Sadler and Fossil Downs Formations give rise to some of the highest towers in the Ranges, though they are somewhat squat and blocky because of their smaller number and larger individual area. A similar tabular type of tower is found in the Pillara Formation in an area of advanced dissection E. of Leopold Downs on the Oscar Plateau and also east of Bugle Gap.

III The Modern Planation Surface

When the tower karst stage is reached, none of the upper surface of erosion survives and the new planation surface is established over most of the ground. However, most of the modern surface in the area has developed in a different way; even on the rocks giving rise to the full karst sequence there is a separate manner of planation in action.

Much of the outer marginal plain and of the plains separating the smaller ranges of the south-east such a Bugle-Gap, is developed on the Carboniferous Laurel Beds, the Devonian Fairfield Beds and Mt. Pierre Group. All include a high proportion of impure calcareous and non-calcareous beds so that these parts of the plains did not develop in the karst sequence described above. Moreover the Lamboo Complex underlies much of the inner marginal plains. Also, both inner and outer plains are traversed by the broad flood-plains of the Margaret, Fitzroy, Lennard and Barker, where lateral river erosion has been at work. Nevertheless, portions of the plains remain unaccounted for and the contact of plain and range throws light on them.

This contact has already been described as exceedingly abrupt, so much so that the margin of the ranges can have the steepness of a marine cliff. This similarity has given rise to the hypothesis that features such as the Morown Cliff are indeed ancient sea cliffs exhumed from beneath a cover of Permian rocks. This interpretation cannot be contraverted simply by pointing to the coincidence of the most striking cliffs with the massive algal reef facies, since structural control could have determined the varying nature of the Permian marine cliffs. Nevertheless there is a strong case against the exhumed sea cliff concept.

1. Equally steep cliffs occur along the inner side of the Napier Range overlooking the inner marginal plain, sometimes where it is very narrow, e. g. near the eastern ends of Windjana George and of The Tunnel. The possible fetch is far too small to produce waves capable of these effects.
2. Equally steep cliffs occur within the marginal ampitheatres, the larger

enclosed depressions, and along some of the box-valleys where wave action cannot possibly have occurred.

3. The outer wall and scarp of the northern Napier Range, for example, follows completely the winding strike of the forereef beds. This includes the Barent Spring promontory which projects 2 ½ miles from a base width of about one mile to its rounded tip of less than half a mile. Marine action powerful enough to produce cliffs up to 250 feet high on both sides of this promontory, would not not have respected the structure so completely; the tip would have been cut back across the strike in some degree at least. Processes more subject to structural control than wave attack have been responsible for this delicate etching out of structure.

It has already been made clear that steep scarps and vertical walls are generally characteristic of the karst cycle operating in this area, the steepness varying with the dip, massiveness and purity of the facies.

Similarly, the hypothesis that the outer marginal walls and scarps represent in general the original outer face of the reef structure revealed by differential erosion, may be rejected. The backreef side can have had no such steep initial face towards the landmass beneath the lagoon, yet it presents a steep wall in this direction along much of its length. Why should the outer margin fail to be due to modern erosion when all the other steep cliffs in the limestone are unavoidably so interpreted? Occasionally differential erosion at the reef front does seem to occur. Thus on both sides of Bugle Gap the scarps in the forereef beds seem to coincide with the contact of the Sadler Formation with the Mt. Pierre Group and the eastern tip of the Pillara Range also appears to represent the actual point of a reef. But in general this exact correspondence of range margin and formation boundary does not apply.

That the marginal cliffs are actively developing features, is suggested by the hanging character of numerous valleys in the ranges. Thus several valleys in the Morown Cliff open out 50—150 feet up the cliff with a sheer fall below. In the Napier Range two miles north of Stumpy's Soak, a valley from the range summit ends in a very steep waterworn bed, recessed only slightly into the cliff margin; about halfway between Barker Gorge and Old Napier Downs Homestead, a reliable water supply point is found in a large plunge pool at the foot of a 25 feet waterfall in the course of a streambed descending abruptly from the Napier Range. With such evidence of erosional action, it is hard to see how the hanging relationship has survived without retreat on the part of the cliff as a whole.

There is also direct evidence that the outer marginal scarps and walls are not differentially eroded primary depositional features. Along the foot of these cliffs magnificent examples of bedrock pediments are found. Close to the cliffs, the proportion of rock outcrop to soil varies from between 50 % to 95 % of the ground, but away from the cliffs the proportion of the outer-cropping rock is only a small percentage. Between the outcrops are thin veneers of soil, generally black and heavy textured, together with lighter coloured loamy soils. The rock pediments are so well planed by erosion that it is possible to drive a vehicle readily along with no track preparation. The piedmont angle is nearly everywhere sharp and a vehicle can usually be brought within a foot or two of the cliff. In cross-profile, there is considerable variation (Fig. 8[1]). Sometimes it is gently concave or convex, with average slopes of 2—3°; at other times virtually horizontal, diversified only by low strike ribs rising no more than a foot or two from the general level. Shallow solution pans are common on the outcrops. Occasionally small dolines 1—3 feet deep and 10—20 feet across occur on these pediments. Additionally small inselbergs or towers detached from the main scarp diversify them, but these are unsual. The link with the tower karst areas can be illustrated, however, by the instance of the field of towers east of J. K. Yard, where they are set on fine bare rock pediments of convex profile, with a little soil and vegetation lining the joint pattern.

Most of these exposed pediments have the same rock types with the same attitude as seen in the marginal scarp or wall behind. There has been erosional retreat of the reef margin, even if this only demonstrable for a few hundred feet. Many of the pediments are not shown as bedrock areas on the published 4-mile geological maps but are shown as covered with superficial deposits. Often this may be due to their narrow width preventing their representation on this scale, but this is not always so, e. g. the wide rock pediment near Wire Springs on the southern side of the Fairfield Valley. The reconnaissance photogeological mapping tends to use the marginal scarp as the boundary of the bedrock. However, the 8-mile solid geology map does extend the boundary of the reef formations outwards from the ranges to include all the exposed pediments.

The morphology of the exposed pediments is continued both longitudinally (along scarp foot) and transversely (outwards into the marginal plains) into similar surfaces which carry covers of calcrete (caliche), black soils, other residual soils, alluvium, or combinations of these superficial deposits. These are also pediments. In transvere profile, such veneered pediments are usually concave, uniformly sloping, or flat, with average slopes up to 3°. Longitudinally they are exceedingly level like the exposed pediments, and are only crossed by stream beds. Such streams issuing from the Limestone Ranges rarely have beds more than a few feet deep, though the allogenic rivers crossing the Ranges have beds up to 30 feet deep. Where calcrete is developed, ridges and berms are common, such ridges being up to 10 feet high and 200 feet across; in plan they form complex patterns but a usual direction is parallel to the bedrock strike in the nearby range margin or exposed pediment. Where a bare pediment lies behind a belt of calcrete ridges, the innermost ridge is often parallel to the strike. Near Yammera Creek in the Napier Range, a low calcrete ridge occurs entirely surrounded by bedrock pediment surface. It has been suggested that the innermost caliche ridge represents the outer limit of the reef formations and that the less purely calcareous Fairfield Beds underlie the calcrete farther out. However, the instance just mentioned and the fact that calcrete covered pediment in places reach to the foot of the range wall, e. g. along parts of the Morown Cliff and along parts of the northern side of the Pillara Range, argue against this adoption of the innermost calcrete ridge as the boundary of the reef formations.

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[1] See appendage.

The calcrete ridges resemble the caliche ‚pseudo-anticlines' of PRICE (1925), which are derived from shale-sandstone-limestone interbeds, more comparable to the Fairfield Beds rather than to the Oscar Formation. However, true caliche ‚pseudo-anticlines' along joint patterns occur south of the J. K. Yard on the Fossil Downs Formation, where it appears to consist entirely of calcarenite (JENNINGS and SWEETING, 1961). Thus, there do not seem to be lithological factors which restrict calcrete ridges to the less purely calcareous formations.

The view that the calcrete and other covered pediments usually rest on the formations composing the nearby ranges is in general sustained by the mapping of the solid geology of the 8-mile Bureau of Mineral Resources geological map of the area. Occasionally, this is not so and the solid geology mapping can be called in question.[1])

The most extensive plain undoubtedly developed on the reef complex, as part of the modern surface, is the plain east of the Geikie Range on the Fossil Downs Formation. From Neilabublica Bore on the south to the J. K. Yard in the north it is 10 miles long and 3—5 miles, west to east, wide. It is a gently domed surface with widely spaced shallow drainage lines. Low strike ribs occur with calcrete ridges in fields. The occurrence of calcrete pseudo-anticlines and also the pedimented tower karst east of the J. K. Yard rest on this surface. It has a gentle rise to the west so that its rather irregular margin with the Geikie Range is a much less sharp feature than usual. Nevertheless, this area provides a fine example of a small pediplain; it is dominated by a gentle convexity of form in contrast to the multi-concavity attributed to such erosional surfaces by L. C. KING (1953).

It is now appropriate to consider the processes whereby the marginal scarps and pediments of the Limestone Ranges originated and are maintained. It is, of course, recognised that pediments are characteristic of other rocks in the morphoclimatic system involved. For example, parts of the inner marginal plain are composed of pediments in the Lamboo Complex, which make a sharp piedmont angle with the steep margin of the hill country on the crystalline basement. Similarly, near the Devonian conglomerates, e. g. east of the Van Emmerick Range, there are pediments in these rocks abutting abruptly on the steep margins of the conglomerate ranges. However, the greater perfection of the pediments, steepness of the range fronts, and sharpness of the piedmont angle in the Limestone Ranges calls for special discussion, even though the general problem of pediment formation will not be considered.

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1) In N.Australia, black soil plains seem to be closely associated with calcareous or partly calcareous formations. Large areas of the inner marginal plain behind the Napier Range, which possess a cover of black soils are mapped as Lamboo Complex on the 8-mile geological map. It is likely that a thin veneer of back reef facies remains beneath these black soils despite the presence of small Precambrian hills projecting through in the vicinity. A little south of the Van Emmerick Range, strike ribs of limestone show that the planed rock surface of Pillara extends two miles east of the Pillara Range there. Immediately south of the Pillara Range near Menyous Gap, there is a small black soil plain which is also likely to be veneered with Pillara rather than resting directly on Lamboo as is shown on the geological map.

The initiation of the outer scarps of the reef complex is readily understood in terms of the etching out of the reef face from the less pervious and mechanically weaker Fairfield Beds banked against it. On the other side, however, the backreef facies would act as weak rock vis a vis the Lamboo Complex despite its considerable perviousness. But runoff from the crystallines would be concentrated against the margin of the soluble limestones and produce an inward-facing scarp. The maintenance of these range margin scarps by extension of surrounding pediments follows.

On the inner side, in particular, the effects of the big rivers from the impervious oldland of W. Kimberley are to be noted. For some distance on either side of the entrance of the Fitzroy into the Geikie Gorge and of the Lennard into Windjana Gorge, alluvium reaches to the foot of the limestone wall. Even though the gorges are filled deeply from side to side in wet season floods, they cannot cope with the volume of discharge and so the rivers spill over their banks and spread widely along the inner side of the limestone. By lateral corrosion, these aggressive waters maintain the steepness of the marginal wall and cause it to retreat. Eastwards from the northern end of the Geikie Gorge to the J. K. Yard, the alluvial plain was examined and the abrupt margins of the small hillocks and towers which project through the alluvium, clearly result from the attack of the flood waters. There is also a nearly flat area of bedrock limestone almost entirely surrounded by alluvium and traversed by several flood channels of the Fitzroy in which billabongs persist into the dry season. Intense spongework in the rock floor of the billabongs results from solution by the standing flood water. A remarkable number of limestone flags and boulders rest on the surface of the alluvium; they appear to have risen to that surface and to float as if in a denser medium. Flood waters of the Fitzroy also help to break up the plateau enclosing the northern end of the Geikie Gorge. Here levees have been built across the mouths of the box-valleys tributary to the gorge; in the wet season flood waters are impounded behind these levees and no doubt contribute by lateral corrosion to account for the disproportionately wide, flat alluviated floors of the lower parts of these side valleys.

Similar action takes place on a lesser scale where the rivers emerge from their gorges through the limestone. Thus a great leaning pillar some 80 feet high just east of the exit of Windjana Gorge is in active process of breaking away from the Napier Range Cliff; alluvium from the Lennard laps around the rock debris at its foot. Alluvium of the Margaret and the Fitzroy is also banked against the southern flank of the Geikie Range for many miles; depressions between the main levees and the range margin are regularly occupied by flood waters. But important as they are locally, the direct effects of the major rivers do not affect the main part of the range fronts and other processes must therefore be sought.

Rainfall sinking into the limestone and underground streams draining from the enclosed depressions emerge at the outer foot of the limestones, undercut and steepen the marginal scarp. Small cliff-foot caves where such underground water emerges are numerous. Most of these caves are dry in the dry season but in some, water persists throughout the year, though not generally in sufficient volume to flow more than a few yards down a small silt fan into the plan. Spongework and anastomosing tubework are common features of these cliff-foot caves indicative of saturation of the rock at times up to 5—10 feet above the plain level. Often there is a rising exit to these caves.

It might be expected that risings of this type would render the marginal cliff or scarp extremely irregular; this occurs only occasionally. In this connection a fine example from the cliff-foot caves beneath a 250 feet wall in algal reef facies N. E. of Barnet Spring in the northern Napier Range must be described[1]) (Fig. 9[2]). For 100 yards between two rockfalls there stretch shallow caves usually only 15—20 feet deep from the cliff face, but with a maximum of 40 feet. Solutional undercutting leads to debris falls from the face but the debris is not always removed pari passu with its accumulation. Hence a low ridge of rock fragments and soil accumulates in front of parts of the cliff-foot cave. One result of this is that drainage from the solution tubes in the limestone runs laterally along the cave and in some cases back into the rock, extending the cave laterally in consequence. Rock benches 5—8 feet above the cave floor and above the nearby plain, together with roof rock pendants, indicate a slightly higher relict level of corrosion of the cliff-foot corresponding to a former higher pediment level. The pediment here was almost entirely soil-covered, with occasional small occurrences of calcrete; its longitudinal and crossprofiles were extremely flat. On the south side of the Barnet Spring promontory, a shallow channel 3—4 feet deep in silt and rock debris lay along the foot of the cliff for 50—60 yards and was followed by a stream flowing even in the 1959 dry season. This stream emerged at one end but went back into the cliff in an „in-out“ cave for some 20—35 yards of this length.

Lehmann (1956, 1960), has stressed the importance of cliff-foot caves in tropical humid karst development but he was dealing with inflow caves in the cliffs bounding poljes and karst margin plains. Such an arrangement leads much more readily to undercutting and cliff maintenance than the instances described. This type of inflow cliff-foot cave is, however, rare in the Limestone Ranges though not entirely absent.

Although rock shelters were frequent, long lengths of cliff-foot cave, the products of lateral diversion of outflowing drainage, were the exception rather than the rule. Cliff collapse induced by cave development can block particular exits completely and cause outflow at an independent point. Moreover, dry season precipitation of secondary calcite can raise the level of outflow and so lead to deflection to a fresh point of rising. An example at the foot of the Morown Cliff had a 12 feet high series of travertine terraces nearly blocking the mouth of a cliff-foot cave and this may well cause a lateral shift of emergence, tending to maintain a continuous cliff. Thus at Elimberrie Spring in the Oscar Range there are two former outlets apart from the present one.

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1) It seems likely that these caves form part of those named Wangahinnya Caves by Basedow (1918).

2) See appendage.

Many important springs do not possess such cliff sites, but lie along the intermittent drainage lines breaking up the marginal cliffs and scarps. They may rise in the stream beds (a) in the marginal pediment, e. g. Moolee Spring (Oscar Range), Pinnacle Yard Spring (Emanuel Range), (b) approximately in line with the scarp, e. g. Horse Spring (Horse Spring Range), Brooking Spring, or (c) within the range, e. g. Palm Spring, Nullara Spring (Oscar Range), Siphon Spring (Horse Spring Range), Pillara Spring (Pillara Range). The springs in the last group lie at varying heights in relation to the nearby pediment; such diverse relationships suggest that the springs are not invariably contributing to the development of the marginal scarps.

There remain long stretches of range margin where the processes so far discussed — lateral corrosion by river waters flooding over an alluvial blanket, undercutting in cliff-foot caves by rising underground water — do not apply. We are faced with the fundamental problem of pediment formation in the semi-arid tropics.

Examples of small rock fans of predominantly convex profile, where streams emerge from marginal scarps, occur in the area, notably along the N.E. Flank of the Pillara Range but also in the Oscar Range 2 miles S.W. of Brooking Gorge. On this basis D. Johnson's theory of lateral river planation cannot be excluded completely from the origin of the area's pediments. They are so occasional, however, that this mechanism cannot be considered of the first importance and the paucity of adequate abrasional tools calls for planation by corrosion as much as by corrasion.

The high intensity of precipitation and the lack of a closed vegetative cover in the area favour sheetflood action, which many authorities regard as vital in pediment formation. In the Limestone Ranges where a bare rock pediment merges downslope with a black soil plain, a line of shallow crabholes often marks this junction. These could be the result of water flowing off the rock pediment in a complete sheet and sinking underground along this line. Abrasional tools for sheetflood action occur in places in the Ranges. Some of the impure facies yield appreciable amounts of quartz sand; thus the pediments on the eastern side of the Napier Range east of Wagon Pass carry a great deal of sand derived from the Pillara Formation. Quartz gravels from the Van Emmerick Range are carried by Hawkestone Creek onto the pediments close to the Barnet Spring promontory. There are also the inliers of Precambrian; thus it is significant that in two short sectors S. W. of the Oscar Range core of Proterozoics, the Oscar Formation has been completely planed by pediments, which now reach right through to the quartzites. Because of its susceptibility to solution, limestone must be particularly responsive to sheetflood action. Any projections of rock through the thinnest of impervious veneers will be subject to lateral corrosion during sheetfloods. Solution pans are common on the bare rock pediments and become the locus of solutional activity during light falls of rain and at the closing stages of the sheetflood activity associated with heavy precipitation.

The concentration of the rainfall into a very short rainy season means that for most of the year surface drainage is negligible and even groundwater movement is extremely restricted in many years. Very few springs were flowing at all in the dry season of 1959. Subsurface rotting is impeded which in turn limits linear mechanical erosion along stream courses, a factor which BIROT (1949) has stressed in relation to pediment formation. In the carbonate rocks of the Limestone Ranges solutional preparation of the rock is inhibited, which will prevent stream incision in the wet season.

Nevertheless, soil and ground water movement is, or has been, sufficient for the formation of calcrete ridges. Where these are parallel to the strike and the range front, they promote pediment formation by ponding back sheetfloods along the foot of the scarps. There is a good correlation between extremely flat bare rock pediments and well-defined bounding clacrete ridges. This intervention of calcrete ridges in pediment formation seems especially important along the S. W. flank of the Oscar Range. It represents a significant karst particularity in the general problem of pedimentation.

The pediments of the Limestone Ranges seemed to be generally active, not relict, landforms. Pediment dissection is rare. The clearest case occurs east of the Castle Rocks, where incision of about 10 feet has left the pediment as a rock terrace. There is also some pediment dissection of 10—15 feet depth east of the Home Range and south of this end of the Pillara Range.

5. THE GORGES AND GAPS

Although the gorges and gaps of the Limestone Ranges can only be fully understood as part of a wider study of the drainage of the whole Fitzroy Basin, some discussion of them is necessary. The impressive Geikie and Windjana Gorges were among the major watergaps, which led to the recognition of an important transverse or discordant element in the Fitzroy Basin drainage. Higher up their courses, both the Fitzroy and the Lennard rivers break through the quartzite ridges of the King Leopold Range also in discordant gorges. Much of the drainage is, however, adjusted to structure and longitudinally arranged along the strike; in the Devonian belt the S. E. - N. W., drainage along the Fairfield Valley virtually parallel to the Napier Range may be mentioned as an instance. JUTSON (1934) discussed five possible explanations of the water gaps and favoured their development on a S.W., sloping surface followed by the growth of subsequent elements and piracy.

(a) *The Watergaps*

The Geikie Gorge is incised about 200 feet below the flat plateau level, its width is usually about 300 yards but it is in places about 900 yards. The course is generally N. E. - S. W., swinging only gently from it apart from two pronounced meanders near the southern end. The walls are nearly vertical, except at meander spurs, but even there they are steep. They conform much more closely to the style of intrenched than of ingrown meanders (RICH, 1914). Crossing Pillara, Copley and Geikie Formations, the gorge is mainly in subhorizontal brackreef but near its southern end, it cuts through the line of the barrier reef and across the strike of the forereef beds.

The Lennard River passes through both Pillara and Napier formations and crosses the trend of the Napier Range obliquely along an E. - W. line. The gorge, known as the Windjana, varies between 150 and 250 yards in width and is about 250—300 feet deep. It meanders markedly in that its length is about 2 ½ miles in crossing the mile-wide range. The walls are vertical or near vertical hence again the meanders are intrenched, not ingrown. The meandering river and the winding barrier reef cross each other three times. Neither the strike of the forereef beds nor the jointing have any effect on the course of the river (PLAYFORD and JOHNSTONE, 1959).

Two other watergaps in the Limestone Ranges are due to major rivers rising well away from the Devonian belt. First, the Barker River flowing S. W. from the King Leopold Range crosses the Napier Range at right angles to the strike of the Napier Formation; the gorge is short and straight, broader in relation to its height than the previous watergaps, and its walls are still steep though broken. It is localised along a wrench fault (RADE, 1961). Secondly, not long after breaching the King Leopold Range, the Margaret River cuts through the Hull Range, near its southern end, in a short straight watergap at right angles to the N.W.—S. E., strike; it is significant that only a fragment of the cuesta, some 900 yards long, lies south of the river. Beyond is a broad alluvial plain over which the Margaret spreads in flood time; the river thus goes round the end of the range as well as through it (Fig. 10).

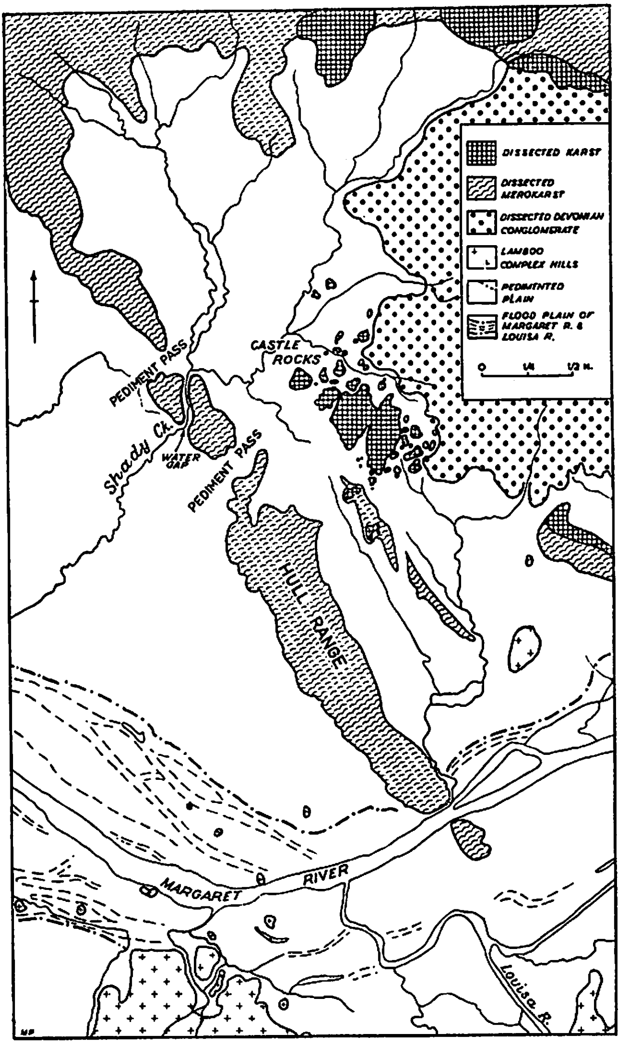

Fig. 10. Water-gaps and pediment passes in Hull Range.

Smaller watergaps arise where rivers and creeks of local origin traverse the Ranges. Near the northern end of the Napier Range, Hawkestone Creek and a left bank tributary break through the limestone in adjacent watergaps. The tributary rises in the Van Emmerick Range as does another tributary of Hawkestone Creek a little farther south. All these three gaps are found at inflections in the course of the Devonian reef and some structural guidance is possible. Between the Barker and Windjana Gorges, Yammera Creek, which rises in the inner marginal plain, cuts through the narrow Napier Range at right angles to the strike. Farther south still along the Napier Range, McSherrys Gap is a short E. N. E. - W. S. W. watergap almost at right angles to the strike of the Napier Formation; tributary streams from N. and S. E. along the strike join just before the gap.

A number of small streams rising on the limestone of the Oscar Plateau flow S. W. in narrow valleys and gorges through the Proterozoic quartzite ridges and then transect the strike of the Oscar Formation. Such are the 95 Mile, Mt. Wynne, Camaratoechia and Speiler Creeks. Others such as the 97 Mile and Linesman Creeks rise within the Proterozoic, cross some of the quartzite ridges and then the limestone belt. Once they are outside the range, some of the creeks are deflected N. W. or S. E. along the outer marginal depression, though others such as 97 Mile and Linesman Creeks continue roughly in their original direction. Through the northern end of Emanuel Range, Gap Creek has cut a slightly curving gorge across the strike of the Pillara; it is underfit and seems to have lost some of its headwaters by capture.

Mt. Pierre Creek has produced one of the most spectacular watergaps in the region but with a trend different from N.E.—S.W. It rises on the Permian plateau S. E. of the Limestone Ranges and persists in a N. W. course more or less all the way to its junction with the Margaret. Mt. Pierre Gorge is cut into the pure calcareous rocks of the Sadler Formation. The Gorge is about 700 yards long, only about 30 yards across, but 250—300 feet deep. A strong N. W. dip is dominant through the gorge, which is, however, situated at a pronounced inflection in the strike of the forereef beds.

The problem of interpretation can be considered in the light of this knowledge of the transverse drainage elements. Antecedence can be rejected; stratigraphical knowledge today indicates that the main barrier reef of the Napier, Oscar and Geikie ranges has suffered little or no tectonic disturbance, apart from a slight basinward tilt. The transected ranges are clearly due to differential erosion. The intrenched meanders are clearly due to rejuvenation since the time of the upper planation surface. Yet this notion only leads to the further question as to why the rivers were discordant in the previous cycle. The upper surface represents an advanced degree of development during which a close adaptation of drainage to structure is to be expected.

Furthermore, headward erosion and stream piracy as an explanation is competent to account for isolated occurrences of watergaps, but is hardly likely to be the origin of a systematic pattern of those such as is found in the Ranges. Headward erosion also would be guided by structural weaknesses in the resistant ridges; the complete disregard for structural detail of the reef complex in such cases as Windjana and Geikie Gorges argues strongly against this manner of formation.

Superimposition was set aside by JUTSON[1]) on the grounds of lack of evidence for any sedimentary cover from which transverse drainage could be superimposed. However, the idea of such a sedimentary cover inclining gently S. W. from the uplifted heart of the Kimberleys, over which consequents extended on emergence and later cut through to become locked in positions across the strike of the undermass, seems to be the most satisfactory interpretation. Small patches of Grant Formation are now known within the Oscar Plateau and there is now no stratigraphical objection to regarding the streams as former consequents draining N. E. - S. W. over a Permian cover at some stage in the Mesozoic, which were later imposed on the Devonian beneath. It is true that the limestone is particularly favourable to the preservation of remnants of overlying formations and that the Permian may have extensed farther N. E. over the impervious PreCambrian and later removed entirely. Indeed this seems quite an acceptable likelihood over the Lamboo Complex, which does not ride much higher than the Devonian. It is much more demanding, however, to postulate a Permian cover the high ridges of the King Leopold Ranges. Nevertheless, it cannot be completely ruled out as an explanation of the watergaps found in them. Another possibility is that these relate to an earlier phase of superimposition (? Ordovician).

The drainage history is therefore a long and complex one. The subparallel transverse drainage, through the Oscar Range from the Oscar Plateau, also poses a problem. There are streams so close together that it is hard to envisage them as survivals from ancient extended consequents. In fact the Oscar Plateau is a centre of outward drainage; admittedly the streams draining N. E. are short and soon join longitudinal elements, but the elements draining N. W. and S. E. are substantial. The centrifugal drainage of the Oscar Plateau may be due to a slight doming of the former Permian cover at a time later than that of the establishment of the main transverse drainage on the Permian cover.

To summarise, regional superimposition seems the most likely origin of the water gaps in the Limestone Ranges, possibly in more than one phase.

(b) *The Tunnel*

The Tunnel is the best known cave of the Limestone Ranges (JACK, R. L., 1906) and its origin is clearly linked with the watergaps of the area. It was surveyed by the authors and will be discussed in more detail in a separate publication.

In its uppermost course, Tunnel Creek flows S. W. across the Lamboo Complex, then longitudinally N. W. along the inner marginal plain behind the Napier Range, before turning at right angles to enter The Tunnel.

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1) Jutson's own theory is not discussed here because his initial assumptions seem to the present writers to be quite untenable.

The river passes through half of the width of the range in this cave. It emerges in the medial depression of the range in a gorge, with steep walls rising to a maximum of about 200 feet. The significant element in the morphology is that the line of this gorge is continued in virtually a straight line as a windgap above The Tunnel to a point above its entrance. A large, conical doline occurs in the middle of this windgap, leading down through a large roof collapse into the cave about halfway along its length. The resulting two cols along the line of the gap are about 60—70 feet below the general level of the top of the Range. It is clear that down this col level, the Tunnel Creek formerly flowed in a shallow gorge right across the range transverse to the strike of the forereef beds. Later an underground course through the first half of the range developed, leaving part of the gorge as a wind gap to be modified by later solution and collapse to produce the central doline. Meanwhile, the gorge in the second half of the range continued to be deepened as a surface feature. It is a case of underground autopiracy in a transverse gorge of superimposition, though there are complexities of detail. There is a difference in plan of the relict wind gap and the underground river course. The former is almost straight, whereas The Tunnel Cave consists essentially of two reaches at right angles to the strike, joined by a middle reach along the strike. In substituting its underground course for its former surface course, Tunnel Creek has achieved a greater degree of adjustment to structure and has increased its length from about 550 yards to about 750 yards. In several sectors of the cave there are sidewall niches, which relate to former higher levels of the river bed. Some of these seem to indicate a stage of cave development related to a level of the outer marginal plain some 20—25 feet higher than at present.

(c) *The Windgaps*

Menyous Gap falls without discussion into the category of windgap due to capture. It crosses in a gently swinging N.-S. line the N.W.-S.E. strike of the Pillara Range, is about 200 yards long, variers between 50 and 150 yards across and is about 100 feet deep. The steep to vertical walls make right angles with the flat, loam-covered floor of what is in fact a dry gorge. Longitudinally the floor rises very gradually about 25 feet from the N.E. end to an almost imperceptible divide, beyond which a gradual fall of about 10 feet leads to the S.W. end.

It is a simple step from these facts to postulate that here is a former watergap of the Margaret River, when it previously flowed farther S.W. than it does now. On this hypothesis the Margaret from its watergap. through the Hull Range to its present junction with the Fitzroy represents a subsequent element in the drainage eroded for the most part along the less pervious Fairfield Beds and Mt. Pierre Group. This captured the upper Margaret and left Menyous Gap as a windgap. Although the Hull Range Gap and Menyous Gap are not actually in line with each other, this fact does not seriously weaken the argument. Nor is the 15 feet greater altitude of the S.W. end of Menyous Gap over its N.E. end of any moment; this slight reversal of slope does not require much work on the part of the reversed drainage flowing N. E. to the subsequent sector of the Margaret. However, whatever the former direction of flow (and the N. E. - S. W. one seems the most likely) Menyous Gap is undoubtedly an abandoned discordant river course.

Other windgaps in the area differ in character and most probably in origin too. Carpenter Gap is a good example in this group. It breaches the Napier Range about 3 miles S. E. of Windjana Gorge, where the range is only 1,100 yards across. The gap varies in width from 600 to 250 yards. A narrower S. W. part joins a wider N. E. part to give it a „doglegged“ plan. The broad flat floor rises gently from the N. E. to a flat divide almost at the S. W. end, from which there is a gentle fall over a convex pediment with much planed rock outcropping and in front of the outer flank of the range. The sidewalls, in a thin-bedded forereef facies, for the most part are steep but by no means so steep as in the watergaps or in Menyous Gap. It has all the characters of a pediment pass (HOWARD, 1942), due to the meeting of pediment embayments from the two sides of the range — a broader one from the N.E. and a narrower one from the S.E. The conjunction of pediment embayments from the inner side of the range with recesses in the outer side of the range is all that is necessary to produce a gap like Carpenter's Gap.

Recession from both flanks may not be necessary for a pediment pass, however. The broad major box-valley system one mile north of Windjana Gorge (page 26) is virtually an elongated pediment embayment and has nearly breached the range; only a narrow wall 250 yards across remains of the 2,400 yards of the range between the head of the valley and the unrecessed outer wall.

Wombarella Gap is similar to Carpenter Gap; it breaches Napier Range about halfway between Barker Gorge and the watergap of Yammera Creek. It also has the character of a pediment pass, but two residual hillocks project from the floor so that in detail the gap is a threefold one. This detail accords more with the notion of a pediment pass than with that of a water gap. Planed limestones are evident in its crest. There is also a change of facies across the gap, so that it may be partly structurally controlled (RADE, 1961). East of the gap there it a group of Lamboo Complex hills due to a rise in the Precambrian floor. The possibility that runoff from this area at some stage gave rise to a stream crossing the range here cannot be excluded, though any original watergap has since been much modified by pedimentation. However, there is no compelling reason to adopt this more complex history. At two points between Wombarella Gap and Yammera Creek Gap, the Napier Range is nearly breached by pediment recessing from both flanks, leaving narrow but high barriers about 100 yards across. There are numerous other instances of the Limestone Ranges being nearly breached by pediment recessing from one or both flanks.

The most convincing instance of a pediment pass origin for some of the windgaps is found in the Hull Range. Half a mile to the S.E. of the Shady Creek watergap, there is a broad pediment pass about 550 yards across at its narrowest point. Furthermore, just where the Shady Creek enters the range to cross it obliquely, another pediment pass of about the same width breaks directly through the range. In its length of 20 miles, Hull Range is breached by two watergaps, the Margaret River and Shady Creek, ten miles apart. It seems unlikely, then, that formerly there were three watergaps close together within 1 ½ miles of the cuesta's length. In process of superimposition, some integration of drainage must take place and only the major consequents will usually survive to become discordant. These windgaps are more satisfactorily regarded as pediment passes not as former windgaps of capture modified by pedimentation (Fig. 10).

(d) *Certain Special Cases*

Bugle Gap is genetically closely associated with the pediment passes but cannot be classed with them without qualification. This gap is an elongated plain, varying in width between $^{3}/_{4}$ and 1 $^{3}/_{4}$ miles, and between 4 and 9 miles long according to which is chosen of two possible southern limits. The gap is due to differential erosion of the more impervious Mt. Pierre Group between the karst plateaus of the Emmanuel and Sadler Ranges on the west and the unnamed range running southwards from Mt. Pierre Gorge on the east. There is a very flat E.-W. divide about 1 ½ miles across from which streams run to the N. and the S. but they scarcely indent the plain, which is made up of confluent pediments. The divide is thus a broad pediment pass occasioned by the weak Mt. Pierre rocks.

Dingo Gap is more complex in nature than the others, with two distinct halves on either side of the broad median depression or strike vale in the southeastern part of the Napier Range. The S. W. part is a short, straight watergap cutting perpendicularly across the strike of the forereef beds. Immediately across the vale opposite the watergap is a windgap. This has a meandering plan, is narrow in proportion to its length and has steep walls. It thus suggests a former watergap along the course of a S. W.-flowing consequent superimposed on the Devonian rocks and afterwards beheaded by the subsequent sector of Tunnel Creek flowing along the inner marginal plain. However, since capture, the gap has been modified by erosion because there is quite a steep, if low, rock divide in the windgap. North of the rock divide, a cave penetrates deeply into a meander spur. It is possible that a stream flowing through this gap, cut off this meander by an underground course; this would account for the rock divide in the present day windgap.

The gorge behind Barnet Spring also presents a particular problem. This gorge runs through the middle of a narrow promotory (only $^{3}/_{4}$ mile across) projecting from the range; it is also transverse to the strike of the forereef beds at the tip of the promontory. The gorge is narrow (100 yards), vertically walled, 200 feet deep in parts. The intermittent stream it now carries is completely underfit and at present is chiefly despos-siting. The head of the valley merges with a broad shallow depression in the plateau top. The explanation of these facts seems to be in terms of the dismemberment of a N. E. - S. W. flowing river rising in the Van Emmerick

Range or farther N.E. It was superimposed on to the Devonian and began cutting the Gorge before the promontory had been etched out during the development of the outer marginal plain and its pediments. The river was then beheaded by subsequent tributaries of Hawkestone Creek. Finally the promontory was defined through scarp retreat and pedimentation, guided by the strike of the forereef beds, to leave the gorge in its present most anomalous position.

In terms of the karst sequence, the most important point emerging from this discussion of the gaps in the Limestone Ranges is the additional evidence it provides for the vital role played by pedimentation particularly by the fashioning of pediment embayments and pediment passes.

6. DISCUSSION

No mention has so far been made of climatic change, yet this is a factor already widely recognised as vital in karst development and is indeed a corollary to the concept of karst evolution varying with climate geographically. It has been considered both in relation to temperate karst (MELIK, 1955; ROGLIČ, 1954; TRICART, 1955; WARWICK, 1955) and to tropical karst (TRICART, 1956; TRICART and DA SILVA, 1960).

Little is directly known of climate during the upper Tertiary and the Pleistocene in the Fitzroy Basin, but that there have been appreciable changes can hardly be doubted in the light of evidence from other parts of Australia. This evidence points to more widespread wetter conditions than now until late in the Tertiary, whilst the Pleistocene has been marked by arid-humid oscillations. Within the Basin itself, however, the only evidence so far observed is provided by the fixed longitudinal dunes of the Quaternary 'pindan' sands of the Fitzroy valley. Their direction is predominantly E. - W., but varies from E. N. E. - W. S. W. to E. S. E. - W. N. W. They reach quite close to the Limestone Ranges, in fact to within 2 miles of the limestone hills west of the Pillara Range, Though MADIGAN (1936) has interpreted the regional dune direction as in adjustment with the present wind system, a drier climatic phase for their construction is implied, since they are no longer in motion and carry a complete cover of scrub and sparse woodland. The Limestone Ranges must have suffered a similar climatic change and some of the karst phenomena observed seem to call for explanation in terms of arid-humid oscillations. However, the strongly concentrated rainfall régime with a pronounced contrast between the 'wet' and the 'dry' seasons makes the discrimination between the present and past climatic effects a sensitive task. Closer study of superficial deposits in the future may reveal the effects of the interplay of more arid and more humid phases but at the moment, since there is litle evidence of wetter Pleistocene climates in the area, the most valid course seems to be to interpret the landforms in terms of present climatic conditions.

In the field experience of the present writers, the Fitzroy Basin karst appears to be a distinctive one, in which lithological and structural factors, small available relief and especially climatic conditions are operative.

The minor surface solution features, which are elaborate and actively developing, have a certain degree of similarity with those of the climatically homologous bare karst of the Bom de Jesus Lapa in Bahia province, Brazil. The karst of the Hadramaut (WISSMANN, 1957), with similar temperature conditions but less rainfall, has a paucity of surface solution phenomena, being marked instead by the development of protective skins of secondary sinter. This skin is not due to deposition of transported calcium carbonate but to a recrystallisation and hardening of the rock surface in situ. This resembles in some ways the development of calcrete on the pediments of the Limestone Ranges. Within Australia, an example of a drier karst than that of the Fitzroy Basin is provided by the Nullarbor Plain, though this verges on the warm temperate in temperature conditions; here also small-scale solution features are meagrely developed in comparison (JENNINGS, 1961).

The nature of the solution features beneath soil or superficial deposits was seen at only a few points in the Limestone Ranges. Smoothed surfaces were characteristic of this subsoil solution and no great depth of solution feature was observed. This contrasts with the conditions described by TRICART (1956) from the wetter tropical savannah karst of Belo Horizonte in Brazil, where very large lapiés have developed there beneath soil cover in humid Pleistocene phases to be etched out in dry phases. However, the geological structure of partially metamorphosed calcareous formations there complicates the comparison. In a simpler geological context, the tropical monsoonal karst of the Katherine area in the Northern Territory of Australia has a rainfall of 35". Here surface solution features in bare karst are well developed. Much of this karst however is soil-covered and a recently developed doline, by the side of the Stuart Highway, 17 miles south of Katherine, shows that pronounced solution of the limestone goes on beneath it. So it is possible that a higher rainfall may be necessary for the development of the deep soil cover and the more pronounced subsoil solution features. The difference in the residuals soils also bears on the question. The grey and brown soils of heavy texture and the loams of the Limestone Ranges are more calcic and less leached than the red earths at Katherine and the terra rossa of rainier climates.

Both BIROT (1954) and CORBEL (1959) have expressed the view that surface solution effects are meagre in tropical dry climates and pronounced in tropical humid climates. With their fairly low rainfalls of today and in the absence of evidence of Pleistocene humid periods as yet, the Limestone Ranges seem to contradict this rule.

Neither the cockpit karst of tropical humid climates nor the doline karst more characteristic of temperate climates, is found in the Limestone Ranges. Instead the early stage of the karst development is dominated by the karst corridor topography. These 'giant grikes' can be regarded as extremely structurally controlled dolines, for which competent limestone and strong jointing are necessary. Nevertheless, these structural conditions do not explain their occurrence since such conditions are met with frequently in karst of other climatic conditions without the development of such landforms. Arid landforms in other rock types are well known to display greater angularity than their counterparts of humid lands. The development of a thick soil mantle, which might soften contours, is minimised by lack of moisture and of much vegetation. However, the Nullarbor Plain, with jointed, crystalline limestones at its surface, is largely a covered karst despite low rainfall, and dolines are the characteristic karst landform, though they are few and far between. Admittedly the collapse dolines show joint influence in their plan and retain sharp cliff margins for a long time. The close fields of karst corridors of the Fitzroy Basin karst therefore seem best attributed to a combination of a short season when surface solution is very active with a long, dry season when conditions inhibit the development of soil and rock mantle, which might tend to obliterate the previous etching out of structural weaknesses.

The less frequent larger enclosed depressions, polje-like in nature, and some of the marginal ampitheatres again require strong, jointed limestone to allow for their very steep bounding walls but lateral corrosion is implied as the active agent. Lateral corrosion is generally accepted as being widely operative in tropical humid karst. In the Limestone Ranges the intensity of the precipitation could account for the importance of this process.

However, the somewhat contradictory evidence from the Katherine area must be accounted for. Its higher rainfall is received over a longer wet season, yet it remains very intense in its occurrence. Nevertheless the karst here is characterised by dolines of normal type (LITCHFIELD, W. H., 1952). This discrepancy may find explanation along the following lines. The limestone at Katherine has only recently been and is still being stripped of a sandstone cover belonging to the same formation. Karst dissection of the limestone is only beginning and there is much residual impervious material remaining to help produce a higher proportion of covered karst. This interpretation may also help to reconcile the facts that the Katherine limestone seems to be of a high degree of purity and that in tropical humid conditions, doline karst seems to be associated with impure limestone series. (LEHMANN, 1955; SWEETING, 1958).

The only moderate importance of enclosed depressions and the preponderance of integrated valley systems through much of the karst development in the Limestone Ranges may be in part due to the small available relief. Because of this, cave roofs lie not far from the surface and roof collapse is more likely; this latter process is also promoted by the intense surface solution, a climatic effect. To a limited extent the tendency for valley floors to be sealed by travertine deposition, prevents the preservation of enclosed depressions and this is also a response to climatic conditions. Cave development is much more important in the Limestone Ranges than in the drier Hadramaut karst and the frequency of caves as a whole, if not of large caves, is greater area for area than in the drier Nullarbor Plains. Nevertheless as stressed above, the limited available relief together with quite strong surface solution seem to restrict the occurrence of large and complex caves. Despite its immaturity the wetter Katherine karst seems to have more long caves, area for area, than the Limestone Ranges. Calcite decorations in the Limestone Ranges caves are much more frequent than in the Hadramaut or the Nullarbor Plains but are inevitably dulled by the long inactivity of the dry season.

The later tower karst stage of the Fitzroy Basin links it more closely with the tropical humid karst than with the style of temperate karsts. Comparing the distribution of tower and cockpit karst in humid tropical areas, LEHMANN (1955) has concluded that the former is associated with greater available relief and more massive limestones. The Limestone Ranges provide neither of these conditions. Indeed the tower karst here is of small dimensions because of low available relief yet it retains the essential characters in predominantly well-bedded limestones. SWEETING (1958) stresses the connection between tower karst and a watertable or rest-level close to the ground surface in the depressions and valleys of the karst, which promotes lateral corrosion and the undercutting of projecting limestone residuals. This view has greater relevance in the Limestone Ranges, for the towers project from the modern surface there which is graded to sea level. But once more the extremely intense precipitation of this region must be stressed as a factor promoting lateral corrosion round the bases of the towers.

Nevertheless although lateral corrosion at the margins of flat alluviated surfaces plays quite a large part in the fashioning of the landforms of the Limestone Ranges, not all the lateral corrosion is quite of this type. Instead there is the lateral corrosion associated with the pedimentation of the bare rock pediments, pediment embayments and passes. The floors of many of the box-valleys may be placed here also. Here much rock is exposed and there is a far from complete cover of soil and alluvium. Rainwater and sheetfloods do not perforate these outcrops and develop underground drainage to any extent; the solution pan, not the solution slot, is dominant. Closeness to base level and the large amount of rain when it falls lead to lateral planation of the rock surface. Insofar as mechanical abrasion is involved through the provision of rock tools from the Pre Cambrian inliers and other sources, it is a case of normal semi-arid pedimentation entering into the karst development. But planation by solution of exposed limestone surfaces is a special type of semi-arid karstic pedimentation. Where calcrete ridges promote in their own peculiar way the development of flat rock pediments, there is yet another expression of the tropical semi-arid climate in the karst here.

Thus the inner and outer marginal plains of the Napier, Oscar and Geikie Ranges and the plains between and around the smaller southeastern ranges have been produced, not only by lateral corrasion by the major rivers and by pedimentation of normal type, but also by lateral corrosion by flooding from an alluvial cover and by karstic pedimentation. To the extent that the latter two processes are involved over pure calcareous formations, these plains are ‚karst margin plains‘ or Karstrandebenen (e. g. LEHMANN, et al., 1954). That a form of pedimentation peculiar to karst can contribute to the formation of such plains does not seem to have been recognised before. The portion of the inner marginal plain behind the Napier Range, which drains through The Tunnel, almost falls into the category of ‚marginal polje‘ or Randpolje (LEHMANN, 1956).

It is unfortunate that no study of a substantial area of karst in closely comparable climatic conditions is known to the writers for comparison. The Bom de Jesus Lapa (TRICART and DA SILVA, 1960) is climatically very homologous but unfortunately conprises only one large hill of limestone. Limestone does, however, underlie parts of the surrounding pedimented plain, though the exact extent is not known. The two karsts have much in common, especially when allowance is made for the greater available relief of the restricted Brazilian example. The comparison of the two certainly supports the claim made by TRICART and DA SILVA that there is a new variety of karst to be recognized in the tropical semi-arid climate, differing substantially from the ‚classical' tropical karst of more humid conditions, but which is more closely related to that karst style than to any other.

This comparison leads to a final point since TRICART and DA SILVA are concerned to demonstrate that the karst features of their area are developing very slowly and have in fact done so for a long time. In their view the Bom de Jesus Lapa has scarcely changed in overall shape since late Miocene times when a more humid climate came to an end. What then has been the rate of development of the Fitzroy Basin karst? It is unfortunate that the data are very imperfect for answering this question which is really compounded of two others — (a) how long has the present karst cycle been developing? (b) how far has the new cycle gone in destroying the old? A third question as to what is the present rate of erosion provides another approach.

The date of the rejuvenation which set in motion the destruction of the upper planation surface can only be placed within broad limits resting on general argument less than on direct evidence. The range of time given for the beginning of this rejuvenation is unfortunately very wide, from the Oligocene to the Pliocene.

On the more impervious calcareous formations such as the Fairfield Beds and Mt. Pierre Group, the older surface nowhere survives intact; it has usually been replaced entirely by the modern surface. Fairly substantial residual relief survives only in a few places, usually where the facies is rather more purely calcareous. On the other hand on the Devonian formations, pure enough to give rise to a predominantly karst evolution, a very large proportion remains in the undissected old surface and in the dissected relief derived from it. It is true that it is not known precisely how far these formations reach under the outer marginal plain; it is possible that the published geological maps are a little conservative in this respect. Nor can we be sure how far across the inner marginal plains the limestone formations formerly reached over the Precambrian, though the further they reached, the more impure they are likely to have been and in this sense may not be relevant to the question at issue. Nevertheless, even if the published geological maps are not quite exact in this respect, it is apparent that the main bulk of the Devonian formations, which are subject to a karst cycle because of their purity, has so far survived the erosional attack brought about by the rejuvenation of the old surface of planation.

If that rejuvenation goes back to the Oligoceme, without doubt the karst cycle of the Fitzroy Basin has proceeded very slowly. Even if it reaches back only to the upper Pliocene, the rate of limestone erosion still seems to be moderate.

There is a fundamental cleavage of view about rates of limestone erosion between those who regard the optimal conditions for solution as occurring in the humid tropics and those who favour cool to cold temperate regions of high precipitation. In the latter category, CORBEL (1957) stresses the greater solubility of CO_2 and of calcium carbonate at the lower temperatures, the high CO_2 content of air in snow and the smaller losses of moisture by evapotranspiration. In the former school, there are authorities such as LEHMANN (1955) and BIROT (1954), who argue that the faster rate of chemical reactions at the higher water temperatures in the tropics matters more than the lower saturation level for bicarbonates. They point to the higher rate of production of ‚biological CO_2', because of the rapid growth and decay of vegetation and soil micro-organisms in the tropics; moreover organic acids capable of dissolving limestones are more prevalent for the same reason. Furthermore, vegetation colonies steeper slopes in the tropics.

Both schools agree, however, in thinking that the rate of solution is low in tropical dry karst because of the low level of biological activity, the very high loss of evaporation from an initially low rainfall and the discontinuity of a soil cover, which could act as a humidity reservoir promoting subsoil solution. CORBEL stresses also the low saturation level at the high water temperatures experienced. The general argument presented previously about the rate of limestone erosion in the Fitzroy Basin reaches only a rather loose conclusion, which is, however, in agreement with this consensus of opinion.

CORBEL (1959) and others have been concerned to develop quantitative methods in the problem of the comparative rates of limestone solution in different climatic conditions. Adequate data are not available to apply these methods to the Limestone Ranges. Certain observations, made in 1959, are discussed in Appendix I, but they are inconclusive as regards the question under discussion. However, the Limestone Ranges provide a warning with respect to one aspect of these quantitative measures. CORBEL has made important use of the amount of calcium carbonate being removed annually in the rivers of a karst area as a measure of the rate at which the karst in evolving. The fairly common occurrence of surface travertine features in the Limestone Ranges is an indication, however, that the rate of removal of calcium carbonate is not a full measure of the rate of solution of the limestone by the natural waters of the area. Nor can we be certain that the calcrete of the area does not receive an accession of $CaCO_3$ from upstanding limestone of the area through the medium of groundwater, even though the calcrete does predominantly represent a weathering or pedogenic product of the rock in situ. Thus there is an element of redistribution of calcium carbonate within the karst area as well as one of complete removal of the solution products. CORBEL has pointed to the great frequency and bulk of secondary calcite deposition within caves in tropical humid areas as a measure of the slow rate of erosion of tropical karst; it is, however, a further reason for recognising that CORBEL's figures for annual removal of limestone should not be regarded as a full measure of the rate of development of karst landforms at all stages. Additional solution may be occurring at least in the earlier stages.

This factor of redistribution however is not the major reason why advanced stages of karst landform development are found in the Limestone Ranges despite a probable slow rate of development. It has been recognised that most tropical humid karsts have had long periods of geological time for their development, uninterrupted by glacial periods in the Pleistocene, when karst development was largely inhibited. The same prolonged opportunity for development has been the case in the Fitzroy Basin karst, though there may have been drier phases in the Pleistocene when the rate of development was slower even that at present.

Table 2

Water determinations from Limestone Ranges, Fitzroy Basin

No.	Point of Collection	Date	Temp.°F	pH	$CaCO_3$ mg/1	$MgCO_3$ mg/1	Free CO_2 mg/1	Other Analyses +
1	Pool in Surface Solution Pan near Geikie Gorge	22/5/59	76.5	9.2	109	3	Nil	+
2	Pool in Small Doline near Moolee Spring	27/5/59	63	7.5	28	4	1.6	+
3	Drip in cliff-foot cave near Barnet Spring	13/6/59	75	8.3	117	7	—	—
4	Rimstone pool in Old Napier Downs Cave	14/6/59	71	8.2	120	7	—	—
5	Fitzroy River at mouth of Geikie Gorge in moderate flood	22/5/59	75	7.9	46	21	—	—
6	Stagnant river pool in The Tunnel Cave	1/6/59	66	8.3	147	45	Nil	+
7	Brooking Gorge river pool at very small flow	23/5/59	70	7.6	140	50	1.4	+
8	Brooking Spring	23/5/59	77.5	7.3	332	8	0.55	+
9	Elimberrie Spring	29/5/59	80	7.1	312	16	10.4	+
10	Wire Spring (E) at point of issue from rock	29/5/59	92.5	6.8	174	130	18.0	+
11	Wire Spring (E) at lowest rimstone pool	29/5/59	69	8.7	172	121	1.0	—
12	Siphon Spring at point of issue from rock	25/6/59	78	7.0	299	9	—	+
13	Siphon Spring at lowest pool	25/6/59	76	7.9	285	13	—	—
14	Pillara Spring at point of issue from rock	2/7/59	72.5	7.2	198	25	—	+
15	Pinnacle Yard Spring at point of issue from rock	7/7/59	71	7.0	330.4	Nil	—	+

1. Temperature, pH and ‚free CO_2‘ determined at point of collection. Others in laboratory.
2. Methods — Ca and Mg by E.D.T.A. methods; ‚free CO_2‘ by sodium hydroxide (standardised against potassium hydrophthallate) and phenolphthalein; pH by Lovibond Comparator.
3. Most of the samples as indicated in final column were analysed for other constituents.
   Mrs. I. A. SERJEANT determined Na, K, Cl and checked our Ca and Mg determinations.
   Mr. P. SERJEANT determined SO_4. All values of Na, K, Cl. and SO_4 were so low as to be negligible.

APENDIX I: WATER DETERMINATIONS

The quantitative measures, which have been employed in recent years in the discussion of the problem of relative rates of limestone solution and other karst problems are:

1. The calcium and magnesium carbonate contents of surface and underground waters at various types of collecting point, but especially at rivers.
2. The river discharges from the karst areas.
3. The so-called 'free CO_2' contents of surface and underground waters.

No run-off data were available from the Limestone Ranges and only a restricted number of chemical determinations from the dry season of 1959 were made (Table 2).

The figures for 'free CO_2' were the last of a series of such determinations by the authors from various limestone areas of Australia and this parameter has since been abandoned by them on two counts, (1) the unreliability of the experimental techniques available in the field and the fact that this determination must be made at the point of collection or nearby in unchanged atmosperic conditions, (2) the doubtful value of even accurate determinations as an indication of corrosive power with respect to limestone when the pH is above 7.2 and this occurs quite commonly.

It is true that the two high values for 'free CO_2' listed here come from springs at the point of issue from small, water-filled openings in the bedrock so that there had been no opportunity for attaining equilibrium with the free atmosphere. In the other samples, including that for Brooking Spring, the water had been exposed from some time to the open air or the atmosphere of a well-ventilated cavern. Moreover the change from 18 mg/l at the rock outlet of Wire Spring to 1 mg/l at the lowest rimstone pool to which the spring was flowing at the time, does seem to register an adjustment to equilibrium with normal atmospheric partial pressure of CO_2. Nevertheless neither here nor in other areas is there any close correspondence with the results obtained by applying TROMBE's graph of pH, temperature and calcium carbonate content to indicate the corrosive capacity of the waters (TROMBE, 1952; CORBEL, 1959). This second method is preferred as being based on measurements which can be made more reliably and more conveniently.

In these climatic conditions, there was the possibility of the presence of large amounts of other salts such as sodium chloride, magnesium and calcium sulphate, which might invoke the law of mass action and which might vitiate the conversion of calcium and magnesium determinations by the E. D. T. A. method into carbonate equivalents. Therefore a representative series of 10 samples were analysed for the Cl and SO_4 anions, the Na and K cations by Mr. P. SERGEANT and Mrs. I. A. SERGEANT at our request. All of them were of such low value that the anticipated difficulties do not in fact arise.

The low ratio of magnesium to calcium in most samples points to the virtual absence of dolomite in the rocks affecting them. There must, however, be some dolomite in The Tunnel, Brooking Gorge and Geikie Gorge, and a great deal in the area feeding Wire Spring.

A comparison will now be made of the Fitzroy samples (Table 2) with a number of samples from other Australian limestone areas determined by the present writers either separately or in collaboration.

Sample 1. This saturated surface solution pan pool has a much higher $CaCO_3$ content than two saturated and two aggresive pan samples from Cooleman Plain, a high plain at 4,000 feet in southern N.S.W., a very slightly higher value than an aggressive pan sample from Buchan, Victoria, (107) and a much higher value than a sample from Mole Creek (Tasmania), (70).

Sample 2. The pool in a small doline near Moolee Spring has a low $CaCO_3$ content and is aggressive. The tiny pool was sitting on silty clay and the amount of contact the water had had with the limestone rock may have been very slight.

Sample 1 was not collected until 2½ days after the relevant rain, Sample 2 until 8½ days after; there may have been marked concentration by evaporation. Therefore it is not possible to argue from the figures as to how surface solution compares between the hotter and the cooler climates.

Sample 3. This cave drip was saturated at much lower values of $CaCO_3$ than 6 determinations of cave drips at Wee Jasper and Jenolan in N.S.W. (5 saturated and 1 aggressive).

Sample 4. The rimstone pool from Old Napier Downs Cave was saturated at a lower $CaCO_3$ level than 5 saturated and 1 aggressive rimstone pools in S.E. Australia and Tasmania, but has a slightly higher value than 3 other pools from Tasmania, 2 of which were aggressive and 1 was saturated.

These two comparisons suggest that secondary calcite precipitation may occur more readily in the caves of this tropical semi-arid area than in the mid-latitude caves of the continent. Remarkably low relative humidities can reach well into many of the Fitzroy Basin Caves (e. g. 32%, 38%) so that it is possible that evaporation really can play the role in the precipitation of cave calcite, which is often wrongly attributed to it elsewhere in humid cave atmosphere.

Sample 5. During a moderate flood, the Fitzroy River had a fairly low calcium carbonate content and was still aggressive where it left the long length of Geikie Gorge. This can be compared with the higher contents of still aggressive water from the Murrindal River, Buchan, Victoria, Jenolan River and Yarrongobilly Rivers, New South Wales, and with the higher centents of saturated waters from Grove Creek, Abercrombie and Belubula River, Cliefden, both in New South Wales. However, all these rivers of S.E. Australia had higher proportions of their catchments above the point of sampling in limestone than in the case of the Fitzroy.

Sample 6. This large, stagnant river pool in the Tunnel cave was saturated at a much lower $CaCO_3$ content than an almost stagnant river pool in Dogleg Cave, Wee Jasper, NSW., though the two cases were not fully comparable.

Sample 7. Brooking Gorge pool is part of a river entirely in limestone; however the flow was small at the time of sampling. The water was slightly aggressive and its carbonate content, though substantial, was much less han Davy's Cree, Cliefden, New Souuth Wales, when this latter was at different times saturated and slightly aggressive. On the other hand, its content was equal to those of Cave Creek, Cooleman Plain, N.S.W. and Mole Creek, Tasmania, when these were saturated. Both of these rivers have a substantial part of the catchment in limestone.

Samples 8, 9, 10, 12, 14, 15. These Fitzroy Basin springs gave a mean $CaCO_3$ content of 274 mg/l (total magnesium and calcium carbonates 306 mg/l). This compares with 177 mg/l (210) as the mean of 18 springs from S.E. Australia in areas of mean annual temperature of 50—60° F., and with 80 mg/l (91) as the mean of 7 springs from S.E. Australia and Tasmania in areas with mean annual temperature below 50° F. The Fitzroy Basin springs were nearly all almost saturated or saturated when they emerged, whilst the springs from the mid-latitudes were mainly aggressive but included some saturated ones. The flows of all the Fitzroy Basin springs were small when sampled and it was the springs of small flow from the other areas, which had high values and were on the whole the saturated ones. Therefore not a great deal of significance can be attached to these high values from the Limestone Ranges. The total flow from all springs of the area was very low in the dry season of 1959 and the high carbonate content may be merely a reflection of the concentration of surface water by evaporation before it goes underground (ANDERSON, 1945). If, however, the springs could be shown to maintain these high values in the time of greater flow in the wet season, there remains the possibility of a quite substantial rate of underground solution today in the area.

It is claimed locally that the springs do not yield as well as they did in the early days of white settlement. But this based on oral tradition, which is notoriously unreliable in such matters; only the good ‚wets‘ of former years may have been remembered to be compared with the poor ‚wets‘ of the present time. In fact, as has been mentioned earlier, there is no direct evidence of past periods of greater rainfall to explain the karst of this semi-arid area in the manner suggested for other areas (BIROT, 1954; D. KING, 1950). There is only the evidence of the fixed dunes pointing to drier times.

The water observations are then too limited in several respects to support or modify the contention that the rate of removal of limestone is slow in this climate. They are presented and discussed here largely because the illustrate some of the difficulties and complexities facing this type of approach.

ZUSAMMENFASSUNG

Die Kalkketten (Limestone Ranges) bestehen aus devonem Riffkalk und liegen an der Nordseite des Fitzroy Beckens im nordwestlichen Teil des Staates Westaustralien. Im großen und ganzen liegen sie in einem einzigen Klimagebiet, dem heißen, halbariden Klima Köppens BSwh — und sie sind der Schauplatz einer tropisch-semiariden Karstbildung. Die Kalkketten werden von einer bedeutenden Einebnungsfläche geschnitten, die in dieser Arbeit als die „Ältere Einebnungsfläche“ bezeichnet wird. Das Ansteigen der Ketten von einer Einebnungsfläche jüngeren Alters ist ebenfalls ein sehr unvermitteltes.

Von der älteren Einebnungsfläche sind nur kleine Reste erhalten. Diese bilden unzerschnittene, rasenbedeckte Flächen mit schwarzem Boden, die voneinander durch in größerem Abstand befindliche Entwässerungslinien getrennt sind. Der größte Teil der Kalkketten besteht jedoch aus zerschnittenem, vorwiegend nacktem Karst. In den Frühstadien seiner Entwicklung wird der zerschnittene Karst durch Karstgassen (karst corridors, bogazi) beherrscht, die sich in der weiteren Entwicklung in ein zusammenhängendes System von Tälern mit kastenförmigem Querschnitt erweitern. Geschlossene Senken sind verhältnismäßig selten, Dolinen, wie sie für den Karst des gemäßigten Klimas typisch sind, kommen nur gelegentlich vor, und die Cockpits des feuchttropischen Karstes fehlen völlig. Hin und wieder gibt es geschlossene Senken mit rechteckigem Grundriß, flacher Sohle und sehr steilen Wänden; sie lassen sich nicht ohne weiteres in eine der klassischen Kategorien der geschlossenen Karstsenken einordnen, weisen jedoch einige Kennzeichen von Poljen auf. Die größte dieser Art von Senken wird beschrieben. Die fortgeschrittenste Stufe der Zerschneidung der älteren Einebnungsfläche wird von einer Abart des Turmkarstes (tower karst) gebildet.

Dort wo die obere Einebnungsfläche zerstört ist, wurde die jüngere Einebnungsfläche gebildet. Die randlichen Steilhänge, die unvermittelt aus dieser Ebene ansteigen, werden von den Autoren als in aktiver Entwicklung befindliche Formen angesehen und nicht als exhumierte oder von Zerstörung verschont gebliebene Steiluferstücke. Man kann am Fuße dieser „Steiluferstrecken“ ausgezeichnete Beispiele von Sockelbildungen des Untergrundes finden, und auch diese werden als aktive, nicht fossile, Landformen angesehen. Ihre Form wird im einzelnen beschrieben. Die Fußhöhlen, die im Zusammenhang mit diesen „Steiluferstrecken“ auftreten, werden ebenfalls besprochen.

Was die Einzelzüge anbelangt, so kann gezeigt werden, daß die Entwicklung des Karstreliefs stark durch die Gesteinsart und Struktur der verschiedenen Riffkalkfazien der Kalkketten bedingt ist. Kleinere Formen, die ihren Ursprung Lösungsvorgängen verdanken, kommen ebenfalls sehr häu-

fig vor und bestehen u. a. aus Rillen- und Rinnenkarren. Diese werden kurz gesteift.

Die Ketten werden durch eine Reihe von transversalen Tälern und Paßfurchen gequert. Der Ansicht der Autoren nach ist der wahrscheinlichste Ursprung der Täler eine regionale Überlagerung des Entwässerungssystems, möglicherweise in mehr als einer Phase. Einige der Paßfurchen werden als Sockelpässe angesprochen.

Zum Abschluß werden die Beweisstücke für die Auswirkung früherer Klimate auf die Entwicklung der Karst-Landformen des Gebietes besprochen; es wird daraus der Schluß gezogen, daß sich diese in den Kalkketten sehr langsam entwickelt haben. In einem Anhang wird eine Zusammenfassung von Wasseranalysenproben gegeben.

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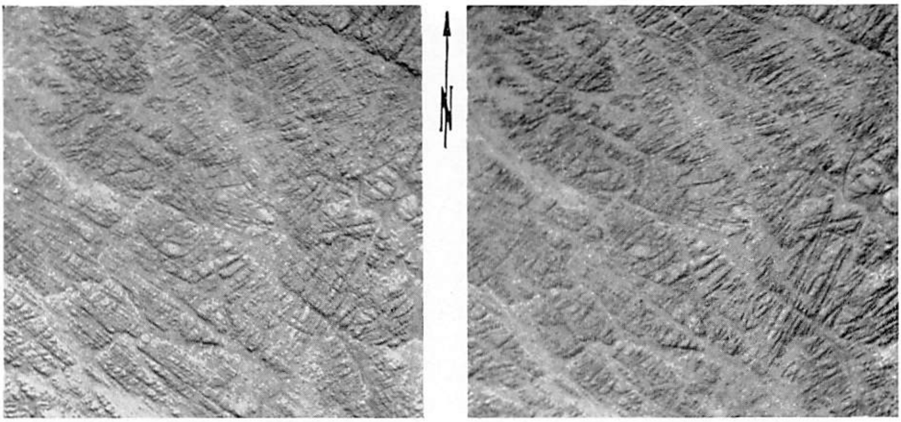
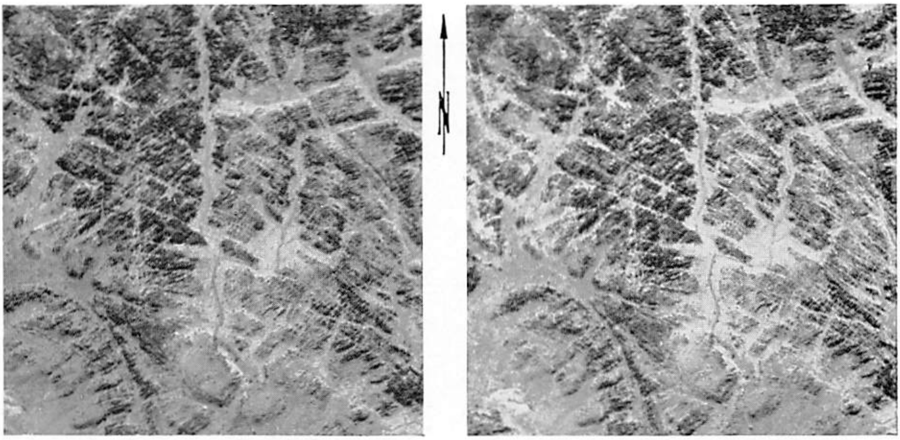
Appendix



A



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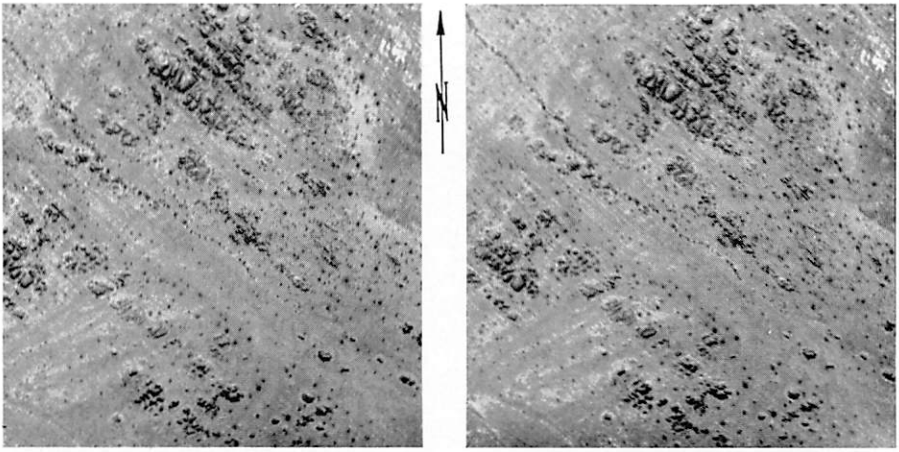

C

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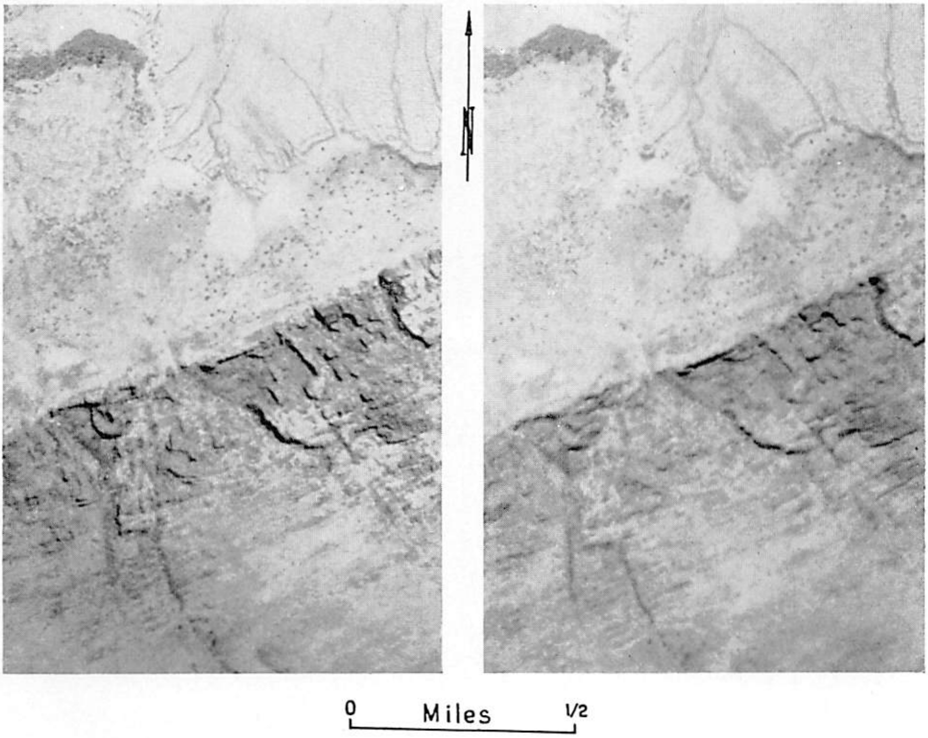
1. A. *Giant grikeland near Geikie Gorge.* In horizontal backreef facies. Early stage of dissection of Tertiary planation surface. Beginnings of box-valley development.

B. *Box-valleys in Oscar Range.* In horizontal backreef and steeply dipping forereef facies. Later stage of dissection but giant grikeland survives between the valleys.

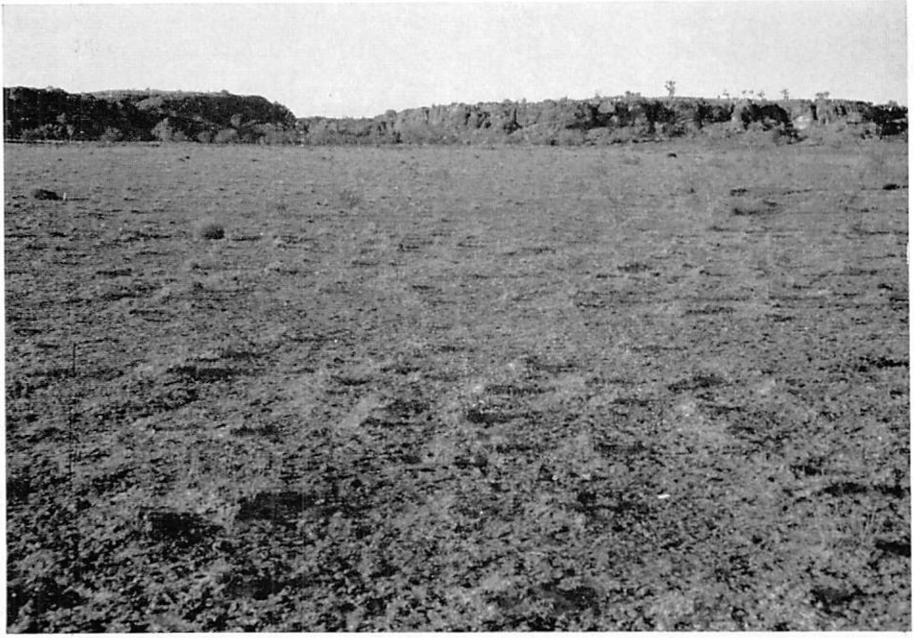
C. *Tower karst east of Geikie Range.* In nearly horizontal forereef facies. Advanced stage of dissection. Steepsided residuals separated by bare-rock pediments.

‚By permission of Royal Australian Air Force‘.

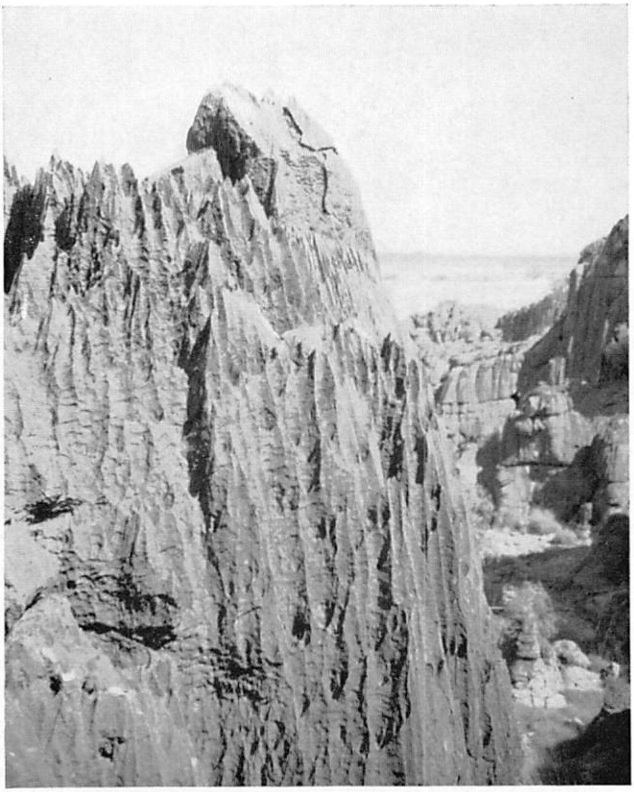


2. *Morown Cliff at northern end of Oscar Range.* To north, pediments partly under caliche, partly under black soil. Cliff in algal reef facies. Marginal amphitheatres and „storying“ in dissected karst behind. To south, undissected Tertiary planation surface.

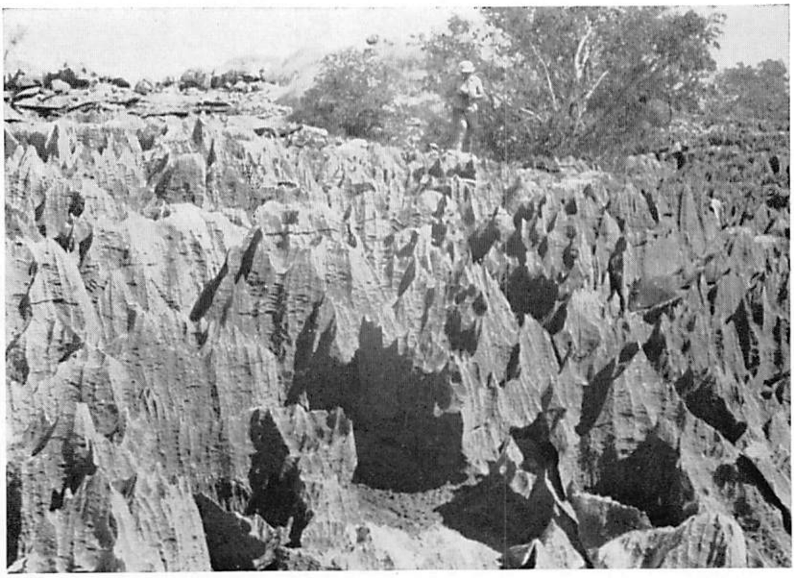
‚By permission of Royal Australian Air Force‘.



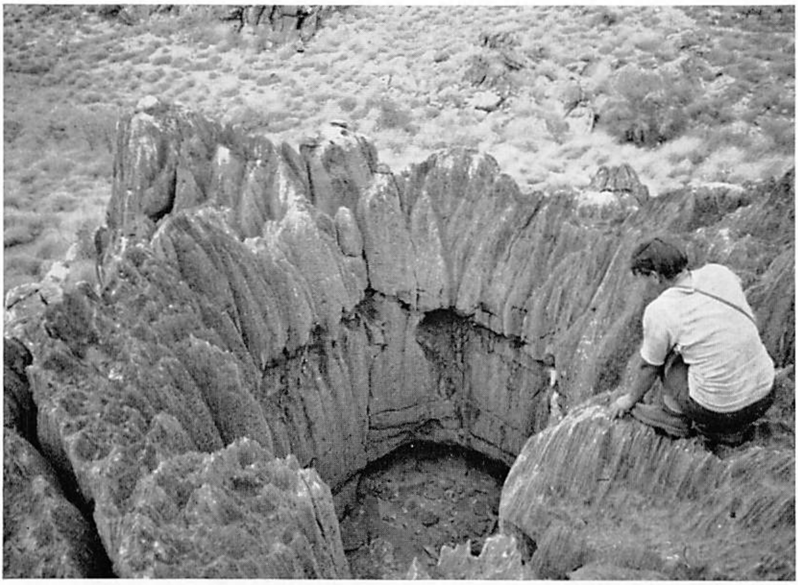
3. Steep edge of the Limestone Ranges and the inner marginal plain; Napier Range.



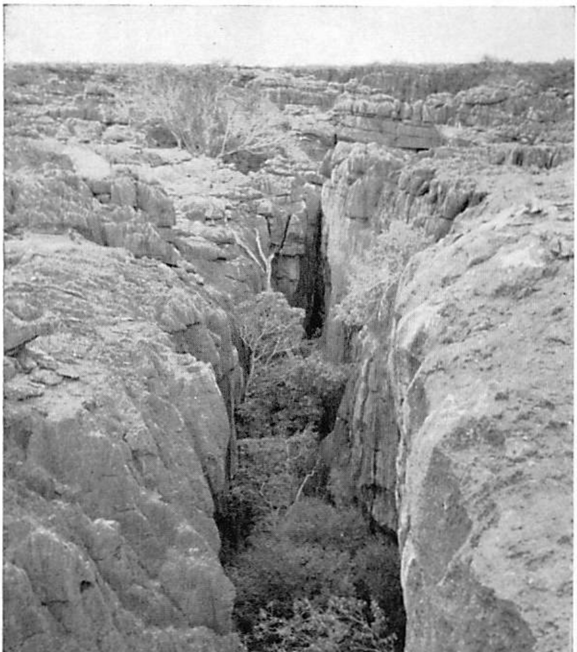
4. Rillen karren and rain pits: Emanuel Range.



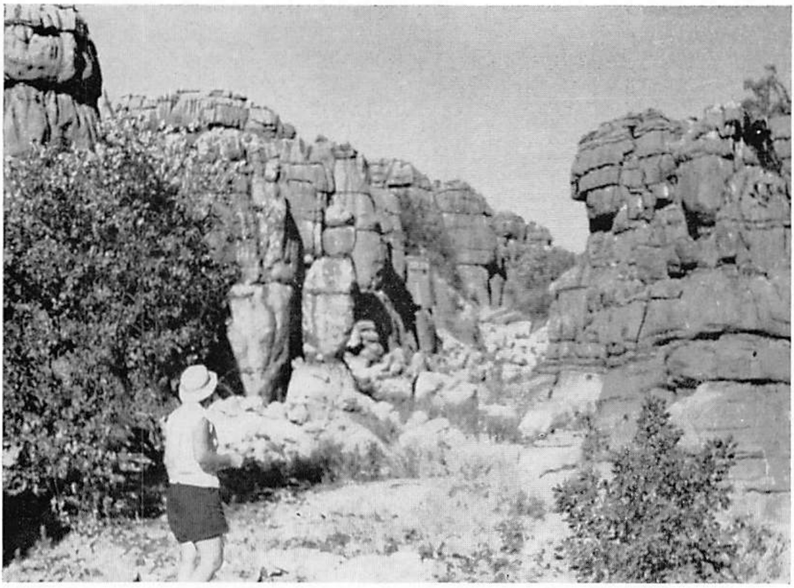
5. Karren: near Barnet Spring, Napier Range.



6. Pot-hole like pit: near Bugle Gap.

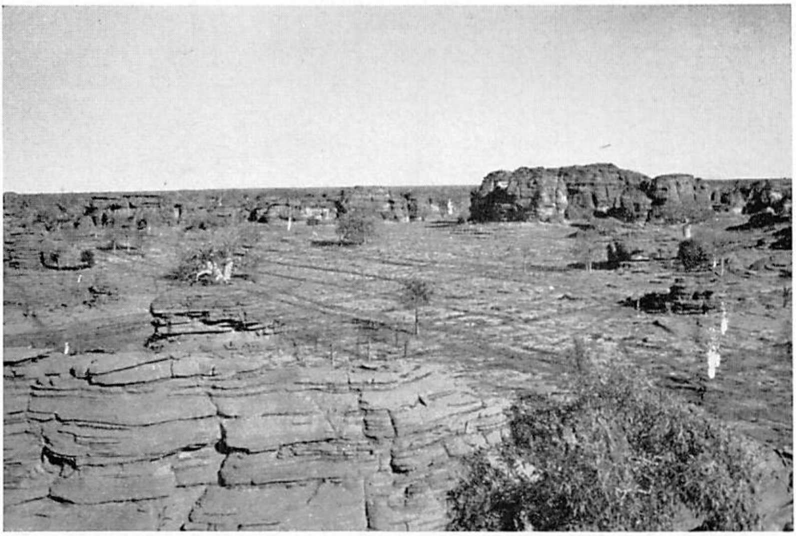


7. Giant Grike, (bogaz): Emanuel Range.



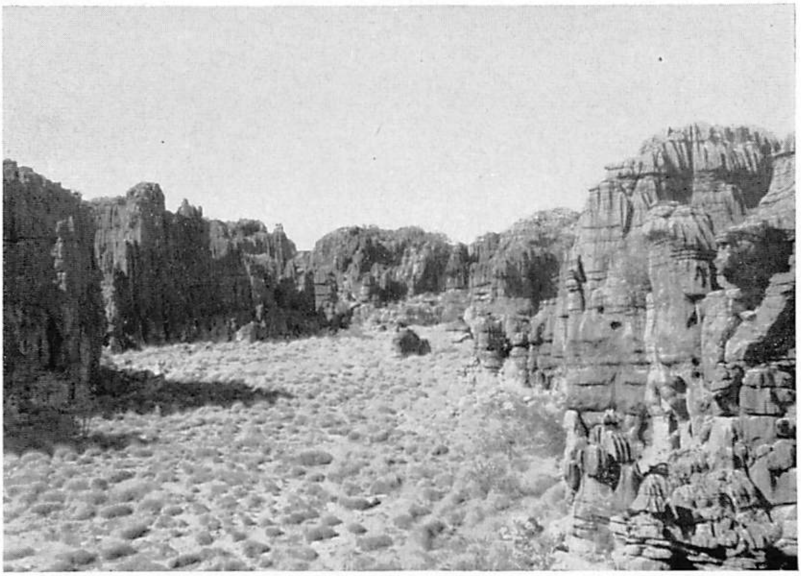
8. Box-like valley: near Geikie Gorge.

9. Tufa barrier in dry valley: near Barnet Spring.

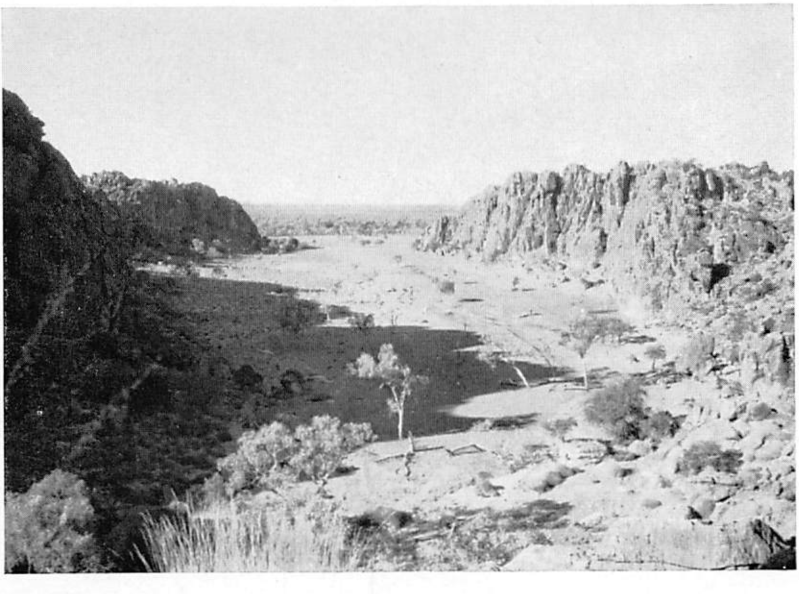


10. Turm karst: near J. K. Yard.

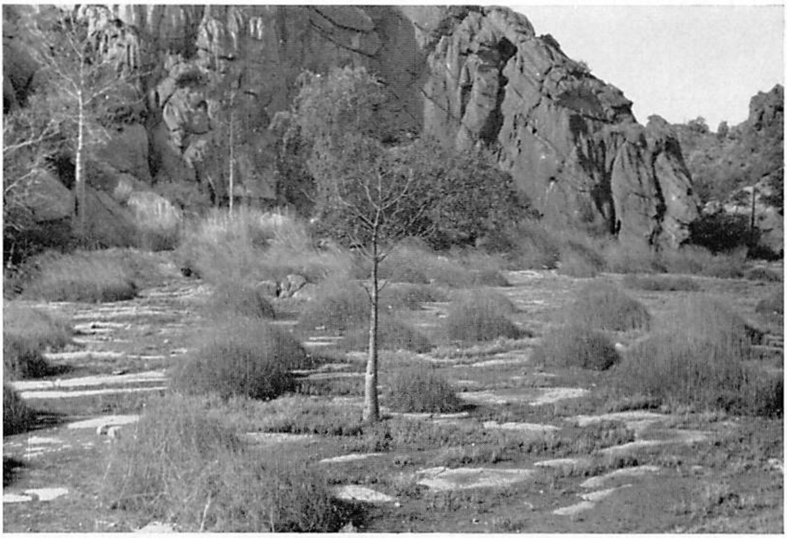
11. Isolated turm karst feature: near Barnet Spring.



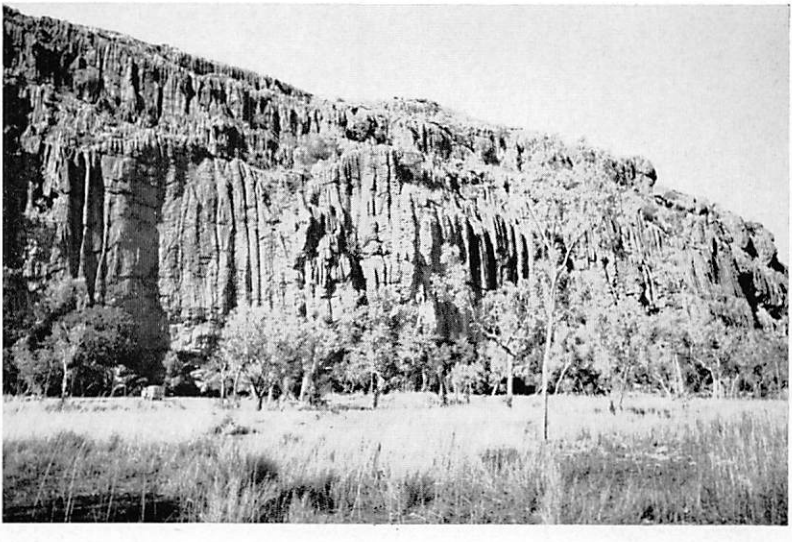
12. Enclosed depression: east of Bugle Gap.



13. Brooking Yard, marginal amphitheatre: Oscar Range.



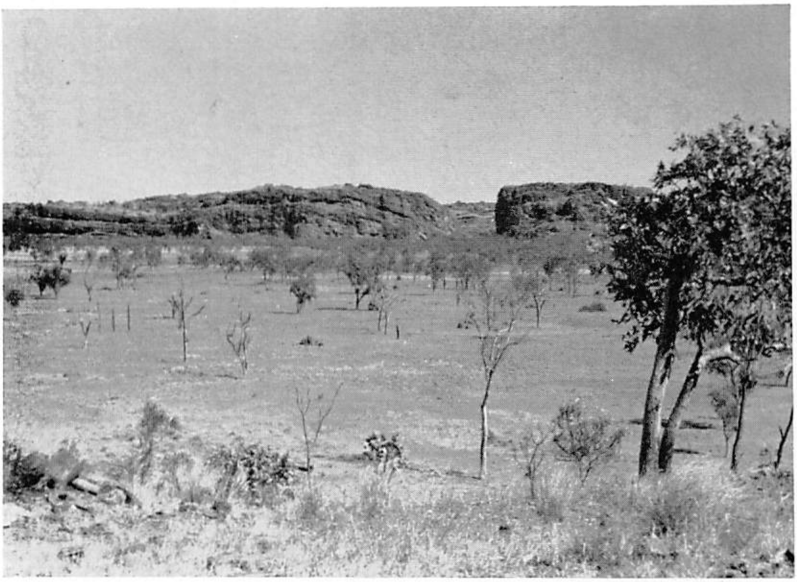
14. Pediment cut in dipping fore-reef limestones: Napier Range.



15. Locality of cliff-foot caves, near Barnet Spring: almost vertical cliff in algal limestones

16. Cliff-foot cave: near Barnet Spring.

17. Pseudo-anticlines in caliche: near J. K. Yard.



18. Eastern Entrance to the Windjana Gorge: Napier Range.

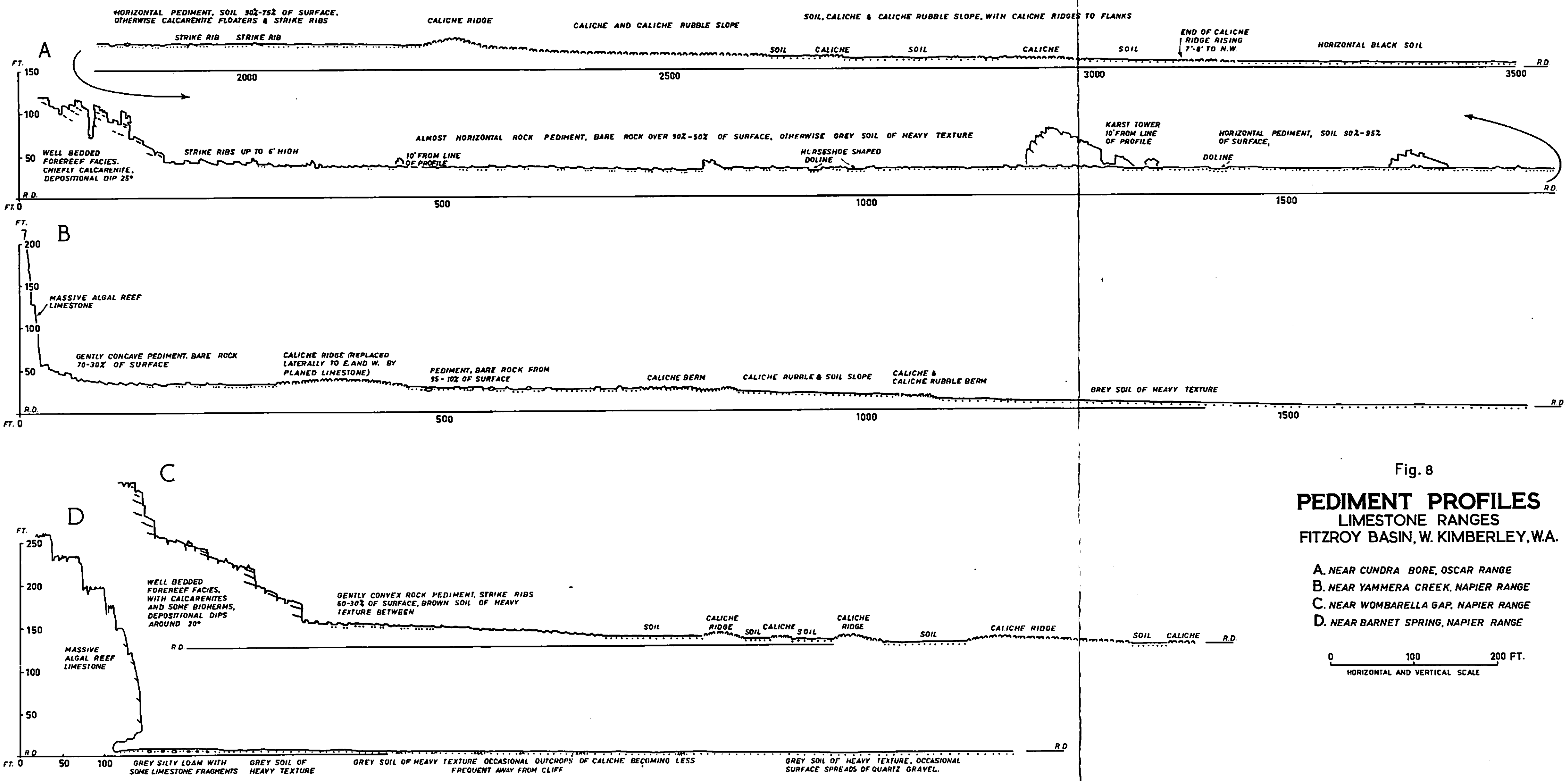


Fig. 8

PEDIMENT PROFILES
LIMESTONE RANGES
FITZROY BASIN, W. KIMBERLEY, W.A.

A. NEAR CUNDRA BORE, OSCAR RANGE
B. NEAR YAMMERA CREEK, NAPIER RANGE
C. NEAR WOMBARELLA GAP, NAPIER RANGE
D. NEAR BARNET SPRING, NAPIER RANGE

Fig. 9

CLIFF-FOOT CAVES

NEAR BARNET SPRING, W. KIMBERLEY, W.A.